EVALUATION AND VALIDATION OF PHENOMENA CULMINATING IN CARGOES OF IRON ORE FINES SHIFTING DURING MARINE TRANSPORTATION

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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July 2017
“It is an undoubted truth, that the successive improvements in the condition of man, from a state of ignorance and barbarism to that of the highest cultivation and refinement, are usually effected by the aid of machinery in procuring the necessaries, the comforts, and the elegancies of life; and that the pre-eminence of any people in civilization, is, and ought ever to be estimated by the state of industry and mechanical improvement among them.”

(Royal Institution of Great Britain, 1800)
DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

I gratefully acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship and also a domestic scholarship provided through the School of Engineering, Civil Engineering at RMIT University.

Michael Colin Munro

2 July 2017
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ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my senior supervisor, Dr. Abbas Mohajerani, for his guidance and continuous support throughout the duration of this PhD research. The knowledge, optimism, and enthusiasm he presented were my central motivation to complete the work, in its entirety, and to the best of my ability. I would also like to thank my associate supervisor, Dr. David Law, for his encouragement and support offered during this period.

Also, from RMIT University, my sincere thanks to the technical laboratory staff. These individuals, including: Bao Thach Nguyen, Kee Kong Wong, and Pavel Ryjkov, were not only a great support, but key to the successful installation and implementation of the apparatus designed and developed during this study, and for that I am grateful.

Unfortunately, due to the powers that be, others who were fundamental and indispensable due to their ability, immense knowledge, and overall competence, cannot be mentioned herein. Under these unintentional circumstances, it is here I express that without their advice and guidance, this research would not only be partial to what it is today, but the commencement would have likely never arisen.

Undoubtedly, the most indispensable encouragement and support originated from those who are closest, that being family and friends. I would like to specifically single out my father, Colin Ross Munro, because without his guidance, support, and practical knowledge, the design, development, and implementation of major aspects of this research, would have been near inconceivable.

To my other immediate family; Susan Munro, Taegan McNamara and Laura Munro, I would like to give thanks for your continuous encouragement, cheer and praise throughout my years of study, explicitly thanking my mother, Susan, for supplying me with the simple necessities to continue my research.

Finally, there is one more special thanks to give, that is to one of the most important people in my life, Antoinette Eva Yelayotis. I would like to thank you for your endless and resilient love, passion and overall friendship provided throughout these strenuous, yet most important, years of my life. I look forward to continuing our lives together, long into the future.

Michael Colin Munro

2 July 2017
TABLE OF CONTENTS

Declaration ......................................................................................................................... iii
Disclaimer and Copyright Notice .................................................................................... iv
Acknowledgements ......................................................................................................... v
Table of Contents ............................................................................................................. vi
List of Publications .......................................................................................................... xiv
Introduction .................................................................................................................... xiv
Peer-reviewed Manuscripts .............................................................................................. xiv
Conference Manuscript ................................................................................................... xiv
Unpublished Manuscripts ................................................................................................. xv
List of Tables .................................................................................................................... xvi
List of Figures .................................................................................................................. xx
List of Equations ............................................................................................................. xxxvi
List of Appendices .......................................................................................................... xxxviii
Abbreviations and Acronyms ......................................................................................... xxxix
Nomenclature .................................................................................................................. xli
Executive Summary ........................................................................................................ 44

Chapter 1  Introduction ................................................................................................... 46
1.1  Background .............................................................................................................. 46
1.2  Research Objectives ............................................................................................... 48
1.3  Significance ............................................................................................................. 49
1.4  Research Scope and Design ................................................................................... 50
1.4.1  Physical Properties of Iron Ore Fines ............................................................... 50
1.4.2  Phenomena Relating to Cargo Shift ................................................................. 51
1.4.3  Methods used for Prevention ........................................................................... 51
1.4.4  Suspected liquefaction Incidents ..................................................................... 52
1.4.5  Preliminary Test Design and Development ..................................................... 53
1.4.6  Computational Modelling ................................................................................. 53
1.4.7  Test Development and Utilization .................................................................... 54
1.4.8  Validity of Phenomenon and Testing Methods ............................................... 55
1.4.9  Preventing Future Incidents ............................................................................. 55
1.5  Structure of Thesis .................................................................................................. 56
Chapter 2  Literature Review ........................................................................................................ 58
  2.1  Introduction .................................................................................................................. 58
  2.2  Iron Ore ...................................................................................................................... 58
    2.2.1  Iron Ore Fines .................................................................................................... 59
  2.3  Transportation Vessels ............................................................................................... 61
  2.4  Loading and Unloading Techniques .......................................................................... 64
  2.5  Bulk Carrier Stability ................................................................................................. 64
  2.6  Cargo Shift Phenomenon ............................................................................................ 65
    2.6.1  Liquefaction ....................................................................................................... 65
    2.6.2  Cyclic Mobility, Incremental Collapse, and Shakedown .................................. 66
    2.6.3  Shearing (Slope Stability Analysis) .................................................................. 66
  2.7  Suspected Liquefaction Incidents .............................................................................. 67
  2.8  International Maritime Solid Bulk Cargoes Code (IMSBC Code) .............................. 68
    2.8.1  Iron Ore Technical Working Group (TWG) ....................................................... 69
    2.8.2  Original TML Test Methods ............................................................................ 70
    2.8.3  Modified Proctor/Fagerberg Test (MPFT) and Schedule for Iron Ore Fines ...... 71
    2.8.4  Trimming .......................................................................................................... 72
  2.9  Additional Susceptible Solid Bulk Cargoes ................................................................. 73
Chapter 3  Experimental Materials .......................................................................................... 77
  3.1  Introduction ................................................................................................................ 77
  3.2  Properties of Research Materials .............................................................................. 78
  3.3  Figures ......................................................................................................................... 81
Chapter 4  Experimental Methods ......................................................................................... 85
  4.1  Introduction ................................................................................................................ 85
  4.2  Particle Size Distribution and Hydraulic Conductivity .............................................. 85
    4.2.1  Particle Size Distribution .................................................................................. 85
    4.2.2  Hydraulic Conductivity ...................................................................................... 86
  4.3  Preliminary Resistivity Testing .................................................................................. 86
    4.3.1  Experimental Procedure .................................................................................... 88
    4.3.2  Experimental Outcome ...................................................................................... 89
  4.4  Preliminary Vibratory Testing ................................................................................... 89
  4.5  Preliminary Repeated Load Triaxial (RLT) Testing .................................................... 90
  4.6  Preliminary Monotonic Triaxial Testing ..................................................................... 92
    4.6.1  Computational Modelling .................................................................................... 93
Table of Contents

Chapter 5 Determination of Transportable Moisture Limit of Iron Ore Fines for the Prevention of Liquefaction in Bulk Carriers ................................................................. 104

5.1 Introduction ............................................................................................................. 104
5.2 Citation .................................................................................................................... 104
5.3 Manuscript Contents ............................................................................................... 105
  5.3.1 Abstract ............................................................................................................. 105
  5.3.2 Introduction ....................................................................................................... 105
  5.3.3 Liquefaction ..................................................................................................... 107
  5.3.4 TML Test Procedures ...................................................................................... 109
  5.3.5 Materials .......................................................................................................... 121
  5.3.6 Experimental Results from this Study ............................................................ 123
  5.3.7 Supporting Results ........................................................................................... 129
  5.3.8 Discussion and Recommendations ................................................................ 132
  5.3.9 Conclusion ....................................................................................................... 134
  5.3.10 Appendix A – Terminology ........................................................................... 136
  5.3.11 Appendix B – Calculations ............................................................................ 138
  5.3.12 Appendix C – Typical TML Results .............................................................. 141

5.4 Supplementary Results and Figures ...................................................................... 142

5.5 Summary After the Fact ......................................................................................... 142

Chapter 6 A Review of the Newly Developed Method used to Prevent Liquefaction of Iron Ore Fines on Bulk Carriers ............................................................................. 143

6.1 Introduction ............................................................................................................. 143
6.2 Citation .................................................................................................................... 143
6.3 Manuscript Contents ............................................................................................... 144
  6.3.1 Abstract ............................................................................................................. 144
  6.3.2 Introduction ....................................................................................................... 144
  6.3.3 Iron Ore Fines .................................................................................................. 144
  6.3.4 Modified Proctor/Fagerberg Test for Iron Ore Fines ...................................... 148
  6.3.5 Discussion ....................................................................................................... 156
Table of Contents

6.4 Supplementary Results and Figures ................................................................. 157
6.5 Summary After the Fact ..................................................................................... 157

Chapter 7 Moisture Content Limits of Iron Ore Fines to Prevent Liquefaction during Transport: Review and Experimental Study ......................................................................................................................... 158
7.1 Introduction ......................................................................................................... 158
7.2 Citation .................................................................................................................. 158
7.3 Manuscript Contents .......................................................................................... 159
  7.3.1 Abstract ........................................................................................................... 159
  7.3.2 Introduction ..................................................................................................... 159
  7.3.3 Original Test Methods ..................................................................................... 163
  7.3.4 Recent Developments in TML Testing .......................................................... 164
  7.3.5 Experimental Results ..................................................................................... 169
  7.3.6 Conclusion ....................................................................................................... 173
  7.3.7 Timeline References ....................................................................................... 174
  7.3.8 Appendix A – TML Testing Timeline .............................................................. 175
7.4 Supplementary Results and Figures .................................................................. 176
7.5 Summary After the Fact ..................................................................................... 176

Chapter 8 Carriers Moisture Content Limits of Iron Ore Fines for the Prevention of Liquefaction in Bulk

8.1 Introduction ......................................................................................................... 177
8.2 Citation .................................................................................................................. 177
8.3 Manuscript Contents .......................................................................................... 178
  8.3.1 Abstract .......................................................................................................... 178
  8.3.2 Introduction ...................................................................................................... 178
  8.3.3 Original Test Methods .................................................................................... 180
  8.3.4 Recent Developments in Transportable Moisture Limit Testing .................. 182
  8.3.5 This Studies Experimental Work .................................................................... 185
  8.3.6 Discussion ....................................................................................................... 186
8.4 Supplementary Results and Figures .................................................................. 187
8.5 Summary After the Fact ..................................................................................... 187

Chapter 9 Variation of the Geotechnical Properties of Iron Ore Fines under Cyclic Loading ........ 188
9.1 Introduction ......................................................................................................... 188
9.2 Citation .................................................................................................................. 188
9.3 Manuscript Contents .......................................................................................... 189
Table of Contents

Chapter 10  Bulk Cargo Liquefaction Incidents during Marine Transportation and Possible Causes 224
10.1 Introduction .................................................................................................................. 224
10.2 Citation .......................................................................................................................... 224
10.3 Manuscript Contents ...................................................................................................... 225
  10.3.1 Abstract .................................................................................................................. 225
  10.3.2 Introduction .......................................................................................................... 225
  10.3.3 Analysis of Recent Suspected Liquefaction Incidents ........................................... 229
  10.3.4 Experimental Study ............................................................................................... 234
  10.3.5 Conclusion ............................................................................................................. 245
  10.3.6 Appendix A – Suspected Liquefaction Incidents (Table) ....................................... 247
  10.3.7 Appendix B – Suspected Liquefaction Incidents (Localities) ................................. 249
10.4 Supplementary Results and Figures .............................................................................. 252
10.5 Summary After the Fact .............................................................................................. 252

Chapter 11  Liquefaction Incidents of Mineral Cargoes on Bulk Carriers .......................... 253
11.1 Introduction .................................................................................................................... 253
11.2 Citation .......................................................................................................................... 253
11.3 Manuscript Contents ...................................................................................................... 254
  11.3.1 Abstract ................................................................................................................ 254
  11.3.2 Introduction .......................................................................................................... 254
  11.3.3 Case Studies .......................................................................................................... 255
  11.3.4 Discussion and Recommendations ....................................................................... 285
  11.3.5 Conclusion ............................................................................................................. 287
11.4 Supplementary Results and Figures .............................................................................. 289
11.5 Summary After the Fact .............................................................................................. 289
# Table of Contents

Chapter 12  Analyzing the Failure Mode of Iron Ore Fines under Repeated Load Triaxial Testing to Determine Likelihood of a Cargo Shifting during Marine Transportation ........................................... 290

12.1 Introduction ............................................................................................................................. 290
12.2 Citation .................................................................................................................................... 290
12.3 Manuscript Contents .............................................................................................................. 291
  12.3.1 Abstract .............................................................................................................................. 291
  12.3.2 Introduction ....................................................................................................................... 291
  12.3.3 Hypothesis ........................................................................................................................ 291
  12.3.4 Material and Method ........................................................................................................ 296
  12.3.5 Experimental Results ....................................................................................................... 303
  12.3.6 Conclusion ...................................................................................................................... 310
12.4 Supplementary Results and Figures ...................................................................................... 312
12.5 Summary After the Fact ......................................................................................................... 312

Chapter 13  Slope Stability Evaluation of Iron Ore Fines During Marine Transportation in Bulk Carriers 313

13.1 Introduction ............................................................................................................................. 313
13.2 Citation .................................................................................................................................... 313
13.3 Manuscript Contents .............................................................................................................. 314
  13.3.1 Abstract .............................................................................................................................. 314
  13.3.2 Introduction ....................................................................................................................... 314
  13.3.3 Material and Methods ........................................................................................................ 317
  13.3.4 Experimental Results ....................................................................................................... 324
  13.3.5 Conclusion ...................................................................................................................... 332
  13.3.6 Appendix A – Average Rotational Analysis Computational Results ............................ 333
13.4 Supplementary Results and Figures ...................................................................................... 340
13.5 Summary After the Fact ......................................................................................................... 340

Chapter 14  Cyclic Behaviour of Iron Ore Fines on board Bulk Carriers: Scale Model Analysis .... 341

14.1 Introduction ............................................................................................................................. 341
14.2 Citation .................................................................................................................................... 341
14.3 Manuscript Contents .............................................................................................................. 342
  14.3.1 Abstract .............................................................................................................................. 342
  14.3.2 Background ...................................................................................................................... 342
  14.3.3 Objective ......................................................................................................................... 348
  14.3.4 Materials and Methods ................................................................................................. 349
Chapter 17       Summary Discussion of Experimental Results ................................................................. 440

Chapter 16       Scale Analysis of the Behaviour of Iron Ore Fines under Cyclic Loading for the
                  Prevention of Liquefaction During Marine Transportation ....................................................... 403

Chapter 15       Simulating Marine Transportation using a Cyclic Triaxial to Determine the Liquefaction
                  Potential of Iron Ore Fines ............................................................................................................. 372

Chapter 14       Summary Discussion of Experimental Results ......................................................................... 356

Chapter 13       Conclusion .......................................................................................................................... 369

Chapter 12       Supplementary Results and Figures .................................................................................... 371

Chapter 11       Summary After the Fact ....................................................................................................... 371

Chapter 10       Manuscript Contents ........................................................................................................ 373

Chapter 9        Citation .............................................................................................................................. 372

Chapter 8        Conclusion ........................................................................................................................ 397

Chapter 7        Discussion ........................................................................................................................ 376

Chapter 6        Experimental Results ....................................................................................................... 390

Chapter 5        Method ............................................................................................................................. 376

Chapter 4        Material ............................................................................................................................ 374

Chapter 3        Introduction ..................................................................................................................... 372

Chapter 2        Citation ............................................................................................................................. 372

Chapter 1        Manuscript Contents ........................................................................................................ 373

14.3.5 Analysis of Results ...................................................................................................................... 356

14.3.6 Conclusion ................................................................................................................................. 369

14.4 Supplementary Results and Figures ............................................................................................... 371

14.5 Summary After the Fact .................................................................................................................. 371

15.1 Introduction ..................................................................................................................................... 372

15.2 Citation ........................................................................................................................................... 372

15.3 Manuscript Contents ....................................................................................................................... 373

15.3.1 Abstract ...................................................................................................................................... 373

15.3.2 Introduction ............................................................................................................................... 373

15.3.3 Material ...................................................................................................................................... 374

15.3.4 Method ....................................................................................................................................... 376

15.3.5 Experimental Results ............................................................................................................... 390

15.3.6 Discussion ................................................................................................................................. 397

15.3.7 Conclusion ................................................................................................................................. 398

15.3.8 Appendix A – Typical Cyclic Triaxial Results ......................................................................... 399

15.4 Supplementary Results and Figures ............................................................................................... 402

15.5 Summary After the Fact .................................................................................................................. 402

16.1 Introduction ..................................................................................................................................... 403

16.2 Citation ........................................................................................................................................... 403

16.3 Manuscript Contents ....................................................................................................................... 404

16.3.1 Abstract ...................................................................................................................................... 404

16.3.2 Introduction ............................................................................................................................... 404

16.3.3 Material and Method ............................................................................................................... 405

16.3.4 Experimental Results ............................................................................................................... 414

16.3.5 Discussion ................................................................................................................................. 432

16.3.6 Conclusion ................................................................................................................................. 433

16.3.7 Appendix A – Pore Air and Water Pressures during Scale Model Testing ............................ 435

16.4 Supplementary Results and Figures ............................................................................................... 439

16.5 Summary After the Fact .................................................................................................................. 439

440
# Table of Contents

17.1 Introduction .......................................................................................................................... 440
17.2 Referenced Figures .................................................................................................................. 440
  17.2.1 Sample MA004 .................................................................................................................. 440
  17.2.2 Sample MA003 .................................................................................................................. 449
17.3 Discussion ............................................................................................................................... 451
Chapter 18 Conclusions and Recommendations ........................................................................ 455
  18.1 Conclusions .......................................................................................................................... 455
  18.2 Key Findings ......................................................................................................................... 457
  18.3 Detailed Recommendations ................................................................................................. 458
Chapter 19 Further Research ....................................................................................................... 464
Chapter 20 References .................................................................................................................. 465
Appendix A – Major Australian Iron Ore Deposits .................................................................... 478
Appendix B – Supplementary Results for Manuscript Presented in Chapter 5 ......................... 479
Appendix C – Supplementary Results for Manuscript Presented in Chapter 7 ......................... 485
Appendix D – Supplementary Results for Manuscript Presented in Chapter 13 ....................... 487
Appendix E – Supplementary Results for Manuscript Presented in Chapter 14 ....................... 492
Appendix F – Supplementary Results for Manuscript Presented in Chapter 15 ....................... 501
Appendix G – Supplementary Results for Manuscript Presented in Chapter 16 ....................... 514
LIST OF PUBLICATIONS

INTRODUCTION

It is noted that this thesis is by publication. The content of the following publications is the result of work which was carried out since the official commencement date of the approved research program. All publications listed within this chapter are presented in full in this document. Please refer to the relevant chapter, which is listed alongside, to sight the publication. Publications listed in each section are given in the order in which they appear in this document.

PEER-REVIEWED MANUSCRIPTS


CONFERENCE MANUSCRIPT

UNPUBLISHED MANUSCRIPTS

The following manuscripts have not yet been published, but are currently being prepared or reviewed for publication:


LIST OF TABLES

Table 1 – Appendices ........................................................................................................................................... xxxviii
Table 2 – Abbreviations and Acronyms .................................................................................................................. xxxix
Table 3 – Nomenclature ......................................................................................................................................... xli
Table 4 – Approximate bulk carrier subclass terminology and sizes (United Nations Conference on Trade and Development (UNCTAD), 2016) ........................................................................................................ 61
Table 5 – References to information regarding the original TML test methods given in Appendix 2 of the 2013 Edition of the IMSBC Code ........................................................................................................................................ 71
Table 6 – References to information regarding the MPFT given in Appendix 2 of the 2016 Edition of the IMSBC Code ........................................................................................................................................ 72
Table 7 – Incidents and resulting casualties for individual solid bulk cargo, 1988-2016, including group classification as of 2016 (Munro and Mohajerani, 2017b) ........................................................................................................ 73
Table 8 – Worldwide production of bauxite, fluorspar and nickel ore in relation to the worldwide production of iron ore in 2015 (United States Geological Survey, Undated-d) ........................................................................ 76
Table 9 – Physical properties of the three samples of iron ore fines utilized during this study .......................... 78
Table 10 – Hammer weights and drop heights used during the development of the Proctor/Fagerberg test (Fagerberg and Stavang, 1971) ........................................................................................................ 112
Table 11 – Standard tamping pressures for the Flow Table and Penetration tests according to the 2012 IMSBC Code (International Maritime Organization, 2012b) ........................................................................................................ 118
Table 12 – Typical properties of IOF tested during this study .............................................................................. 121
Table 13 – Typical properties of a sample of IOF that were tested during this study ........................................ 121
Table 14 – Typical particle size distribution data, obtained using AS1289.3.6.1, of IOF tested during this study ........................................................................................................................................ 121
Table 15 – Comparison of IOF TML values using the Proctor/Fagerberg and Flow Table tests .................. 124
Table 16 – Proctor/Fagerberg TML value compared with the Flow Table FMP value (10kg.f) for the same sample of IOF ........................................................................................................................................ 126
Table 17 – IOF Proctor/Fagerberg TML value compared with the Flow Table FMP values at 35kg.f and 10kg.f ........................................................................................................................................ 127
Table 18 – Comparison of IOF Proctor/Fagerberg TML value and Flow Table FMP value ........................ 128
Table 19 – Comparison by Brazil of IOF TML values using all three test methods (International Maritime Organization, 2012a) ........................................................................................................................................ 130
Table 20 – Comparison by Brazil of IOF TML values using the Proctor/Fagerberg and Penetration tests (International Maritime Organization, 2012a) ........................................................................................................................................ 131
Table 21 – Comparison by Brazil of IOF TML values using the Proctor/Fagerberg and Flow Table tests (International Maritime Organization, 2012a) ........................................................................................................................................ 132
Table 22 – Typical IOF Proctor/Fagerberg TML test results from this study .................................................. 141
Table 23 – Typical IOF Flow Table TML test results from this study .............................................................. 141
Table 24 – Typical IOF Penetration TML test results from Brazil (International Maritime Organization, 2012a) ........................................................................................................................................ 141
Table 26 – Worldwide production of nickel ore, bauxite and manganese ore in relation to the worldwide production of iron ore in 2011 (United States Geological Survey, Undated-d) ........................................................................................................................................ 147
Table 27 – Hammer masses and drop heights used during the research into the PFT (Fagerberg and Stavang, 1971) .................................................................................................................................................. 150
Table 28 – Recent bulk carrier incidents where the suspected cause was liquefaction of the cargo of IOF (Bulk Carrier Guide, 2010; Devanney, Undated; Intercargo, 2007; Maritime Bulletin, 2013b; Roberts, 2012; Substandard Ship, 2013) ......................................................................................................................... 161
Table 30 – IOF TML values using the PT, FTT and PFT and relevant increase percentages produced by the TWG (Iron Ore Technical Working Group, 2013a) ........................................................................................................................................ ... 165
Table 31 – Hammer masses and drop heights used by Fagerberg and Stavang, 1971 (Fagerberg and Stavang, 1971) .................................................................................................................................................. 166
Table 32 – Typical properties of IOF samples used during this study as well as in the related publication (Munro and Mohajerani, 2015) ........................................................................................................ 169
Table 33 – Properties of a typical sample of IOF that was used during this study as well as in the related publication (Munro and Mohajerani, 2015) ........................................................................................................ 169
Table 34 – Typical particle size distribution sieve data of IOF used during this study as well as in the related publication (Munro and Mohajerani, 2015) ........................................................................................................ 169
Table 35 – Comparison of IOF TML values using the PFT and FTT produced during previous research and presented in a related publication (Munro and Mohajerani, 2015) ........................................................................................................ 170
Table 36 – IOF TML values from the PFT and MPFT produced during this study .................................................................................................................................................. 172
Table 37 – Recent bulk carrier incidents possibly caused by the iron ore cargo shifting [2-7] .................................................................................................................................................. 179
Table 38 – IOF TML values produced by the TWG using the PT, FTT and PFT (Iron Ore Technical Working Group, 2013a) ........................................................................................................................................ 184
Table 39 – Increases from the TWG IOF TML values from the PT, FTT and PFT (Iron Ore Technical Working Group, 2013a) ........................................................................................................................................ 184
Table 40 – Properties of a typical sample of IOF that was used in this study .................................................................................................................................................. 185
Table 41 – Typical ranges of properties of IOF used in this study .................................................................................................................................................. 185
Table 42 – IOF TML values from the PFT and MPFT produced during this study .................................................................................................................................................. 186
Table 43 – Recent incidents involving bulk carriers transporting IOF (Munro and Mohajerani, 2016b; TML Testing Wiki, 2015) ........................................................................................................................................ 189
Table 44 – Differences between the test methods currently used to determine the TML of ‘Group A’ or liquefiable solid bulk cargoes ........................................................................................................................................ 197
Table 45 – Geotechnical properties of the two samples of IOF used during this study .................................................................................................................................................. 201
Table 46 – Vibration Test moisture contents for sample MA002 and sample MA003 .................................................................................................................................................. 208
Table 47 – sample MA002 and MA003 average variation of the angle of repose during the Vibration Test .................................................................................................................................................. 209
Table 48 – sample MA002 and MA003 variation in dry density, void ratio and degree of saturation during the Vibration Test (point A) .................................................................................................................................................. 210
Table 49 – sample MA002 and MA003 variation in dry density, void ratio and degree of saturation during the Vibration Test (point B) .................................................................................................................................................. 211
Table 50 – sample MA002 and MA003 variation in dry density, void ratio and degree of saturation during the Vibration Test (point C) .................................................................................................................................................. 211
Table 51 – Summary of final sample geotechnical properties after 1500 seconds with vibration only and no surcharge .................................................................................................................................................. 212
Table 52 – Summary of final sample geotechnical properties after 2100 seconds with the addition of the surcharge ........................................................................................................................................ 212
Table 53 – Moisture contents of sample MA003 where the IOFP was applied .................................................................................................................................................. 218
Table 54 – Coefficients of compressibility (mₚ), coefficient of consolidation (Cᵥ), void ratio (e) and hydraulic conductivity (k) of a typical sample of IOF under varying consolidation pressures (ø) .................................................................................................................................................. 220
Table 55 – Incidents and resulting casualties for individual solid bulk cargo, 1988-2016, including group classification as of 2016 (see Section 10.3.6) .................................................................................................................................................. 230
Table 56 – Incidents and resulting casualties for bulk carrier subclasses, 1988-2016 (see Section 10.3.6) ........................................................................................................................................................................... 231
Table 57 – Incidents and resulting casualties for export countries, 1988-2016 (see Section 10.3.6) ........................................................................................................................................................................... 231
Table 58 – Percentage of iron ore fines (IOF) tonnage transported and voyages for specific subclasses of bulk carrier, 2012 (Iron Ore Technical Working Group, 2013b) .................................................................................................................................................. 233
Table 59 – Physical properties of the sample of IOF used during this study ................................................................................................................................................................................................. 235
Table 60 – Identification and moisture contents of the samples of IOF tested during this study ........................................................................................................................................................................... 239
Table 61 – The variation in penetration by the IOFP for Point A after the initial 3600 seconds (1 hour) of vibration .................................................................................................................................................. 241
Table 62 – The variation in penetration by the IOFP for Point B after the initial 3600 seconds (1 hour) of vibration .................................................................................................................................................. 241
Table 63 – The variation in penetration by the IOFP for Point C (MPFT TML) after the initial 3600 seconds (1 hour) of vibration .................................................................................................................................................. 241
Table 64 – The variation in penetration by the IOFP for Point D after the initial 3600 seconds (1 hour) of vibration .................................................................................................................................................. 242
Table 65 – The variation in penetration by the IOFP for Point E after the initial 3600 seconds (1 hour) of vibration .................................................................................................................................................. 242
Table 66 – Bulk carrier incidents from 1988 to 2016 involving suspected liquefaction of the solid bulk cargo being transported .................................................................................................................................................. 247
Table 67 – Major incidents investigated during this study along with the main vessel and incident details (Australian Transport Safety Bureau, 2000; Panama Maritime Authority - Maritime Accident Investigation Department, 2011a, 2011b, 2011c; The Bahamas Maritime Authority, 2015; The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005, 2015).................................................................................................................................................. 256
Table 68 – Cargo distribution of the Hong Wei when departing Kolonodale, Indonesia (Panama Maritime Authority - Maritime Accident Investigation Department, 2011a) .................................................................................................................................................. 272
Table 69 – The loading sequence of the Trans Summer (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015) .................................................................................................................................................. 275
Table 70 – Cargo distribution of the Trans Summer when departing Subaim, Indonesia (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015) .................................................................................................................................................. 276
Table 71 – Physical properties of the iron ore fines sample used during this study ................................................................................................................................................................................................. 296
Table 72 – The combination, application and cycle period of the stresses applied during the RLT test ........................................................................................................................................................................... 300
Table 73 – sample identifications with initial physical properties and failure conditions under which the sample failed under the load combination given in Table 72 .................................................................................................................................................. 303
Table 74 – Physical properties of the iron ore fines sample used during this study ................................................................................................................................................................................................. 318
Table 75 – The angles of heel used to perform the trimmed and untrimmed slope stability analysis
.......................................................................................................................... 322
Table 76 – The initial and final physical properties of the samples tested................................. 325
Table 77 – The 3-point monotonic shear test conditions and results produced during the triaxial testing
.................................................................................................................................. 325
Table 78 – The results of the rotational slope stability analysis for each of the samples of iron ore fines
........................................................................................................................................ 327
Table 79 – The results of the translational slope stability analysis for each of the samples of iron ore fines ........................................................................................................................................ 329
Table 80 – The average angle of heel at failure for varying factors of safety ........................................ 331
Table 81 – Recent incidents involving bulk carriers transporting IOF .................................................. 342
Table 82 – The classification system by Robertson and Fear (Robertson and Fear, 1996) to define soil liquefaction, as summarized by Rauch (Rauch, 1997) .................................................................................. 346
Table 83 – Physical properties of the IOF sample used during this study ........................................ 349
Table 84 – Vibration intervals when measurements were taken during the SCT and penetration of the IOFP ............................................................................................................................................ 355
Table 85 – IOF sample identification and their respective moisture content ........................................ 356
Table 86 – The variation of physical properties of the samples of IOF produced during the SCT .... 357
Table 87 – The variation in physical properties of IOF produced during the SCT for the 4 hours and 1 hour tests at TML% .............................................................................................................. 364
Table 88 – Physical properties of the iron ore fines specimen used during this study .................... 374
Table 89 – Critical state line parameters of the specimen of iron ore fines used during this study.. 391
Table 90 – Identification of the samples tested along with their respective stress paths ................. 392
Table 91 – Physical properties of the iron ore fines specimen used during this study ..................... 405
Table 92 – A summarized version of the classification system to define soil liquefaction (Rauch, 1997; Robertson and Fear, 1996) .............................................................................................................. 408
Table 93 – Identification of the samples tested along with their overall physical properties during the tests .......................................................................................................................................... 414
Table 94 – Comparison between Flow Table and Penetration tests TML values for ore concentrates (T Ura, 1992) ........................................................................................................................................ 483
Table 95 – Comparison between Proctor/Fagerberg TML and Flow Table FMP values for ore concentrates (Fagerberg and Stavang, 1971) ......................................................................................... 484
Table 96 – Photos of the samples during cyclic loading at specific time intervals during the preliminary scale model testing (Note: Photos for TML – 1.6% were corrupted so are unavailable) .......... 497
Table 97 – Sample profiles before and after the cyclic loading was applied during the advanced scale model testing ................................................................................................................................................. 518
LIST OF FIGURES
Figure 1 – Typical bulk carrier used for the marine transportation of solid bulk cargoes (Imabari Shipbuilding Co. Ltd., 2016).................................................................................................................................................................................. 46
Figure 2 – Samples of iron ore fines with varying physical properties tested during this study (Munro and Mohajerani, 2016c)................................................................................................................................................................................. 50
Figure 3 – Four types of phenomena relating to a solid bulk cargo shifting; a) translational shear failure, b) rotational shear failure, c) liquefaction, and d) sliding en-masse (Munro and Mohajerani, 2017f) 51
Figure 4 – 2016 Edition of the International Maritime Solid Bulk Cargoes Code (IMSBC Code) (TML Testing Wiki, 2016a) .......................................................................................................................................................................................................................... 52
Figure 5 – Bulk carrier Asian Forest transporting iron ore fines after a suspected liquefaction incident off the coast of Malaysia in 2009 (Ship.gr - World Shipping Directory, 2009).......................................................... 53
Figure 6 – Computational modelling using rotational analysis showing the minimum factor of safety at a 20-degree heel for an untrimmed cargo (Munro and Mohajerani, 2017f) ............................ 54
Figure 7 – Scale model that was designed, developed and utilized during this research (Munro and Mohajerani, 2017d) .................................................................................................................................................................................. 55
Figure 8 – Estimated iron ore production of the top producing countries in 2015 (United States Geological Survey) ........................................................................................................................................................................................................... 58
Figure 9 – Iron ore lump (By Luis Miguel Bugallo Sánchez (Own work)) ........................................................................................................................................................................................................ 59
Figure 10 – Iron ore fines (Munro and Mohajerani, 2016d) .................................................................................................................................................................................................................................................. 60
Figure 11 – Iron ore pellets (By Harvey Henkelmann (Own work)) .......................................................................................................................................................................................................................... 60
Figure 12 – General bulker (ship.gr, Undated).................................................................................................................................................................................................................................................. 62
Figure 13 – Handysize subclass of bulk carrier (similar to Handymax subclass) (ship.gr, 2013b)............. 62
Figure 14 – Panamax subclass of bulk carrier (Imabari Shipbuilding Co. Ltd., 2016)................................. 62
Figure 15 – Capesize subclass of bulk carrier (ship.gr, 2013a) ...................................................................... 63
Figure 16 – Typical profile and plan view of a Geared Handysize or Handymax subclass of bulk carrier (By Rémi Kaupp and Calips (Own work)).................................................................................................................................................................................. 63
Figure 17 – Loading operation of a Geared Handymax subclass of bulk carrier at Kolonodale, Indonesia (Munro and Mohajerani, 2016a; Panama Maritime Authority - Maritime Accident Investigation Department, 2011c) ........................................................................................................................................................................................................... 64
Figure 18 – Illustrations depicting a stable (left and middle) and unstable (right) vessel (Munro and Mohajerani, 2017b, 2017f) ........................................................................................................................................................................................................... 65
Figure 19 – Two shearing phenomena, rotational (middle) and translational (right), that may result in a solid bulk cargo to shift during transportation (Munro and Mohajerani, 2017f) ............................... 66
Figure 20 – Solid bulk cargo shifting en-masse (Munro and Mohajerani, 2017f) ........................................ 67
Figure 21 – View from a rescue helicopter of the Trans Summer (Munro and Mohajerani, 2016a; The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015) ........................................................................................................................................................................................................... 68
Figure 22 – Depictions of hypothetical trimmed (left) and untrimmed (right) cargos with and without an angle of heel (Munro and Mohajerani, 2017f) ........................................................................................................................................................................................................... 72
Figure 23 – Incidents (left) and resulting casualties (right) for individual solid bulk cargoes, 1988-2016 (Munro and Mohajerani, 2017b) ........................................................................................................................................................................................................... 74
Figure 24 – Bauxite from Northern Australia .............................................................................................................. 74
Figure 25 – Combined nickel ore production from Indonesia, New Caledonia and the Philippines alongside suspected liquefaction incidents involving bulk carriers transporting nickel ore (Munro and Mohajerani, 2017b; United States Geological Survey)................................................................................................. 75
Figure 26 – Worldwide production of bauxite, fluorspar and nickel ore in relation to the worldwide production of iron ore in 2015 (United States Geological Survey, Undated-d)................................................................. 76
Figure 27 – Australia’s Economic Demonstrated Resources (EDR) of iron ore in 2015 (Geoscience Australia, 2016)................................................................................................................................................................. 77
Figure 28 – Sample MA002 .............................................................................................................................................................................. 78
Figure 29 – Sample MA003 .............................................................................................................................................................................. 78
Figure 30 – Sample MA004 .............................................................................................................................................................................. 78
Figure 31 – Standard (PFT) and Modified Proctor/Fagerberg (MPFT) compaction curves and resulting TML values for sample MA002......................................................................................................................... 81
Figure 32 – Standard (PFT) and Modified Proctor/Fagerberg (MPFT) compaction curves and resulting TML values for sample MA003......................................................................................................................... 81
Figure 33 – Standard (PFT) and Modified Proctor/Fagerberg (MPFT) compaction curves and resulting TML values for sample MA004......................................................................................................................... 82
Figure 34 – Standard and modified Proctor compaction curves for sample MA002................................................................. 82
Figure 35 – Standard and modified Proctor compaction curves for sample MA003................................................................. 83
Figure 36 – Shrinkage limit density curve for sample MA004 .................................................................................................................... 83
Figure 37 – Soil-Water Characteristic Curve for sample MA004 .................................................................................................................... 84
Figure 38 – Particle size distributions of the samples of iron ore fines utilized during this research .................................................................................................................. 84
Figure 39 – Mastersizer Aero 3000 utilized during this study (www.malvern.com) ................................................................. 86
Figure 40 – Preliminary resistivity mould design with compaction collar removed................................................................. 87
Figure 41 – Preliminary resistivity mould design with compaction collar attached................................................................. 88
Figure 42 – Preliminary resistivity mould design showing internal resistivity probes................................................................. 88
Figure 43 – Sample of iron ore fines after vibratory testing ..................................................................................................................... 90
Figure 44 – Sample of iron ore fines after vibratory testing and removal from mould ................................................................. 90
Figure 45 – Repeated load cyclic triaxial apparatus utilized during this research (1) .................................................................................. 91
Figure 46 – Repeated load cyclic triaxial apparatus utilized during this research (2) .................................................................................. 92
Figure 47 – Preliminary scale model design concept (sketch 1) ..................................................................................................................... 93
Figure 48 – Preliminary scale model design concept (sketch 2) ..................................................................................................................... 94
Figure 49 – Preliminary scale model design concept (sketch 3) ..................................................................................................................... 94
Figure 50 – Preliminary scale model design concept (sketch 4) ..................................................................................................................... 95
Figure 51 – Final dimensions and features of the scale model designed, developed and utilized during the preliminary stages of this research (Munro and Mohajerani, 2017c) ..................................................................................... 95
Figure 52 – Completed construction of part of the scale model, the acrylic mould .................................................................................. 96
Figure 53 – Coming together of the acrylic mould and steel base plate .......................................................................................... 96
Figure 54 – Final scale model designed, developed and utilized during the preliminary stages of this research, placed upon a vibrating table ..................................................................................... 97
Figure 55 – Design of the Iron Ore Fines Plunger (IOFP) shown alongside the scale model designed, developed and utilized during this research (Munro and Mohajerani, 2017c) ..................................................................................... 98
Figure 56 – Advanced cyclic triaxial utilized during this study, after successful relocation and installation (1) ..................................................................................... 99
Figure 57 – Advanced cyclic triaxial utilized during this study, after successful relocation and installation (2) ..................................................................................... 100
Figure 58 – Data loggers and breakout boards being installed for use with the advanced scale model .......................................................... 101
Figure 59 – Initial modifications being made to the scale model itself (advanced plunger and full-length resistivity probes shown installed) .......................................................................................................................... 101
Figure 60 – Computer, data loggers, breakout boards, tensiometers and transducers along with vibrating table controls all attached to the mould to monitor and record data during vibration (Munro and Mohajerani, 2017d) .................................................................................................................................................................. 102
Figure 61 – Scale model with front panels removed on top of the vibrating table showing transducer locations (the rear probes seen in this image were not used in this study) (Munro and Mohajerani, 2017d) .................................................................................................................................................................. 103
Figure 62 – Asian Forest (Ship.gr - World Shipping Directory, 2009) ........................................................................................................ 106
Figure 63 – Back Rose (Kalinga Divers, 2009) ........................................................................................................................................ 106
Figure 64 – Idealized response of saturated cohesionless tailings under monotonic and cyclic loading (Davies et al., 2002) ........................................................................................................................................ 107
Figure 65 – Wetted particles ........................................................................................................................................ 108
Figure 66 – Partially saturated particles ................................................................................................................................. 108
Figure 67 – Dry IOF being loaded onto a bulk carrier (Crouch and Aamlid, 2009) ........................................................................ 109
Figure 68 – Partially saturated IOF in the hold of a bulk carrier in India (Crouch and Aamlid, 2009) 109
Figure 69 – Proctor/Fagerberg test apparatus ............................................................................................................................... 110
Figure 70 – Sample after compaction ........................................................................................................................................ 110
Figure 71 – Typical graphical representation of the compaction curve and resulting TML from the Proctor/Fagerberg test ............................................................................................................................... 110
Figure 72 – Comparison by Fagerberg and Stavang in 1971 of in situ void ratios of ore concentrates on board a vessel and compaction methods C and D (Fagerberg and Stavang, 1971) .......................................................................................................................... 113
Figure 73 – Flow Table apparatus ........................................................................................................................................ 115
Figure 74 – Compaction into the mould on the Flow Table .............................................................................................................. 115
Figure 75 – The same material slightly over FMP, showing minor plastic deformation ................................................................. 115
Figure 76 – Material under FMP, showing crumbling ...................................................................................................................... 115
Figure 77 – The preliminary Flow Table test’s graphical representation showing the approximate moisture content of the material’s FMP ........................................................................................................ 116
Figure 78 – Penetration test apparatus ........................................................................................................................................ 119
Figure 79 – Penetration bits .................................................................................................................................................. 119
Figure 80 – Particle size distribution boundaries of liquefiable materials, determined by Ishihara (Ishihara, 1985), and boundaries of IOF determined during this study ........................................................................................................ 122
Figure 81 – Comparison of IOF TML values using the Proctor/Fagerberg and Flow Table tests ............................................. 124
Figure 82 – Comparison of IOF TML values using the Proctor/Fagerberg and Flow Table tests ............................................. 125
Figure 83 – Proctor/Fagerberg compaction curve compared with the Flow Table compaction curve (10kg.f) for the same sample of IOF ................................................................................................................... 126
Figure 84 – IOF Proctor/Fagerberg TML value compared with the Flow Table FMP values at 35kg.f and 10kg.f ................................................................................................................................................ 127
Figure 85 – Comparison of IOF Proctor/Fagerberg TML value and Flow Table FMP value. Data from Brazil is integrated with the results from this study (International Maritime Organization, 2012a). 128
Figure 86 – Comparison of IOF Proctor/Fagerberg TML value and Flow Table FMP value ................................................................. 129
Figure 87 – Comparison by Brazil of IOF TML values using all three test methods (International Maritime Organization, 2012a) ........................................................................................................................................ 130
Figure 88 – Comparison by Brazil of IOF TML values using the Proctor/Fagerberg and Penetration tests (International Maritime Organization, 2012a) .................................................................................................................. 131
Figure 89 – Comparison by Brazil of IOF TML values using the Proctor/Fagerberg and Flow Table tests (International Maritime Organization, 2012a) .................................................................................................................. 132
Figure 90 – Various types of iron ore fines commonly transported on bulk carriers ........................................... 145
Figure 91 – Particle size distribution boundaries of 45 typical samples of iron ore fines transported in bulk carriers (Munro and Mohajerani, 2015) .................................................................................................................................. 145
Figure 92 – Iron ore fines after loading in the hold of a bulk carrier (Crouch and Aamlid, 2009) .... 146
Figure 93 – Iron ore fines after transportation in the hold of a bulk carrier (Crouch and Aamlid, 2009) .................................................................................................................................. 146
Figure 94 – Approximate yearly iron ore fines tonnage transported worldwide by bulk carriers (Iron Ore Technical Working Group, 2013b) .................................................................................................................. 147
Figure 95 – Approximate yearly iron ore fines voyages by bulk carriers (Iron Ore Technical Working Group, 2013b) .................................................................................................................. 147
Figure 96 – PFT apparatus and compacted sample of iron ore fines .................................................................. 149
Figure 97 – Example of graphical compaction curve and resulting transportable moisture limit of iron ore fines produced by the PFT .................................................................................................................................. 150
Figure 98 – Comparison of in situ void ratios of magnetite on board bulk carriers compared with compaction methods C and D performed during the research into the PFT (Fagerberg and Stavang, 1971). .................................................................................................................................. 151
Figure 99 – Compaction test results of a sample of Australian iron ore fines performed by the TWG (Iron Ore Technical Working Group, 2013c) .................................................................................................................................. 152
Figure 100 – Comparison between the compaction hammers used during the PFT and the MPFT. 154
Figure 101 – Comparison between the compaction curves produced by the PFT and the MPFT on the same sample of iron ore fines .................................................................................................................................. 154
Figure 102 – IOF after loading into the hold of a bulk carrier (Crouch and Aamlid, 2009) ..................... 161
Figure 103 – Typical loading profile of IOF in the hold of a Capesize bulk carrier ........................................ 162
Figure 104 – IOF TML values using the PT, FTT and PFT produced by the TWG (Iron Ore Technical Working Group, 2013a) .................................................................................................................................. 165
Figure 105 – Compaction test with Proctor apparatus performed on Magnetite using methods A through E performed by Fagerberg and Stavang, 1971 (Fagerberg and Stavang, 1971) ...................................................... 167
Figure 106 – Comparison of in situ void ratios of Magnetite onboard bulk carriers compared with compaction methods C and D performed by Fagerberg and Stavang, 1971 (Fagerberg and Stavang, 1971) .................................................................................................................................. 167
Figure 107 – Comparison of IOF TML values using the PFT and FTT produced during previous research and presented in a related publication (Munro and Mohajerani, 2015) ........................................ 171
Figure 108 – IOF TML values from the PFT and MPFT produced during this study ....................................... 171
Figure 109 – Graphical representation of the compaction curves of IOF (sample 011) using the PFT and MPFT produced during this study ................................................................................................................................. 172
Figure 110 – Particle size boundaries of IOF, which were produced during this study, along with the maximum particle size as classified in the 2013 draft schedule (International Maritime Organization, 2013a) .................................................................................................................................. 173
Figure 111 – Graphical representation of a typical PFT compaction curve of IOF produced during this study .................................................................................................................................. 180
Figure 112 – IOF TML values produced by the TWG using the PT, FTT and PFT (Iron Ore Technical Working Group, 2013a) .................................................................................................................. 184
Figure 113 – IOF TML values from the PFT and MPFT produced during this study .................. 185
Figure 114 – Asian Forest (Ship.gr - World Shipping Directory, 2009) ..................................... 190
Figure 115 – Black Rose (Kalinga Divers, 2009) .................................................................... 190
Figure 116 – Graphical representation of a typical PFT compaction curve of IOF produced during a previous study (Munro and Mohajerani, 2015) ................................................................. 191
Figure 117 – PFT 350g compaction hammer and litre mould .................................................... 192
Figure 118 – Flow table and conical mould .............................................................................. 193
Figure 119 – Tamper used during the FTT .............................................................................. 193
Figure 120 – PT apparatus (modified image courtesy of geo-con.com.au) (Geo-Con Products Pty Ltd, 2012) ................................................................................................................................. 194
Figure 121 – PT penetration bits and bit holder (modified image courtesy of geo-con.com.au) (Geo-Con Products Pty Ltd, 2012) .............................................................................................................. 194
Figure 122 – Comparison between the compaction hammers used during the PFT and the MPFT . 195
Figure 123 – Comparison between the compaction curves produced by the PFT and the MPFT (Sample MA003) ............................................................................................................................ 196
Figure 124 – IOF TML values determined using the PT, FTT and PFT produced by the TWG (Iron Ore Technical Working Group, 2013a) .......................................................................................... 199
Figure 125 – IOF TML values determined using the PFT and MPFT (Munro and Mohajerani, 2016b) .................................................................................................................................................... 199
Figure 126 – Sample MA002 .................................................................................................... 200
Figure 127 – Sample MA003 .................................................................................................... 200
Figure 128 – Particle size distributions of the samples of IOF used during this study (AS1289 3.6.1 (Standards Australia, 2009d)) ........................................................................................................ 202
Figure 129 – A cargo of IOF before transportation (Jonas, 2010) ............................................... 204
Figure 130 – A cargo of IOF after transportation (Jonas, 2010) ................................................ 204
Figure 131 – Hypothetical characteristics of IOF before transportation .................................... 204
Figure 132 – Hypothetical characteristics of IOF after transportation ....................................... 204
Figure 133 – Density versus time graph of assumed and simplified cargo densification during transport .............................................................................................................................................. 205
Figure 134 – Vibration Test mould and sample ......................................................................... 206
Figure 135 – Mould on vibrating table ...................................................................................... 206
Figure 136 – Iron Ore Fines Plunger (IOFP) (845 g or 16.36 kPa) ............................................ 207
Figure 137 – Iron Ore Fines Plunger (IOFP) holder ................................................................. 207
Figure 138 – Variation of sample MA002 surface profile during Vibration Testing (Point A) .... 208
Figure 139 – Variation of sample MA003 surface profile during Vibration Testing (point A) .... 208
Figure 140 – Variation of sample MA002 surface profile during Vibration Testing (point B) .... 209
Figure 141 – Variation of sample MA003 surface profile during Vibration Testing (point B) .... 209
Figure 142 – Variation of sample MA002 surface profile during Vibration Testing (point C) .... 209
Figure 143 – Variation of sample MA003 surface profile during Vibration Testing (point C) .... 209
Figure 144 – Sample MA002 and MA003 average variation of the angle of repose during the Vibration Test (Point A = PFT TML, Point B = MPFT TML and Point C = 1% + MPFT TML) ................. 210
Figure 145 – Sample MA002 and MA003 variation in void ratio and dry density versus time during the Vibration Test (Point A = PFT TML) .............................................................. 212
List of Figures

Figure 146 – sample MA002 and MA003 variation in void ratio and dry density versus time during the Vibration Test (Point B = MPFT TML) ........................................................................................................... 213
Figure 147 – sample MA002 and MA003 variation in void ratio and dry density versus time during the Vibration Test (Point C = 1% + MPFT TML) ........................................................................................................... 213
Figure 148 – sample MA002 and MA003 variation in degree of saturation versus time during the Vibration Test (Point A = PFT, Point B = MPFT and Point C = 1% + MPFT TML) ........................................ 214
Figure 149 – sample MA002 and MA003 degree of saturation versus gross water content after 1500 seconds (without surcharge) and 2100 seconds (with surcharge) ........................................................................ 214
Figure 150 – sample MA002 and MA003 variation in dry density versus time during the Vibration Test (Point A = PFT, Point B = MPFT and Point C = 1% + MPFT TML). This figure is the same dry density data seen in Figure 145 to Figure 147 but with a linear scale ......................................................... 214
Figure 151 – sample MA002 dry density versus gross water content produced by the Vibration Test and results from the Proctor/Fagerberg test and Modified Proctor/Fagerberg test ........................................ 216
Figure 152 – sample MA003 dry density versus gross water content produced by the Vibration Test and results from the Proctor/Fagerberg test and Modified Proctor/Fagerberg test ........................................ 216
Figure 153 – sample MA002 void ratio versus gross water content produced by the Vibration Test 217
Figure 154 – sample MA003 void ratio versus gross water content produced by the Vibration Test 217
Figure 155 – Penetration of 845 g (16.36 kPa) IOFP on sample MA003 ......................................................... 219
Figure 156 – Penetration of 845 g (16.36 kPa) IOFP on sample MA003 after 1, 20, 120 and 900 seconds of penetration .......................................................................................................................... 219
Figure 157 – Calculated and directly measured hydraulic conductivity (k) of a sample of IOF under varying consolidation pressures (σ) ........................................................................................................ 221
Figure 158 – Illustrations depicting stable vessels (left and middle) and an unstable vessel (right). 226
Figure 159 – Three strainer plates blocked by the crew of the Canadian Leader ex Feux Follets using cardboard, plastic sheeting, and duct tape to prevent entry of the cargo of iron ore pellets into the bilge pipes and pumps (Transportation Safety Board of Canada, 2005) ......................................................... 228
Figure 160 – Bulk Carrier ‘Chang Le Men’ after suspected liquefaction incident off Mangalore India (2007) (Mangalorean, 2007) - see Section 10.3.6 ................................................................. 229
Figure 161 – Bulk Carrier ‘Anna Bo’ after suspected liquefaction incident off Ningde China (2013) (Asian Marine, 2009) - see Section 10.3.6 ........................................................................................................ 230
Figure 162 – Incidents (left) and resulting casualties (right) for individual solid bulk cargoes, 1988-2016 (see Section 10.3.6) .................................................................................................................... 230
Figure 163 – Incidents (left) and resulting casualties (right) for bulk carrier subclasses, 1988-2016 (see Section 10.3.6) .................................................................................................................... 230
Figure 164 – Incidents (left) and resulting casualties (right) for export countries, 1988-2016 (see Section 10.3.6) .................................................................................................................... 232
Figure 165 – Percentage of tonnage transported and voyages for specific subclasses of bulk carrier, 2012 (Iron Ore Technical Working Group, 2013b) ..................................................................................... 233
Figure 166 – Cumulative liquefaction incidents from 1988 to 2016 and the date, 2011, when the IMSBC Code was adopted on a mandatory basis ..................................................................................... 234
Figure 167 – MPFT compaction curve and resulting TML produced on the sample of IOF tested during this study .......................................................................................................................... 236
Figure 168 – Particle size distribution of the sample of IOF that was used during this study determined using AS 1289.3.6.1-2009 and a Mastersizer Aero 3000 .............................................................................. 236
List of Figures

Figure 169 – Dimensions (left) and image (right) of the IOFP developed and used during this study .................................................................................................................................................................................. 237
Figure 170 – Images of the initial vibration performed for 3600 seconds (1 hour) before the application of the IOFP (Point E) ........................................................................................................................................................................................................... 238
Figure 171 – IOFP penetrating sample during vibration after the initial 3600 seconds (1 hour) of vibration (Point E) ........................................................................................................................................................................................................... 238
Figure 172 – MPFT compaction curve (including TML) and the sample densities produced by the initial 3600 seconds (1 hour) of vibration prior to the application of the IOFP .................................................................................................................................................................................. 239
Figure 173 – The particle size distribution boundaries of most liquefiable soils (Ishihara, 1985) and the particle size distribution of the sample used during this study ........................................................................................................................... 240
Figure 174 – The variation in penetration of the IOFP against time for Points A to E ................................ 242
Figure 175 – The variation in penetration of the IOFP against moisture content for Points A to E .. 243
Figure 176 – Moisture migration occurring during initial vibration within the mould ......................... 244
Figure 177 – The behaviour of soil according to Werkmeister’s ‘shakedown’ theory (Cerni et al., 2011; Werkmeister et al., 2005) .................................................................................................................................................................................. 245
Figure 178 – Locations of where bulk carriers disembarked that have been suspected of undergoing liquefaction from 1988 to 2016 (Source: Google Maps and Section 10.3.6) .......................................................................................... 249
Figure 179 – Locations of incidents, last location and voyage of bulk carriers that have been suspected of undergoing liquefaction from 1988 to 2016 (Source: Google Maps and Section 10.3.6) ............ 250
Figure 180 – Locations of loading ports, incidents, last location destination, voyage and intended voyage of bulk carriers that have been suspected of undergoing liquefaction from 1988 to 2016 (Source: Google Maps and Section 10.3.6) .................................................................................................................................................................................. 251
Figure 181 – The Padang Hawk (Australian Transport Safety Bureau, 2000) ........................................ 257
Figure 182 – Padang Hawk and Jian Fu Star hold and tank layout (Australian Transport Safety Bureau, 2000; Panama Maritime Authority - Maritime Accident Investigation Department, 2011b) .......... 257
Figure 183 – Port of Kouaoua, New Caledonia (Source: Google Maps) ............................................. 258
Figure 184 – Padang Hawk’s voyage from Kouaoua, New Caledonia to Townsville, Australia (Australian Transport Safety Bureau, 2000) .................................................. 259
Figure 185 – Images of the nickel ore in hold number 1 of the Padang Hawk (Australian Transport Safety Bureau, 2000) .............................................................................................................................................................................. 259
Figure 186 – The Hui Long (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005) .............................................................................................................................................................................. 261
Figure 187 – Hui Long’s cargo stowage plan on departure from Sei Pakning (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005) .............................................................................................................................................................................. 262
Figure 188 – Hui Long listing severely to port after suspected liquefaction of the cargo of Fluorspar (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005) ........................................................................................................................................................................................................... 262
Figure 189 – The Jian Fu Star (Sea Breezes, 2010) .............................................................................. 263
Figure 190 – Port of Kawassi, Obi Island, Indonesia (Source: Google Maps) ........................................ 264
Figure 191 – Stowage plan for the Jian Fu Star (Panama Maritime Authority - Maritime Accident Investigation Department, 2011b) .............................................................................................................................................................................. 265
Figure 192 – The Nasco Diamond (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c) ........................................................................................................................................................................................................... 267
Figure 193 – Port of Kolonodale, Central Sulawesi, Indonesia (Source: Google Maps) ...................... 267
List of Figures

Figure 194 – Loading operation at Kolonodale, Indonesia, similar to that of the Nasco Diamond and Hong Wei (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c) ................................................................. 268
Figure 195 – Photographs submitted to the head office by the Master of the condition of the nickel ore cargo at the time of loading at Kolonodale, Indonesia (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c) .................................................................................................. 268
Figure 196 – Nasco Diamond stowage plan (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c) ..................................................................................................................................... 269
Figure 197 – The Hong Wei (Source: Silvio Roberto Smera) (ShipSpotting, 2006) .................................................................................. 271
Figure 198 – The Trans Summer (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015) .................................................................................................................. 273
Figure 199 – Port of Subaim, Indonesia (Source: Google Maps) .................................................................................................................... 274
Figure 200 – Track of ‘Utor’ on 14 August at 1200 (Predicted track in red) (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015) .......................................................... 277
Figure 201 – View from rescue helicopter as the Trans Summer listed 45-degrees to port (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015) ................................................................................................................. 278
Figure 202 – View from rescue helicopter as the Trans Summer listed 90-degrees to port (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015) ................................................................................................................................. 278
Figure 203 – The Bulk Jupiter (The Bahamas Maritime Authority, 2015) ........................................................................................................ 280
Figure 204 – Port of Kuantan, Malaysia (Source: Google Maps) ...................................................................................................................... 280
Figure 205 – December rainfall at the Port of Kuantan, Malaysia (The Bahamas Maritime Authority, 2015) ................................................................................................................................. 281
Figure 206 – Cargo being loaded onto a bulk carrier from the quayside at the Port of Kuantan, Malaysia (The Bahamas Maritime Authority, 2015) .................................................................................................................. 281
Figure 207 – Route of the Bulk Jupiter and location lost (The Bahamas Maritime Authority, 2015) (Source: Google Maps) .................................................................................................................. 282
Figure 208 – View of bauxite cargo in hold number 4 of the Orchid Island after voyage from Kuantan, Malaysia to Qingdao, China (The Bahamas Maritime Authority, 2015) ...................................................... 283
Figure 209 – Bauxite cargo quayside exposed to the elements. Photo taken from the Medi Okinawa at Port of Kuantan, Malaysia (The Bahamas Maritime Authority, 2015) .................................................................................... 284
Figure 210 – Untrimmed cargo at an angle of heel of 10-15 degrees in a Capesize subclass bulk carrier before (left) and after (right) a cargo shift .................................................................................................................. 292
Figure 211 – Trimmed cargo at an angle of heel of 15-20 degrees in a Capesize subclass bulk carrier before (left) and after (right) a cargo shift ............................................................................................................................. 293
Figure 212 – The M.V. Chang Le Men (Mangalorean, 2007) (left) and the M.V. Asian Forest (Ship.gr - World Shipping Directory, 2009) (right) with cargoes of iron ore fines suspected to have undergone liquefaction ................................................................................................. 294
Figure 213 – sample of iron ore fines that was used during this study (sample MA004) ................................................................................ 296
Figure 214 – Particle size distribution of the iron ore fines sample used during this study ................................................................. 297
Figure 215 – Modified Proctor/Fagerberg test compaction curve and TML of the sample of iron ore fines ......................................................................................................................................................... 298
Figure 216 – 14kN pneumatic universal testing machine and data acquisition unit employed to perform the RLT testing ......................................................... 299
List of Figures

Figure 217 – Schematic of apparatus employed to perform RLT testing and initial sample dimensions .................................................................................................................................................................................. 299
Figure 218 – Graphical representation of the stresses applied during the RLT test ........................................................................................................................................................................................................ 301
Figure 219 – Loading diagram of sample with (a) and without (b) the applied deviator stress ($\sigma_d$) causing permanent ($H_p$) and resilient ($H_r$) deformation ........................................................................................................................................................................................................ 301
Figure 220 – Estimated locations of load combination stresses used during the RLT testing .................................................................................................................................................................................................... 302
Figure 221 – A typical averaged stress versus strain graph and image of a sample that failed under less than 1,000 cycles ...................................................................................................................................................................................................... 304
Figure 222 – A typical averaged stress versus strain graph and image of a sample that failed between 1,000 and 10,000 cycles ...................................................................................................................................................................................................................... 304
Figure 223 – A typical averaged stress versus strain graph and image of a sample that survived 10,000 cycles ............................................................................................................................................................................................................ 305
Figure 224 – Sample failure conditions in relation to the void ratio, gross water content, degree of saturation and MPFT results .................................................................................................................................................................................................. 305
Figure 225 – Initial void ratio versus failure conditions of the test samples along with the void ratio at the MPFT TML ........................................................................................................................................................................................................ 306
Figure 226 – Permanent deformation and strain for each sample throughout the duration of the RLT tests ............................................................................................................................................................................................................. 307
Figure 227 – The behaviour of soil according to Werkmeister’s ‘shakedown’ theory (Cerni et al., 2011; Robertson and Fear, 1998; Werkmeister et al., 2005) .............................................................................................................................................................................................................. 307
Figure 228 – Initial gross water content versus failure conditions of the test samples along with the MPFT TML ........................................................................................................................................................................................................ 308
Figure 229 – Initial degree of saturation versus failure conditions of the test samples along with the degree of saturation at the MPFT TML .............................................................................................................................................................................................................. 309
Figure 230 – Initial volume of air versus failure conditions of the test samples along with the volume of air at the MPFT TML ........................................................................................................................................................................................................... 310
Figure 231 – The three distinct modes of slope failure that can cause a solid bulk cargo to shift during transportation; sliding en masse (left), rotational (middle) and translational (right) ................................................................................. 315
Figure 232 – Illustrations depicting a stable (left and middle) and unstable (right) vessel .............................................................................................................................................................................................................. 316
Figure 233 – M.V. Asian forest listing due to the cargo or iron ore fines shifting (suspected liquefaction incident) (Ship.gr - World Shipping Directory, 2009) ............................................................................................................................................................................................................ 316
Figure 234 – Typical iron ore fines sample used during this study (sample MA004) ...................................................................................................................................................................................................................... 317
Figure 235 – Particle size distribution of the iron ore fines sample used during this study ........................................................................................................................................................................................................ 318
Figure 236 – 14kN Pneumatic Universal Testing Machine (UTM-14P) and data acquisition unit ........................................................................................................................................................................................................... 319
Figure 237 – Failure surface and free-body diagram of a slice using rotational analysis (method of slices) (By Fona (Own work) [Public domain], via Wikimedia Commons) ........................................................................................................................................................................................................ 320
Figure 238 – Depictions of hypothetical trimmed (left) and untrimmed (right) cargos with and without an angle of heel .............................................................................................................................................................................................................. 322
Figure 239 – Typical trimmed cargo dimensions used during the rotational analysis (method of slices) ........................................................................................................................................................................................................... 322
Figure 240 – Typical untrimmed cargo dimensions used during the rotational analysis (method of slices) ......................................................................................................................................................................................................... 323
Figure 241 – Trimmed cargo dimensions used during the translational analysis (infinite slope analysis) .............................................................................................................................................................................................................. 323
Figure 242 – Untrimmed cargo dimensions used during the translational analysis (infinite slope analysis) ................................................................. 324
Figure 243 – Initial properties and assumed conditions of each of the samples tested .......... 325
Figure 244 – Mohr’s circles and the resulting total failure envelope of a typical sample (sample 8) 326
Figure 245 – The average rotational analysis factors of safety and boundaries for a trimmed and untrimmed cargo at varying angles of heel (method of slices) ................................................................. 328
Figure 246 – The average translational analysis factors of safety and boundaries for a trimmed and untrimmed cargo at varying angles of heel (infinite slope analysis) ......................................................... 330
Figure 247 – The average results for the translational and rotational stability analysis for factors of safety from 1 to 2 .................................................................................................................. 331
Figure 248 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 10-degree angle of heel rotational analysis (method of slices) ................................................................. 333
Figure 249 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 20-degree angle of heel rotational analysis (method of slices) ................................................................. 333
Figure 250 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 30-degree angle of heel rotational analysis (method of slices) ................................................................. 334
Figure 251 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 40-degree angle of heel rotational analysis (method of slices) ................................................................. 334
Figure 252 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 50-degree angle of heel rotational analysis (method of slices) ................................................................. 335
Figure 253 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 60-degree angle of heel rotational analysis (method of slices) ................................................................. 336
Figure 254 – Untrimmed cargo dimensions and resulting average minimum factor of safety from the 0-degree angle of heel rotational analysis (method of slices) ................................................................. 337
Figure 255 – Untrimmed cargo dimensions and resulting average minimum factor of safety from the 10-degree angle of heel rotational analysis (method of slices) ................................................................. 337
Figure 256 – Untrimmed cargo dimensions and resulting average minimum factor of safety from the 20-degree angle of heel rotational analysis (method of slices) ................................................................. 338
Figure 257 – Untrimmed cargo dimensions and resulting average minimum factor of safety from the 30-degree angle of heel rotational analysis (method of slices) ................................................................. 338
Figure 258 – Untrimmed cargo dimensions and resulting average minimum factor of safety from the 40-degree angle of heel rotational analysis (method of slices) ................................................................. 339
Figure 259 – Anna Bo loaded with IOF, listing due to possible liquefaction of the cargo (Asian Marine, 2009) ................................................................................................................................................. 343
Figure 260 – MPFT compaction curve and TML produced during this study on the sample of IOF .. 344
Figure 261 – Apparatus used to perform the MPFT ................................................................ 345
Figure 262 – Illustration of the behaviour of partially saturated cohesionless soils before, during and after liquefaction ............................................................................................................................. 346
Figure 263 – The sample of IOF used during this study ............................................................... 350
Figure 264 – Particle size distribution of the IOF sample used during this study, determined using AS 1289.3.6.1-2009 (Standards Australia, 2009d) and a Mastersizer Aero 3000 (International Standards Organization, 2009) .................................................................................................................. 351
Figure 265 – Dimensions and features of the scale model developed during this study .......... 352
Figure 266 – Dimensions of the IOFP developed and used during this study .......................... 354
Figure 267 – The IOFP and scale model developed and used during this study ........................ 354
List of Figures

Figure 268 – Typical initial placement of a sample of IOF prior to testing ........................................... 357
Figure 269 – The effect of moisture content on the variation of dry density produced during the SCT .......................................................... 358
Figure 270 – The effect of moisture content on the variation of void ratio produced during the SCT ........................................................................................................ 358
Figure 271 – The effect of moisture content on the variation of degree of saturation produced during the SCT ........................................................................................................ 358
Figure 272 – The effect of moisture content on the variation of angle of repose produced during the SCT ........................................................................................................ 358
Figure 273 – The surface profile of TML-1.9% recorded before and after 3600 seconds (1 hour) of vibration applied during the SCT ........................................................................................................ 359
Figure 274 – The surface profile of TML-1.6% recorded before and after 3600 seconds (1 hour) of vibration applied during the SCT ........................................................................................................ 360
Figure 275 – The surface profile of TML% recorded before and after 3600 seconds (1 hour) of vibration applied during the SCT ........................................................................................................ 360
Figure 276 – The surface profile of TML+0.5% recorded before and after 3600 seconds (1 hour) of vibration applied during the SCT ........................................................................................................ 361
Figure 277 – The surface profile of TML+1.3% recorded before and after 3600 seconds (1 hour) of vibration applied during the SCT ........................................................................................................ 361
Figure 278 – The average variation in void ratio and the degree of saturation produced during the SCT, the MPFT compaction curve and the RMC ........................................................................................................ 362
Figure 279 – The average variation in degree of saturation produced during the SCT for the 1 and 4 hour tests at TML%, along with the changes in the degree of saturation of the layers ........................................................................................................ 363
Figure 280 – The variation of the degree of saturation of each layer against the overall moisture content produced during the SCT after 3600 seconds (1 hour) of vibration ........................................................................................................ 365
Figure 281 – The variation of the moisture content of each layer against the overall moisture content produced during the SCT after 3600 seconds (1 hour) of vibration ........................................................................................................ 366
Figure 282 – Penetration of the IOFP against time for each sample ........................................................................................................ 366
Figure 283 – Penetration of the IOFP against moisture content for each sample ........................................... 368
Figure 284 – Modified Proctor/Fagerberg test compaction curve and TML of the specimen of iron ore fines used during this study ........................................................................................................ 368
Figure 285 – Particle size distribution of the specimen of iron ore fines used during this study ........................................................................................................ 375
Figure 286 – q:ν:p’ relationship under the critical state framework (figure produced by authors) ........................................................................................................ 377
Figure 287 – Effect of coefficient of lateral earth pressure, K, on the q:ν:p’ relationship (figure produced by authors) ........................................................................................................ 377
Figure 288 – Example of the 2D relationship between drained and undrained stress paths for the critical state framework (figure produced by authors) ........................................................................................................ 378
Figure 289 – Example of the 3D relationship between stress paths for the critical state framework (figure produced by authors) ........................................................................................................ 380
Figure 290 – Typical phenomena that occur during drained and undrained cyclic loading (figure produced by authors) ........................................................................................................ 381
Figure 291 – Difference between liquefaction and cyclic mobility in the ν:p’ plane (figure produced by authors) ........................................................................................................ 383
Figure 292 – Monotonic and cyclic behaviour of undrained or partially drained saturated materials ........................................................................................................ 385
List of Figures

Figure 293 – Stresses applied to the specimen during triaxial testing (this figure was produced by the author for this publication) .......................................................................................................................... 386
Figure 294 – IPC Global’s Universal Cyclic Triaxial System (UCTS) employed to perform the monotonic and cyclic triaxial testing ........................................................................................................ 386
Figure 295 – Main aspects of the UCTS used to perform the monotonic and cyclic tests ............... 387
Figure 296 – a) Removal of sample from split mould after tamping, b) Typical sample prior to loading .............................................................................................................................................. 388
Figure 297 – a) Time-domain chart of wave data (Haver, 2003) and b) calculated equivalent initial deviator stress (depth: 2.0 m, bulk density: 2.7 t/m³) ......................................................................................................................... 389
Figure 298 – Frequency-domain chart of wave data shown in Figure 297 ........................................ 390
Figure 299 – The CSL and stress paths in the q:p’ plane determined from the initial three monotonic drained tests ........................................................................................................................................ 391
Figure 300 – The CSL and stress paths in the e:ln(p’) plane determined from the initial three monotonic drained tests ......................................................................................................................... 391
Figure 301 – CSL and cyclic stress paths of the samples in the e:ln(p’) plane .................................... 393
Figure 302 – CSL and average drained cyclic stress path in the q:ln(p’) plane (the maximum deviator stress reached before failure criteria was met is marked for each sample) ......................... 394
Figure 303 – Relationship between void ratio and deviator stress during cyclic loading for sample C .................................................................................................................................................. 395
Figure 304 – Relationship between developed pore pressure and deviator stress during cyclic loading for sample C ............................................................................................................................................. 395
Figure 305 – Cyclic Stress Ratio (CSR) causing dilation that may lead to incremental collapse, and, ultimately, failure of the cargo ............................................................................................................... 396
Figure 306 – Before and after cyclic loading during scale model testing showing moisture migration (Munro and Mohajerani, 2017d) .............................................................................................................. 397
Figure 307 – Stress path of sample B in the q:p’ plane during final stage of cyclic loading .............. 399
Figure 308 – q:p plot of sample B during final stage of cyclic loading ............................................. 400
Figure 309 – Excess pore pressure against strain for sample B during final stage of cyclic loading.. 400
Figure 310 – ΔV:p plot of sample B during final stage of cyclic loading........................................... 401
Figure 311 – Modified Proctor/Fagerberg test compaction curve and TML of the specimen of iron ore fines used during this study .......................................................................................................... 406
Figure 312 – Particle size distribution of the specimen of iron ore fines used during this study ...... 407
Figure 313 – Varying materials liquefiable boundaries (Ishihara, 1985; National Research Council, 1985) and the particle size distribution of the iron ore fines tested during this study ................. 409
Figure 314 – Main features of the scale model designed and constructed for this study .................. 410
Figure 315 – High air entry (ceramic) and low air entry (bronze) filters used to record pore water and air pressure, respectively ............................................................................................................. 411
Figure 316 – Computer, data loggers, breakout boards, tensiometers and transducers along with vibrating table controls all attached to the mould to monitor and record data during vibration ..... 412
Figure 317 – Acrylic mould with front panels removed on top of the vibrating table showing transducer locations (the rear probes seen in this image were not used in this study) ............................. 413
Figure 318 – Sample prior to vibration after placement into the scale model .................................... 414
Figure 319 – Change in void ratio for each sample during vibration ................................................. 415
Figure 320 – Change in degree of saturation for each sample during vibration .............................. 416
Figure 321 – Changes that occurred to the samples throughout the duration of the scale model tests (S = degree of saturation) ........................................................................................................... 417
Figure 322 – Overall change in gross water content against the initial and final gross water content for each sample...................................................................................................................................... 418
Figure 323 – Padang Hawk’s cargo hold of nickel ore after suspected liquefaction incident from New Caledonia to Australia (Australian Transport Safety Bureau, 2000) ........................................................................................................................................ 419
Figure 324 – Cargo hold of bulk carrier transporting iron ore fines in India showing fines and free water pooling on the surface (Crouch and Aamlid, 2009) ................................................................................................................................. 419
Figure 325 – Change in gross water content for each sample comparing the top and bottom layers ........................................................................................................................................................................ 420
Figure 326 – Sample I before and after the scale model testing ........................................................................................................................................................................................................ 420
Figure 327 – Surface water on sample I forming during vibration ......................................................................................................................................................................................................... 421
Figure 328 – Difference between the drainage to the surface and base of each sample during vibration ........................................................................................................................................................................ 421
Figure 329 – Particle size distribution of Layer A (Bottom) for all samples ........................................ 422
Figure 330 – Particle size distribution of Layer B (Middle) for all samples ........................................ 422
Figure 331 – Particle size distribution of layer C (Top) for all samples .............................................. 423
Figure 332 – Liquefiable boundaries of various materials (Ishihara, 1985; National Research Council, 1985) and the particle size distribution of the top 20 mm of sample I ......................................................................................................................... 424
Figure 333 – Percent particles passing 0.075 mm for Layer C (Top) .................................................... 424
Figure 334 – Percent particles passing 0.425 mm for Layer C (Top) ................................................... 425
Figure 335 – Change in void ratio for each layer against the total final gross water content ............ 426
Figure 336 – Change in degree of saturation for each layer against the total final gross water content ........................................................................................................................................................................ 426
Figure 337 – Typical data logged for pore air and water pressure for samples A through D .......... 427
Figure 338 – Peak total pore pressure measured within each layer during vibration ..................... 428
Figure 339 – Residual total pore pressure measured within each layer during vibration ................ 428
Figure 340 – Approximate minimum effective stress calculated within each layer during vibration ........................................................................................................................................................................ 429
Figure 341 – Approximate residual effective stress calculated within each layer during vibration .. 429
Figure 342 – Change in resistivity in layer A (bottom) for Samples F and B showing the expected decreasing trend ........................................................................................................................................................................................................ 430
Figure 343 – Comparison of the decrease in resistivity to the pore water pressure in layer A (bottom) for Samples G, H and I........................................................................................................................................................................ 431
Figure 344 – Comparison of the decrease in resistivity to the pore water pressure in layer B (middle) for Samples G, H and I........................................................................................................................................................................................................ 431
Figure 345 – Comparison of the decrease in resistivity to the pore water pressure in layer C (top) for Samples G, H and I........................................................................................................................................................................................................ 431
Figure 346 – Averaged pore water pressure recorded at layer C (top) during the scale model test. 435
Figure 347 – Averaged pore water pressure recorded at layer B (middle) during the scale model test ........................................................................................................................................................................ 436
Figure 348 – Averaged pore water pressure recorded at layer A (bottom) during the scale model test ........................................................................................................................................................................ 436
Figure 349 – Averaged pore air pressure recorded at layer C (top) during the scale model test ...... 437
Figure 350 – Averaged pore air pressure recorded at layer B (middle) during the scale model test 437
Figure 351 – Averaged pore air pressure recorded at layer A (bottom) during the scale model test 438
Figure 352 – sample failure conditions in relation to the void ratio, gross water content, degree of saturation and MPFT results (Munro and Mohajerani, 2017a) ................................................................. 441
Figure 353 – The average rotational analysis factors of safety and boundaries for a trimmed and untrimmed cargo of sample MA004 at varying angles of heel (method of slices) (Munro and Mohajerani, 2017f) .................................................................................................................................................. 442
Figure 354 – The average translational analysis factors of safety and boundaries for a trimmed and untrimmed cargo of sample MA004 at varying angles of heel (infinite slope analysis) (Munro and Mohajerani, 2017f) .................................................................................................................................................. 443
Figure 355 – The average results for the translational and rotational stability analysis of sample MA004 for factors of safety from 1 to 2 (Munro and Mohajerani, 2017f) ......................................................... 443
Figure 356 – CSL and cyclic stress paths of the samples in the e:ln(p’) plane ........................................... 444
Figure 357 – CSL and average drained cyclic stress path in the q:ln(p’) plane (the maximum deviator stress reached before failure criteria was met is marked for each sample) ................................. 444
Figure 358 – Changes that occurred to the samples throughout the duration of the advanced scale model tests on sample MA004 (S = degree of saturation) (Munro and Mohajerani, 2017d) ........ 446
Figure 359 – Overall change in gross water content against the initial and final gross water content for each sub-sample of sample MA004 (Munro and Mohajerani, 2017d) .............................................. 447
Figure 360 – Change in gross water content for each sub-sample of sample MA004 comparing the top and bottom layers (Munro and Mohajerani, 2017d) .......................................................... 447
Figure 361 – Percent particles passing 0.075 mm for Layer C (Top) for all sub-samples of sample MA004 (Munro and Mohajerani, 2017d) ........................................................................................................... 448
Figure 362 – Percent particles passing 0.425 mm for Layer C (Top) for all sub-samples of sample MA004 (Munro and Mohajerani, 2017d) ........................................................................................................... 448
Figure 363 – Approximate minimum effective stress calculated within each layer during vibration of sample MA004 (Munro and Mohajerani, 2017d) ................................................................. 449
Figure 364 – Approximate residual effective stress calculated within each layer during vibration of sample MA004 (Munro and Mohajerani, 2017d) ................................................................. 449
Figure 365 – The variation of the degree of saturation of each layer against the overall moisture content produced during the preliminary scale model tests on sample MA003 after 3600 seconds (1 hour) of vibration (Munro and Mohajerani, 2017c) ........................................................................................................ 450
Figure 366 – The variation of the moisture content of each layer against the overall moisture content produced during the preliminary scale model tests on sample MA003 after 3600 seconds (1 hour) of vibration (Munro and Mohajerani, 2017c) ........................................................................................................ 450
Figure 367 – Penetration of the Iron Ore Fines Plunger (IOFP) against moisture content for sample MA003 (Munro and Mohajerani, 2017c) ........................................................................................................ 451
Figure 368 – Common solid bulk cargo configuration (multiple stacked configuration) ......................... 453
Figure 369 – Bubbling of iron ore fines during vibration testing indicating changing pore pressures within the material ...................................................................................................................... 462
Figure 370 – Major Australian iron ore deposits (Geoscience Australia, 2016) ........................................ 478
Figure 371 – Particle size distributions of the 45 samples of iron ore fines used to create the boundaries of iron ore fines seen in Figure 371 and a single particle size distribution for a typical sample of iron ore concentrate ...................................................................................... 480
Figure 372 – Samples of iron ore fines used to create the boundaries of iron ore fines seen in Figure 371 split based on particle size .............................................................................................................. 481
Figure 373 – Normal distribution for the TML from the standard Proctor/Fagerberg test ........................ 482
Figure 374 – Comparison between Flow Table and Penetration tests TML values for ore concentrates (T Ura, 1992) .......................................................................................................................... 483
Figure 375 – Comparison between Proctor/Fagerberg TML and Flow Table FMP values for ore concentrates (Fagerberg and Stavang, 1971) .............................................................................. 484
Figure 376 – Sample of iron ore fines undergoing compaction exhibiting moisture flowing from the base reducing the ability to achieve the required degree of saturation as outlined in the PFT or MPFT procedures .................................................................................................................. 485
Figure 377 – Sample of iron ore fines during the MPFT, after levelling, exhibiting dilation .......... 486
Figure 378 – Mohr’s circles and the resulting total failure envelope for sample 1 .......................... 487
Figure 379 – Mohr’s circles and the resulting total failure envelope for sample 2 ......................... 487
Figure 380 – Mohr’s circles and the resulting total failure envelope for sample 3 ......................... 488
Figure 381 – Mohr’s circles and the resulting total failure envelope for sample 4 .......................... 488
Figure 382 – Mohr’s circles and the resulting total failure envelope for sample 5 .......................... 489
Figure 383 – Mohr’s circles and the resulting total failure envelope for sample 6 .......................... 489
Figure 384 – Mohr’s circles and the resulting total failure envelope for sample 7 .......................... 490
Figure 385 – Mohr’s circles and the resulting total failure envelope for sample 8 .......................... 490
Figure 386 – Mohr’s circles and the resulting total failure envelope for sample 9 .......................... 491
Figure 387 – Sample TML% during the preliminary scale model testing after 480 and 1800 seconds of vibration ......................................................................................................................... 492
Figure 388 – Penetration of sample TML% by Iron Ore Fines Plunger (IOFP) ................................. 492
Figure 389 – Void left in sample TML% by Iron Ore Fines Plunger (IOFP) ..................................... 493
Figure 390 – After preliminary scale model testing of TML% had been completed and layer B (top layer) had been removed ........................................................................................................ 493
Figure 391 – Pooling of moisture and fine particles shown after preliminary scale model testing was complete for sample TML + 0.5% ................................................................................. 494
Figure 392 – Pooling of moisture and fine particles shown after preliminary scale model testing was complete for sample TML + 0.5% ................................................................................. 494
Figure 393 – Penetration of sample TML + 0.5% by Iron Ore Fines Plunger (IOFP) ......................... 495
Figure 394 – Void left in sample TML + 0.5% by Iron Ore Fines Plunger (IOFP) ............................. 495
Figure 395 – Penetration of sample TML + 1.3% by Iron Ore Fines Plunger (IOFP) ......................... 496
Figure 396 – Sealed sample within triaxial and attached graduated cylinder for the determination of hydraulic conductivity prior to cyclic loading ..................................................................... 501
Figure 397 – Constant head apparatus used to apply a constant pressure to a sample during the determination of hydraulic conductivity .................................................................................... 502
Figure 398 – Variation of the hydraulic conductivity of sample MA004 at the compacted void ratios prior to the advanced cyclic triaxial testing ................................................................. 503
Figure 399 – Compaction of sample A during preparation for the advanced cyclic triaxial testing .. 504
Figure 400 – After levelling of sample A during preparation for the advanced cyclic triaxial testing 505
Figure 401 – After levelling of sample D during preparation for the advanced cyclic triaxial testing 505
Figure 402 – After placement of top cap during preparation for the advanced cyclic triaxial testing ................................................................................................................................. 506
Figure 403 – After removal of split mould from sample A during preparation for the advanced cyclic triaxial testing .................................................................................................................. 507
Figure 404 – After placement of second membrane and O-rings during preparation for the advanced cyclic triaxial testing ....................................................................................................... 508
List of Figures

Figure 405 – After attaching back pressure tubes and applying initial vacuum to sample during preparation for the advanced cyclic triaxial testing ................................................................. 509
Figure 406 – During filling of cell with confining medium after placement around the sample during preparation for the advanced cyclic triaxial testing ................................................................. 510
Figure 407 – Vacuum flask used to apply suction to sample during preparation and manual saturation for the advanced cyclic triaxial testing ................................................................................. 511
Figure 408 – Measuring temperature of water that passed through the sample to correct permeability readings made prior the advanced cyclic triaxial testing ............................................................... 512
Figure 409 – Set-up prior to loading using the advanced cyclic triaxial apparatus ................................................. 513
Figure 410 – Air dried sample of iron ore fines (MA004) stockpiled with scoop using placements of less than 2 cm .............................................................................................................. 514
Figure 411 – Sample of iron ore fines (MA004) at 10% gross water content stockpiled with scoop using placements of less than 2 cm .............................................................................................................. 515
Figure 412 – Initial set-up of apparatus prior to filling the scale model with the specimen to be tested ................................................... 515
Figure 413 – During placement of sample A into the scale model prior to cyclic loading being applied (1) ............................................................................................................................................. 516
Figure 414 – During placement of sample A into the scale model prior to cyclic loading being applied (2) ............................................................................................................................................. 516
Figure 415 – After placement and levelling of sample A into the scale model prior to cyclic loading being applied ............................................................................................................................................. 517
LIST OF EQUATIONS

Eq. 1.................................................................................................................. 108
Eq. 2.................................................................................................................. 108
Eq. 3.................................................................................................................. 118
Eq. 4.................................................................................................................. 118
Eq. 5.................................................................................................................. 126
Eq. 6.................................................................................................................. 136
Eq. 7.................................................................................................................. 136
Eq. 8.................................................................................................................. 138
Eq. 9.................................................................................................................. 138
Eq. 10............................................................................................................... 138
Eq. 11............................................................................................................... 139
Eq. 12............................................................................................................... 139
Eq. 13............................................................................................................... 139
Eq. 14............................................................................................................... 140
Eq. 15............................................................................................................. 203
Eq. 16............................................................................................................. 203
Eq. 17............................................................................................................. 227
Eq. 18............................................................................................................. 227
Eq. 19............................................................................................................. 294
Eq. 20............................................................................................................. 294
Eq. 21............................................................................................................. 296
Eq. 22............................................................................................................. 296
Eq. 23............................................................................................................. 317
Eq. 24............................................................................................................. 318
Eq. 25............................................................................................................. 321
Eq. 26............................................................................................................. 321
Eq. 27............................................................................................................. 347
Eq. 28............................................................................................................. 347
Eq. 29............................................................................................................. 347
Eq. 30............................................................................................................. 347
Eq. 31............................................................................................................. 347
Eq. 32............................................................................................................. 347
Eq. 33............................................................................................................. 347
Eq. 34............................................................................................................. 348
Eq. 35............................................................................................................. 348
Eq. 36............................................................................................................. 359
Eq. 37............................................................................................................. 359
Eq. 38............................................................................................................. 376
Eq. 39............................................................................................................. 378
Eq. 40............................................................................................................. 384
Eq. 41............................................................................................................. 384
Eq. 42............................................................................................................. 384
Eq. 43............................................................................................................. 407
Eq. 44 .............................................................................................................................. 408
Eq. 45 .............................................................................................................................. 408
Eq. 46 .............................................................................................................................. 411
LIST OF APPENDICES

Individual appendices for each of the included manuscripts are not shown in this table. They are presented as they appear in the original manuscript. They can be seen in the associated chapter at the end of the section named ‘Manuscript Contents’.

Table 1 – Appendices

| Appendix A – Major Australian Iron Ore Deposits | Page 478 |
| Appendix B – Supplementary Results for Manuscript Presented in Chapter 5 | Page 479 |
| Appendix C – Supplementary Results for Manuscript Presented in Chapter 7 | Page 485 |
| Appendix D – Supplementary Results for Manuscript Presented in Chapter 13 | Page 487 |
| Appendix E – Supplementary Results for Manuscript Presented in Chapter 14 | Page 492 |
| Appendix F – Supplementary Results for Manuscript Presented in Chapter 15 | Page 501 |
| Appendix G – Supplementary Results for Manuscript Presented in Chapter 16 | Page 514 |
# Abbreviations and Acronyms

## Table 2 – Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Method</td>
<td>Method used by Fagerberg (Fagerberg and Stavang, 1971)</td>
</tr>
<tr>
<td>ACARP</td>
<td>Australian Coal Association Research Program</td>
</tr>
<tr>
<td>AMIRA</td>
<td>Australian Mineral Industries Research Association</td>
</tr>
<tr>
<td>AMSA</td>
<td>Australian Maritime Safety Authority</td>
</tr>
<tr>
<td>AS</td>
<td>Australian Standard</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>ATSB</td>
<td>Australian Transport Safety Bureau</td>
</tr>
<tr>
<td>B Method</td>
<td>Method used by Fagerberg (Fagerberg and Stavang, 1971)</td>
</tr>
<tr>
<td>BC Code</td>
<td>Code of Safe Practice for Solid Bulk Cargoes</td>
</tr>
<tr>
<td>C Method</td>
<td>Method used by Fagerberg (Fagerberg and Stavang, 1971)</td>
</tr>
<tr>
<td>C70</td>
<td>C Method at 70% Degree of Saturation</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
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<td>CSL</td>
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<td>CSR</td>
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<td>D70</td>
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<td>DIA</td>
<td>Diameter</td>
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<td>DSC</td>
<td>Sub-Committee on Dangerous Goods, Solid Cargoes and Containers</td>
</tr>
<tr>
<td>DWT</td>
<td>Dead Weight Tonnage</td>
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<td>E Method</td>
<td>Method used by Fagerberg (Fagerberg and Stavang, 1971)</td>
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<td>FeOOH</td>
<td>Goethite</td>
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<td>Factor of Safety</td>
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<td>FT</td>
<td>Flow Table Test / Failure Threshold</td>
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<tr>
<td>FTT</td>
<td>Flow Table Test</td>
</tr>
<tr>
<td>GM</td>
<td>Silty Gravel</td>
</tr>
<tr>
<td>GP</td>
<td>Poorly Graded Gravel</td>
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<tr>
<td>GW</td>
<td>Gross Water Content</td>
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<td>GWC</td>
<td>Gross Water Content</td>
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</tr>
<tr>
<td>IMSBC Code</td>
<td>International Maritime Solid Bulk Cargoes Code</td>
</tr>
<tr>
<td>IOF</td>
<td>Iron Ore Fines</td>
</tr>
<tr>
<td>IOFP</td>
<td>Iron Ore Fines Plunger</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standards Organization</td>
</tr>
<tr>
<td>JIS</td>
<td>Japanese Industry Standard</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear Vertical Displacement Transducer</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
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<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>MARIN</td>
<td>Maritime Research Institute Netherlands</td>
</tr>
<tr>
<td>MARINTEK</td>
<td>Norwegian Marine Technology Research Institute</td>
</tr>
<tr>
<td>MDD</td>
<td>Maximum Dry Density</td>
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<tr>
<td>METHOD A</td>
<td>Method used by Fagerberg (Fagerberg and Stavang, 1971)</td>
</tr>
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<td>METHOD B</td>
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<td>METHOD E</td>
<td>Method used by Fagerberg (Fagerberg and Stavang, 1971)</td>
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<tr>
<td>MPFT</td>
<td>Modified Proctor/Fagerberg Test</td>
</tr>
<tr>
<td>MSC</td>
<td>Marine Safety Committee</td>
</tr>
<tr>
<td>N/A, NA</td>
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<td>NC</td>
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</tr>
<tr>
<td>NCL</td>
<td>Normal Consolidation Line</td>
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<tr>
<td>NP</td>
<td>Non-Plastic</td>
</tr>
<tr>
<td>NWC</td>
<td>Net Water Content</td>
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<td>OC</td>
<td>Over-Consolidated</td>
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<td>OCL</td>
<td>Over-Consolidated Line</td>
</tr>
<tr>
<td>OMC</td>
<td>Optimum Moisture Content</td>
</tr>
<tr>
<td>PF</td>
<td>Standard Proctor/Fagerberg Test</td>
</tr>
<tr>
<td>PFT</td>
<td>Standard Proctor/Fagerberg Test</td>
</tr>
<tr>
<td>PT</td>
<td>Penetration Test</td>
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<tr>
<td>RLT</td>
<td>Repeated Load Triaxial</td>
</tr>
<tr>
<td>RLTT</td>
<td>Repeated Load Triaxial Test</td>
</tr>
<tr>
<td>RMC</td>
<td>Restraining Moisture Content</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
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<tr>
<td>SCT</td>
<td>Scaled Cyclic Testing</td>
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<tr>
<td>SOLAS Convention</td>
<td>International Convention for the Safety of Life at Sea</td>
</tr>
<tr>
<td>SG</td>
<td>Specific Gravity (Particle Density)</td>
</tr>
<tr>
<td>TML</td>
<td>Transportable Moisture Limit</td>
</tr>
<tr>
<td>TUNRA</td>
<td>The University of Newcastle Research Associates</td>
</tr>
<tr>
<td>TWG</td>
<td>Iron Ore Technical Working Group</td>
</tr>
<tr>
<td>UCTS</td>
<td>Universal Cyclic Triaxial System</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>UTM-14P</td>
<td>14 kN Pneumatic Universal Testing Machine</td>
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## Nomenclature

### Table 3 – Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$B$</td>
<td>Centre of Buoyancy of Hull of Vessel</td>
</tr>
<tr>
<td>$b_j$</td>
<td>Width of the Slice of Soil for an Infinite Slope</td>
</tr>
<tr>
<td>$c$</td>
<td>Total Cohesion Factor</td>
</tr>
<tr>
<td>$C$</td>
<td>Total Cohesion Factor</td>
</tr>
<tr>
<td>$c'$</td>
<td>Effective Cohesion Factor</td>
</tr>
<tr>
<td>$c_c$</td>
<td>Coefficient of Curvature</td>
</tr>
<tr>
<td>$c_u$</td>
<td>Coefficient of Uniformity</td>
</tr>
<tr>
<td>$D_r$</td>
<td>Relative Density</td>
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<tr>
<td>$e$</td>
<td>Void Ratio</td>
</tr>
<tr>
<td>$e_i$</td>
<td>Initial Void Ratio</td>
</tr>
<tr>
<td>$e_c$</td>
<td>Void Ratio after Consolidation</td>
</tr>
<tr>
<td>$F_B$</td>
<td>Buoyancy Force</td>
</tr>
<tr>
<td>$FS$</td>
<td>Factor of Safety</td>
</tr>
<tr>
<td>$g$</td>
<td>Acceleration due to Gravity</td>
</tr>
<tr>
<td>$G$</td>
<td>Centre of Gravity</td>
</tr>
<tr>
<td>$G_s$</td>
<td>Specific Gravity (Particle Density)</td>
</tr>
<tr>
<td>$h$</td>
<td>Height</td>
</tr>
<tr>
<td>$h_i$</td>
<td>Initial Height</td>
</tr>
<tr>
<td>$H_p$</td>
<td>Resilient / Recoverable Deformation</td>
</tr>
<tr>
<td>$H_r$</td>
<td>Resilient Modulus</td>
</tr>
<tr>
<td>$k$</td>
<td>Hydraulic Conductivity (Permeability) / Factor of Plasticity</td>
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<tr>
<td>$K$</td>
<td>Hydraulic Conductivity (Permeability) / Lateral Earth Pressure Coefficient</td>
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<tr>
<td>$K_f$</td>
<td>Lateral Earth Pressure Coefficient at Failure</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass</td>
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<tr>
<td>$m_v$</td>
<td>Coefficient of Compressibility</td>
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<tr>
<td>$M$</td>
<td>Slope of CSL in the $q:p'$ Plane / Metacentre</td>
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<tr>
<td>$M_o$</td>
<td>Overturning Moment</td>
</tr>
<tr>
<td>$M_R$</td>
<td>Restoring / Resisting Moment</td>
</tr>
<tr>
<td>$M_r$</td>
<td>Resilient Modulus</td>
</tr>
<tr>
<td>$N$</td>
<td>$\nu$-axis Intersection of NCL in the $\nu:p'$ Plane / Number of Cycles</td>
</tr>
<tr>
<td>$N_f$</td>
<td>Number of Cycles before Failure</td>
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<tr>
<td>$N_j$</td>
<td>Normal Force on Slip Plane</td>
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<tr>
<td>$p'$</td>
<td>Mean Effective Stress</td>
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<tr>
<td>$p'_c$</td>
<td>Mean Effective Stress during Consolidation</td>
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<tr>
<td>$p'_{cs}$</td>
<td>Mean Effective Stress at Critical State</td>
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<tr>
<td>$q$</td>
<td>Deviator Stress</td>
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<td>Deviator Stress at Critical State</td>
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<tr>
<td>$r$</td>
<td>Radius</td>
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<td>$R^2$</td>
<td>Coefficient of Determination</td>
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<tr>
<td>$s$</td>
<td>Existing Suction</td>
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<td>$s_e$</td>
<td>Suction resulting in Air Entering Saturated Soil</td>
</tr>
<tr>
<td>$S$</td>
<td>Degree of Saturation</td>
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<tr>
<td>$S_w$</td>
<td>Degree of Saturation</td>
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<td>$T_f$</td>
<td>Mobilized Shear Resistance of Soil</td>
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<tr>
<td>$u$</td>
<td>Pore Pressure</td>
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<tr>
<td>$u_o$</td>
<td>Pore Air Pressure</td>
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<td>( u_a - u_w )</td>
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<tr>
<td>( u_i )</td>
<td>Initial Pore Pressure</td>
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<tr>
<td>( u_m )</td>
<td>Matric Suction</td>
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<td>( u_w )</td>
<td>Pore Water Pressure</td>
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<td>Volume</td>
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<tr>
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<td>Volume of Air</td>
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<td>( w )</td>
<td>Net Water Content</td>
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<tr>
<td>( W )</td>
<td>Weight</td>
</tr>
<tr>
<td>( W_f )</td>
<td>Weight of Slice for Infinite Slope</td>
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<tr>
<td>( w_1 )</td>
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<td>( w_G )</td>
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<tr>
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<td>( w_N )</td>
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<td>( X )</td>
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<td>( z_j )</td>
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<thead>
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<td>Partial Differential</td>
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<td>( \alpha )</td>
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<tr>
<td>( \alpha_f )</td>
<td>Angle of Heel at Failure</td>
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<td>( \alpha_s )</td>
<td>Slope Angle from Horizontal</td>
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<tr>
<td>( \beta' )</td>
<td>Holding or Bonding Factor</td>
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<td>( \Gamma )</td>
<td>( v )-axis Intersection of CSL in the ( v:p' ) Plane</td>
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<tr>
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<td>Bulk Unit Weight</td>
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<td>( \gamma_b )</td>
<td>Bulk Unit Weight</td>
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<tr>
<td>( \gamma_d )</td>
<td>Coefficient of Uniformity</td>
</tr>
<tr>
<td>( \gamma_s )</td>
<td>Saturated Unit Weight</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Difference or Change in Certain Quantity</td>
</tr>
<tr>
<td>( \Delta )</td>
<td>Difference or Change in Certain Quantity</td>
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<td>( \varepsilon )</td>
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<td>Permanent Strain</td>
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<td>Triaxial Shear Strain</td>
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<td>( \varepsilon_r )</td>
<td>Resilient / Recoverable Strain</td>
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<td>Effective Stress Ratio</td>
</tr>
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<td>( \eta_{cs} )</td>
<td>Effective Stress Ratio at Critical State</td>
</tr>
<tr>
<td>( \theta )</td>
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<td>Normalized Volumetric Water Content</td>
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<td>Slope of OCL in the ( v:p' ) Plane</td>
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<tr>
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<tr>
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<td>Microstrain</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Specific Volume</td>
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<tr>
<td>( \rho )</td>
<td>Bulk or Wet Density</td>
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<tr>
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<td>Bulk or Wet Density</td>
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<td>Dry Density</td>
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<td>Normal Stress</td>
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<td>( \sigma' )</td>
<td>Effective Stress</td>
</tr>
<tr>
<td>( \sigma'_1 )</td>
<td>Effective Major Principal Stress (Axial)</td>
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<td>Symbol</td>
<td>Description</td>
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<td>--------</td>
<td>--------------------------------------------------</td>
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<tr>
<td>$\sigma'_3$</td>
<td>Effective Confining Pressure / Effective Cell Pressure</td>
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<td>$\sigma_d$</td>
<td>Deviator Stress</td>
</tr>
<tr>
<td>$\sigma_h$</td>
<td>Horizontal Stress</td>
</tr>
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<td>$\sigma_q$</td>
<td>Deviator Stress</td>
</tr>
<tr>
<td>$\sigma_v$</td>
<td>Vertical Stress</td>
</tr>
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<td>$\sigma_n - u_a$</td>
<td>Net Normal Stress on the Plane of Failure at Failure</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Shear Strength</td>
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<td>$\tau_m$</td>
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<tr>
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<td>Effective Internal Friction Angle</td>
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<tr>
<td>$\phi'$</td>
<td>Total Internal Friction Angle</td>
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<tr>
<td>$\phi'^b$</td>
<td>Effective Internal Friction Angle</td>
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<tr>
<td>$\phi'^b$</td>
<td>Angle Linking Rate of Change of Shear Strength with Matric Suction</td>
</tr>
<tr>
<td>$\chi$</td>
<td>Bishop’s Degree of Saturation Factor for Unsaturated Soils</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>Matric Suction</td>
</tr>
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</table>
EXECUTIVE SUMMARY

In 2011, legislation that governs the safe transportation of solid bulk cargoes, known as the International Maritime Solid Bulk Cargoes Code (IMSBC Code), became mandatory under the SOLAS Convention. Included in this legislation are test methods used to determine a safe moisture content that certain solid bulk cargoes can contain, during transportation, if they have been deemed potentially liquefiable.

Liquefaction of a cargo solid bulk cargo during transportation can result in the cargo shifting and altering the buoyancy of the transporting vessel. Depending on the mass of cargo that shifts, it may result in the vessel listing or capsizing. Between 1988 and 2016, 23 incidents were reported where liquefaction of a solid bulk cargo was suspected. These incidents resulted in 138 casualties and the loss of 17 vessels.

Due to the mandatory implementation of the IMSBC Code and the occurrences of incidents where liquefaction of iron ore fines was suspected during transportation, industries and research institutions were required to consider the adequacy of the current methods and/or amend or introduce a suitable method for testing the cargo. The outcome of this work was the introduction of a new test method specifically designed for the testing of iron ore fines. The test, known as the Modified Proctor/Fagerberg Test (MPFT), was first introduced in 2013 and its use was made mandatory from January 2017.

As previously stated, the MPFT was designed to determine a moisture content under which a cargo of iron ore fines was considered unable to liquefy and therefore safe for marine transportation. During preliminary testing and investigations, questions arose surrounding the; validity of the test, methodology behind its creation, and whether liquefaction was indeed the correct phenomenon that was occurring, which resulted in cargoes of iron ore fines shifting during marine transportation.

The objective of this research was to investigate, at a fundamental level, the possible phenomena that may be responsible for cargoes of iron ore fines shifting, in the holds of bulk carriers, during marine transportation. In this study, both practical and theoretical analysis were employed to visualize as well as objectively quantify, both the cause and type of phenomena that may be possible. To fully understand and reproduce the possible phenomena, standard test methods were used, in combination with unique and novel methods, designed and developed during this study. Summarizing the information that was gathered and produced during this research resulted in conclusions regarding the validity of implementing the MPFT that is used to protect against liquefaction during marine transportation.

It was concluded that there are multiple phenomena that can result in a cargo of iron ore fines shifting in the hold of a bulk carrier during marine transportation, with a sensitive dependence on initial conditions. Although liquefaction was the primary phenomenon suspected, this study concludes that liquefaction of the cargo, as a whole, is unlikely. There are two likely phenomena that both masquerade as full cargo liquefaction. The first phenomenon is identified as liquefaction, although not liquefaction of the cargo as a whole as speculated. It was shown that moisture migration can occur towards the surface of the cargo transporting fine particles creating areas of material with a greater potential to liquefy.
This research also identified incremental collapse as another possible phenomenon that may occur resulting in a cargo of iron ore fines shifting. Unlike partial liquefaction as described above, this phenomenon is most likely to occur to an untrimmed cargo. Incremental collapse may ultimately result in a shear plane developing resulting in the cargo abruptly shearing, such as occurs during a slope failure. These phenomena can be linked to the behaviour of the cargoes and vessels described during the suspected liquefaction incidents investigated during this research.

It was also concluded that the principal theory used to design and develop the MPFT is not one that is widely accepted in geotechnical engineering and soil mechanics to determine the liquefaction potential or cyclic behaviour of soils. It was identified that the moisture-holding ability of iron ore fines is a major influence in the likelihood of partial liquefaction occurring. Preventing moisture migration will likely prevent the possibility of partial liquefaction.

During this research, the Transportable Moisture Limit (TML), the parameter determined using the MPFT, was consistently equal to or higher than the moisture contents measured where migration of moisture and fine particles were recorded. This indicated that if a cargo of iron ore fines is loaded onto a bulk carrier, at the TML, moisture migration may occur resulting in areas within the cargo with a high potential to liquefy.

The results from this study are based on the results from the testing of limited specimens of iron ore fines. The comments and conclusions made within this thesis relate to the assumption that iron ore fines, as a cargo, have a constantly changing and significantly wide range of physical properties, from location to location, which has also been shown to be the case. The majority of the results from this research are presented in eight international journals, which are included in chapters within this thesis. Additional results that have not yet been published are currently being prepared or reviewed for publication.

In this day and age, the loss of human life is unacceptable under any circumstance and must be avoided at all costs. Incidents occurring during the transportation of iron ore fines and other similar solid bulk cargoes can and must be avoided to protect the safety of maritime personnel, the environment, and prevent the needless loss of resources and assets. Hopefully, this research will not only improve safety at sea but may be built upon in the future and used for the analysis of other solid bulk cargoes where the occurrence of such phenomenon is still prevalent, such as nickel ore and/or bauxite.
CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

In 2011, a major change occurred regarding the shipping of solid bulk cargoes, the effect of which can be still felt today and will likely be felt well into the future. On 1 January 2011, the foremost legislation governing the safe transportation of solid bulk cargoes became mandatory under the provisions of the International Convention for the Safety of Life at Sea (SOLAS Convention) (International Maritime Organization MSC85/26/Add.2, 2008). This legislation, known as the International Maritime Solid Bulk Cargoes Code (IMSBC Code), provides specific information, schedules, and procedures to prevent incidents from occurring during marine transportation (International Maritime Organization, 2016).

The vessels used to transport solid bulk cargoes, described in further detail in Chapter 2 Section 2.3, are referred to as bulk carriers, one of which can be seen in Figure 1. The incidents that may be experienced on board bulk carriers during marine transportation include, but are not limited to, structural damage, loss of stability and chemical reactions. A chemical reaction may result in fire, the release of toxic gases and/or the creation of oxygen deficient areas, while structural damage and loss of stability may result in listing or, if severe, foundering of the vessel.

![Figure 1 – Typical bulk carrier used for the marine transportation of solid bulk cargoes (Imabari Shipbuilding Co. Ltd., 2016)](image)

Solid bulk cargoes, especially those deemed hazardous, each have an individual schedule listed in the IMSBC Code that must be followed whilst the material is being loaded, transported or discharged from a bulk carrier. Each schedule includes information, such as the characteristics of the material, hazards it poses, precautions that must be taken, and other requirements specific to the cargo. Also included in the schedule is the group classification of the cargo (International Maritime Organization, 2016). There are three groups into which a cargo can be classified:

1. Group A - cargoes that may possibly liquefy,
2. Group B - cargoes that may pose a chemical hazard, and
3. Group C - cargoes that are deemed neither able to liquefy nor pose a chemical hazard.

The basic procedures that must be implemented during handling and transportation are related to the group classification of the cargo. Resulting from the mandatory implementation of the IMSBC Code, in 2011, was the mandatory testing of Group A or potentially liquefiable cargoes using the procedures.
provided in Appendix 2 of the IMSBC Code (International Maritime Organization, 2016). Using these procedures, the Transportable Moisture Limit (TML) of the cargo can be determined. Referred to extensively herein, the TML is a specific moisture content that if a cargo exceeds during loading may have the potential to liquefy during marine transportation with potentially disastrous results.

In 2011, the IMSBC Code included three test methods that could be utilized to determine the Transportable Moisture Limit (TML) of a Group A cargo. The three test methods, described in detail in Chapter 2 Section 2.8.2, were specifically designed for the testing of ore concentrates and coal (Fagerberg, 1965; Fagerberg and Eriksson, 1962; Fagerberg and Stavang, 1971; International Maritime Organization, 2016; International Standards Organization, 2007; T Ura, 1992).

One cargo that is commonly transported in the holds of bulk carriers is iron ore fines. At the time of the mandatory implementation of the IMSBC Code, cargoes of iron ore fines had been suspected of undergoing liquefaction during marine transportation, which resulted in the listing or foundering of the transporting vessel (Munro and Mohajerani, 2017b). At that time, there was no individual schedule listed in the IMSBC Code for iron ore fines. All that existed was an all-encompassing schedule for iron ore, where the classification was, and for iron ore still is, Group C or deemed neither able to liquefy nor poses a chemical hazard (International Maritime Organization, 2012b).

Iron ore fines is a by-product created during the separation or iron ore lump from the raw ore extracted from the earth. Although it only contains approximately 50% iron, iron ore fines are still considered a valuable commodity that is regularly shipped around the world to be refined in places such as China and South Korea (Ridsdale and Sultan, 2011). As the name suggests, the particles that constitute iron ore fines are considerably finer than that of iron ore lump, which is commonly referred to as simply iron ore. This higher percentage of fines results in the iron ore fines having a higher potential to liquefy during marine transportation (Ishihara, 1985; Munro and Mohajerani, 2015).

Due to the similarities of the physical properties of iron ore fines to other potentially liquefiable materials and the relation to associated incidents, an individual schedule and accompanying test method, specifically designed for iron ore fines, was required (International Maritime Organization, 2011). In late 2012, a group was formed by the International Maritime Organisation (IMO), which is the organization that sets the standards in the IMSBC Code. This group, known as the Iron Ore Technical Working Group (TWG), was created to conduct research and coordinate recommendations and conclusions about the transportation of iron ore fines (Iron Ore Technical Working Group, 2013c).

Over an approximate period of two years, from late 2012, the most notable accomplishment of the TWG was the development of a test method that was specifically designed for the determination of the TML of iron ore fines (AMIRA International, 2012; Iron Ore Technical Working Group, 2013a). This test method, known as the Modified Proctor/Fagerberg Test (MPFT), was first introduced as a draft amendment to the IMSBC Code in late 2013, and implementation of this amendment, by some countries, commenced on a voluntary basis shortly thereafter (Australian Maritime Safety Authority, 2013b; International Maritime Organization, 2013a).

The research herein began two days after the Australian Maritime Safety Authority (AMSA) gave an exemption for the use of the draft individual schedule for iron ore fines instead of the schedule for iron ore that was currently in use (Australian Maritime Safety Authority, 2013b; International Maritime Organization, 2013a).
Having previous knowledge regarding the physical properties of iron ore fines along with the behaviour of potentially liquefiable materials, questions inevitably arose regarding the underlying factors influencing iron ore fines to liquefy (Munro and Mohajerani, 2015). Furthermore, having performed the test methods provided in Appendix 2 of the IMSBC Code, including the MPFT, additional questions arose regarding the methodology used during the creation of the test methods and whether control of a single parameter, the TML, could prevent liquefaction from occurring in a material with such varying properties.

Due to the changes that occurred throughout this research, primarily pertaining to policies and procedures, early publications may include information that differs from that of today. After each manuscript presented in this thesis, there will be a summary where information will be provided in regards to changes that may have occurred after the manuscript was published.

This research focuses on the influencing factors relating to iron ore fines shifting in the cargo hold of a bulk carrier during marine transportation. This includes whether or not it is indeed liquefaction that is the cause of the cargo to shift or another unforeseen phenomenon. It is noted that during the early stages of this research the term liquefaction is used, rather than simply cargo shift or phenomenon, due to the term liquefaction being commonly used in related research, documents, and standards, including the IMSBC Code (International Maritime Organization, 2016). It seemed only appropriate, in some contexts, to refer to what is occurring in the cargo hold as liquefaction. Therefore, when used, sometimes the term liquefaction is not a definitive term describing what is actually occurring rather simply trying to conform to the terms used in the industry.

1.2 RESEARCH OBJECTIVES

The objective of this research is to investigate, at a fundamental level, the possible phenomena that may be responsible for cargoes of iron ore fines shifting, in the holds of bulk carriers, during marine transportation. It is currently speculated that liquefaction is responsible for cargoes of iron ore fines shifting in the holds of bulk carriers, which can result in the listing, capsizing and ultimately foundering of the vessel transporting the material.

To understand the phenomena responsible for cargoes of iron ore fines shifting, several aspects of research must be undertaken. Initially, it is required to understand what is currently known about iron ore fines, as a commodity and cargo, as well as the policies and procedures currently implemented to prevent the cargo from shifting during marine transportation. This includes understanding the typical properties of the material and current test methods that are used to reduce the potential for liquefaction to occur. Understanding the development of the test methods used to prevent the cargo from shifting during marine transportation is not only useful in understanding the relationship of the results to certain phenomena, but also imperative to determine if the principal theory used to design and develop them is one that is widely accepted.

It is then necessary to understand the different types of phenomena that may be the cause of a cargo shifting during marine transportation, including liquefaction. This involves examination of the conditions under which iron ore fines are transported in the holds of bulk carriers and investigations into incidents where cargoes of iron ore fines have shifted. These aspects will assist in the development and design of methods and procedures to be used to analyse the possible phenomena.
In this study, both practical and theoretical analysis are employed to visualize as well as objectively quantify, both the cause and type of phenomena that may be possible. To fully understand the phenomena, standard test methods are used, in combination with unique and novel methods that have been designed and developed, during this study, in order to reproduce possible phenomena.

Conclusions are made concerning the possible phenomena that may be responsible for the listing, capsizing and ultimately foundering of bulk carriers transporting iron ore fines. Summarizing the information that was gathered and produced during this research will result in conclusions regarding the validity of implementing the test method given in the International Maritime Solid Bulk Cargoes Code that is used to protect against liquefaction of iron ore fines during marine transportation.

Finally, recommendations concerning the management and testing policies and procedures are provided to limit the possibility of future incidents from occurring. These recommendations are based on the conclusions from the research and will endeavour to further educate exporters, insurers as well as maritime personnel regarding this issue.

1.3 SIGNIFICANCE

The phenomena that occur to cargoes of iron ore fines undergoing marine transportation have also been deemed to be the cause of incidents involving several other solid bulk cargoes, such as bauxite, nickel ore, fluorspar, and manganese. Since 1988, the phenomenon, suspected to be liquefaction, has been blamed for a total 23 incidents, which resulted in a total of 138 casualties and the total loss of 17 vessels (Munro and Mohajerani, 2017b).

Previous researchers, dating back to 1962, have described what is occurring, causing these solid bulk cargoes to shift during marine transportation, as liquefaction (Fagerberg, 1965; Fagerberg and Eriksson, 1962). It is noted that this description of the phenomenon has not changed since these early days, even after the introduction of the IMSBC Code (Munro and Mohajerani, 2016b).

It has been assumed that from these earlier descriptions of the phenomenon, the focus of researchers has always been liquefaction. It is noted that although liquefaction may be the primary cause of incidents occurring to the cargoes at the time, which were mainly mineral concentrates, iron ore fines is significantly different, and, due to the varying properties, such simple methods for determining a safe moisture content for shipment may not be applicable for this type of cargo. If industry and researchers continue to assume the cause of all similar incidents are related to liquefaction, then, inescapably, this is what future research will continue to focus on. Therefore, if incidents are caused by another unforeseen phenomenon, they may continue to occur.

In this day and age, the loss of human life is unacceptable under any circumstance and must be avoided at all costs. Incidents occurring during the transportation of iron ore fines and other similar solid bulk cargoes can and must be avoided to protect the safety of maritime personnel, the environment, and prevent the needless loss of resources and assets. Hopefully, this research will not only improve safety at sea but may be built upon in the future and used for the analysis of other solid bulk cargoes where the occurrence of such phenomenon is still prevalent, such as nickel ore and/or bauxite.
1.4 RESEARCH SCOPE AND DESIGN

As previously touched upon in 1.2, the research presented herein has several aspects. These aspects have been logically separated to produce the following scope of research that this thesis encompasses. In this chapter, the methodology, objectives, and outcomes are provided for each aspect.

1.4.1 Physical Properties of Iron Ore Fines

During the initial stages of this research, it was necessary to determine the range of physical properties of iron ore fines to comprehend the extent to which they may vary. Previous research performed, in regards to the liquefaction of solid bulk cargoes, indicated that the cargoes under investigation were those that have a uniform particle size distribution (Fagerberg, 1965; Fagerberg and Eriksson, 1962; Fagerberg and Stavang, 1971; International Standards Organization, 2007; T Ura, 1992; Tamaki Ura, 1995).

The particle size distribution is considered to be one of the major influences of a soils liquefiability due to the controlling influence it has on the materials moisture-holding ability, permeability and compaction characteristics (Ishihara, 1985). It was believed that having an understanding of the physical properties iron ore fines would give an indication of the possible phenomena to examine that may be causing the cargo to shift during marine transportation. As seen in Figure 2, multiple samples were initially tested to determine the variation in the range of physical properties.

![Samples of iron ore fines with varying physical properties tested during this study (Munro and Mohajerani, 2016c)](image)

Sourcing samples of sufficient size for this research was somewhat difficult due to the privacy of the industry regarding the properties of individual products and the current publicity and research brought about by the mandatory implementation of the IMSBC Code. It was therefore decided to determine a typical cargo of iron ore fines so that specific enquiries could be made to obtain a similar sample for this research. By using iron ore fines typically transported at sea, this research is expected to be more relevant than if it focussed on a niche cargo with few that export it.
1.4.2 Phenomena Relating to Cargo Shift

One question surrounding this research is whether liquefaction, as described in Chapter 2 Section 2.6.1, is the correct term for describing the phenomenon that occurs resulting in the shifting of a cargo. This aspect of research relates to the physical properties of iron ore fines, as the conditions experienced during transportation will cause a material with certain physical properties to behave in certain ways.

![Figure 3 - Four types of phenomena relating to a solid bulk cargo shifting; a) translational shear failure, b) rotational shear failure, c) liquefaction, and d) sliding en-masse (Munro and Mohajerani, 2017f)](image)

A strong knowledge of the different types of phenomena relating to cargo shifting, some of which are shown in Figure 3, must be obtained to indicate which is likely based on the physical properties of iron ore fines and the system variables under which iron ore fines are transported. Some of the phenomena analysed include liquefaction, cyclic mobility, incremental collapse, shakedown, and shear failure. The methods used and apparatus designed and developed further into this research were based upon the understanding of these different types of phenomena.

1.4.3 Methods used for Prevention

Another question surrounding this research is: are the methods implemented to prevent a cargo of iron ore fines shifting relevant to the phenomena occurring? As liquefaction is the suspected cause of the incidents, this specific phenomenon influenced the design and development of the test methods listed in Appendix 2 of the IMSBC Code; pictured in Figure 4.
An overall review was undertaken on the principal theories behind these preventative methods. This included the history of the methods as well as recent developments that were continuing to occur in respect to the policies and procedures. All the test methods were performed on multiple variants of iron ore fines to determine the relationship of the test results to each other. This provided valuable insights into the behaviour of the material based on both visual observations and the results produced by performing the tests.

Future results from unique and novel methods and procedures designed and developed during this research will be compared with the results from the preventative methods currently in use. It is noted that since the mandatory implementation of the MPFT occurred part way through this research, initial investigations focussed on the three methods listed in the 2012 edition of the IMSBC Code (International Maritime Organization, 2012b). This was then followed by the investigation into the newly developed MPFT included in the 2016 edition of the IMSBC Code, which was specifically designed to test iron ore fines (International Maritime Organization, 2016). The later research solely focused on this new method, as the others fell out of use pertaining to iron ore fines, but not before the relationship between all the results from the test methods were identified (Munro and Mohajerani, 2015, 2016b).

1.4.4 Suspected liquefaction Incidents
To obtain a full understanding of the phenomena that may occur during the marine transportation of solid bulk cargoes, a database of all the suspected liquefaction incidents was created. Analysing the investigation reports, witness accounts and newly created database, similarities and trends between the incidents were discovered that indicated certain types of phenomena may be occurring. A bulk carrier that had a cargo of iron ore fines on board that was suspected to have undergone liquefaction can be seen in Figure 5.
Along with having a good understanding of the different types of phenomena that may cause a cargo to shift during marine transportation, discovering additional evidence indicating specific phenomena helped focus the research.

### 1.4.5 Preliminary Test Design and Development

To determine the behaviour of iron ore fines and observe the potential phenomena that may occur during marine transportation, the methodology of testing incorporated both standard methods and methods designed and developed specifically for this research. During the early stages of this research, preliminary tests were carried out to both determine the potential issues that may arise when performing the chosen tests and determine whether the results produced would assist in achieving the objective of this research.

Preliminary testing included using standard methods with modified procedures, such as cyclic triaxial testing, along with unique methods, such as vibratory, scale model and plunger testing, where the complete apparatus and accompanying procedures had to be designed and developed. The results from the preliminary tests showed the capabilities and limitations of the equipment that was available and the feasibility of designing and developing the new, unique and novel test apparatus.

### 1.4.6 Computational Modelling

From the commencement of this research, it was known that the majority of the methods used would involve physical testing and analysis rather than computational modelling. Although there are many computational modelling methods that could have been used to analyse the liquefaction potential or stability of a solid bulk cargo in the hold of a bulk carrier, this was not the research direction that was chosen. This was partly due to the limited time available and recently released technical reports that already provided a significant amount of computational modelling and analysis (Iron Ore Technical Working Group, 2013b, 2013c).

With this said, there was one aspect that was covered by this research in order to analyse the static stability of cargoes experiencing varying angles of heel under trimmed and untrimmed conditions. Using the results from preliminary monotonic triaxial testing, two variants of analysis, rotational and translational, were performed, an example of which can be seen in Figure 6. The results indicated that...
a single phenomenon, such as liquefaction, may not be the cause of all cargo shifts. Depending on the initial conditions of the cargo, the phenomena causing the cargo to shift may differ. It could be said that a cargo of iron ore fines has a sensitive dependence on the initial conditions within the cargo hold.

Figure 6 – Computational modelling using rotational analysis showing the minimum factor of safety at a 20-degree heel for an untrimmed cargo (Munro and Mohajerani, 2017f)

1.4.7 Test Development and Utilization

Utilizing the preliminary testing, the methods, apparatus, and procedures were chosen that would be used to analyse the behaviour of iron ore fines under cyclic loading. The foremost testing that was performed at this stage was cyclic triaxial and scale model testing.

After installing the new cyclic triaxial equipment, capable of performing the tests required, it was used to apply cyclic loading to samples of iron ore fines that simulated seagoing conditions. Monitoring changing variables during cyclic loading allowed analysis to be performed to determine if liquefaction was possible under the conditions expected within the hold of a bulk carrier. Not only did the cyclic triaxial tests provide relevant information regarding the liquefaction potential of iron ore fines but it also provided visualization of another phenomenon that may be the cause of cargoes shifting.

Due to the physical properties of iron ore fines and the loading expected during marine transportation, it was assumed during preliminary testing that it might not be possible to produce liquefaction within the material using the cyclic triaxial. It was therefore decided that a scale model apparatus would be used in conjunction with the cyclic triaxial to attempt to induce liquefaction and determine the variables associated with the phenomenon. The final design of the scale model designed, developed and utilized during this research can be seen in Figure 7.
The data collected from the cyclic triaxial and scale model tests allowed comparisons to be made in relation to the behaviour of cargoes during the incidents and confirm or otherwise the test method currently being used for the prevention of liquefaction of iron ore fines during marine transportation.

1.4.8 Validity of Phenomenon and Testing Methods

Following on from the previous aspect of this research, an attempt to validate the nature of the phenomenon that is occurring was made, along with an attempt to determine if the use of the current test methods currently in place to prevent a cargo shift could be justified.

As liquefaction is the suspected cause of cargoes shifting, it was deemed appropriate to attempt to validate the current test method both in terms of a single cause, such as liquefaction, or multiple causes masquerading as one. Based on a summary of all the results from this research, along with utilizing newly gained knowledge, conclusions were made regarding the types of phenomena that may be occurring and their relevance to the test methods currently in use.

1.4.9 Preventing Future Incidents

The final aspect of this research is that of prevention. Although there are guides other than the IMSBC Code currently available regarding the prevention of the liquefication of bulk cargoes (The London P&I Club et al., 2017), they do not cover some of the aspects of cargo shifts touched upon herein. It was,
therefore, necessary to identify what measures can be taken to prevent future incidents from occurring.

1.5 STRUCTURE OF THESIS

The structure of this thesis is that of one built upon twelve publications. Excluding information provided previously, which encompasses the summary, introduction, objectives, significance, and scope of the research, this thesis is built upon six significant areas. They are as follows:

- literature review (Chapter 2),
- experimental materials (Chapter 3),
- experimental methods (Chapter 4),
- peer-reviewed and unpublished publications (including supplementary results and summaries) (Chapter 5 to Chapter 16),
- summary discussion of experimental results (Chapter 17), and
- recommendations, conclusions, and future research (Chapter 18 to Chapter 19).

The literature review, presented in Chapter 2, comprises of the fundamental knowledge gained throughout the research. The review includes information on iron ore, marine transportation vessels, material handling techniques, phenomenon relating to cargo shifts, suspected liquefaction incidents, and the preventative policies and procedures currently in place.

Chapter 3 details the physical properties of the specimens of iron ore fines used for experimental testing during this research. The accompanying chapter, Chapter 4, on experimental methods specifies the major test methods designed, developed and utilized during this research. To reduce possible duplication of the literature in these chapters appropriate references have been made to publications included within this thesis where similar information was provided.

As previously mentioned, the majority of this thesis is provided via peer-reviewed publications. These publications provide information on individual aspects of this research detailed in 1.4. In these chapters, not only are the peer-reviewed publications provided, supplementary results along with what are referred to as summaries after the fact are also provided. These summaries discuss the methods used and conclusions made in the publications considering the direction of research, what was known at the time of publication and what changed since the time of publication.

Alongside the peer-reviewed publications are results that have yet to be published. These results are extremely significant in respect of the findings given in this thesis. As these manuscripts are either under review or in press at the time this thesis was submitted, their presentations, are similar to the peer-reviewed publications. These manuscripts also include respective supplementary results and summaries after the fact.

Since each publication and manuscript focusses on an individual aspect of this research, it was necessary to include a section that summarizes all the test results and analyses. The summary discussion of experimental results, given in Chapter 17, provides the reader with a detailed analysis and comparison of the results obtained throughout this research. The majority of this chapter examines results related to a single specimen of iron ore fines that was tested using multiple methods.
Chapter 1 - Introduction

This examination was performed to determine if an association or connection between the varying test methods could be made.

The final section of this thesis includes conclusions based on the knowledge gained throughout the duration of this research. This section also includes recommendations concerning the safe transportation of iron ore fines and future research that can be undertaken relating to the topic presented herein.

For a list of the contents of this thesis, including respective page numbers, please refer to the table of contents on page v.
CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

The following literature review covers the fundamental topics needed to recognize and appreciate the cause and effect of the problem investigated during this research. Although specific literature reviews are given in the peer-reviewed manuscripts provided later, this chapter delivers a structure so that readers can easily navigate the information provided within the manuscripts. This chapter also provides additional information not included in the manuscripts.

Some aspects of this literature review are covered in detail in publications included within this thesis. Therefore, duplication of information is somewhat unavoidable. To reduce the duplication of information, where it was deemed necessary, references have been made to the sections within those publications where the relevant information is provided.

If information was spread amongst many publications regarding a single topic, it might have been considered appropriate to collect that information and combine it in this chapter with additional information. If this is the case, reference will be made to the manuscript in which the information was sourced.

2.2 IRON ORE

In 2015, it was estimated that over 3.3 billion tons of iron ore was produced worldwide with 190 billion tons of crude ore in reserves (United States Geological Survey). Since 98% of iron ore produced is used to make steel, it is said to be more important to the global economy than any other product, except possibly oil (Blas, 2009; Munro and Mohajerani, 2015). Figure 8 shows the estimated iron ore production of the top producing countries in 2015 (United States Geological Survey).

Figure 8 – Estimated iron ore production of the top producing countries in 2015 (United States Geological Survey)
This figure shows the top three producers of iron ore – China, Australia, and Brazil – with 42%, 25% and 13% production worldwide, respectively. Since 2002, China, Germany, Japan and the Republic of Korea have led the global import of iron ore, accounting for more than two-thirds of the total, with China’s share increasing from 21% in 2002 to 68% in 2014 (Tuck, 2017). In 2014, with China leading the global imports of iron ore, Australia led the global exports of iron ore with 53% of the share followed by Brazil, South Africa, and the Ukraine, with 24%, 4.7% and 2.8%, respectively (United Nations Commodity Trade Statistics Database, Undated).

Our current way of life relies heavily on iron ore and the ability for it to be able to be transported from one location to another. Since the extraction and refinement of iron ore commonly take place in different locations, the safe transportation of the material is imperative.

2.2.1 Iron Ore Fines
After its extraction, iron ore is mechanically divided to produce three predominant qualities – lump (6.3 - 30 mm, Figure 9), fines (< 6.3 mm, Figure 10) and pellets (9.5 - 16 mm, Figure 11) ("Fact Sheet: Iron Ore," 2012; Munro and Mohajerani, 2015). In Australia, approximately three times more iron ore fines are produced than iron ore lump (England, 2008; "Outlook fine after Cloud Break Mining Trial," 2006). Iron ore pellets are agglomerated fines, indurated using a furnace (Metso, Undated).
The production and availability of iron ore lump is limited in comparison to iron ore fines due to the particle size and iron content (Fe) required for this classification. Fines, on the other hand, is more abundant simply due to its increased natural occurrence and generation from processes, including extraction and sizing (Jaguar Steel & Coal Pte. Ltd., 2017). Although iron ore fines are commonly
considered to be an inferior product to iron ore lump due to the lower iron content, it is traded heavily due to the availability.

Considering that up to 90% of the iron ore produced in Australia is exported (Department of Industry Innovation and Science, Undated), this amounts to approximately 185 million tons of iron ore fines being exported annually from the largest exporter, Australia. To put this amount of cargo into perspective, this amounts to approximately 925 voyages annually of the larger Capesize subclass of bulk carrier from Australia alone (United Nations Conference on Trade and Development (UNCTAD), 2014). More details are provided about the vessels used to transport iron ore in section 2.3 of this chapter.

For more details on iron ore fines including additional history, transportation and production statistics, please refer to Chapter 6 section 6.3.3 of the related manuscript, which was produced for this study. Additionally, please refer to Chapter 5 section 5.3.5 and Appendix B where the typical physical properties of iron ore fines determined during this research are provided.

### 2.3 TRANSPORTATION VESSELS

Iron ore fines, as well as the majority of other solid bulk cargoes, are transported in bulk carriers. Unlike a tanker, where the cargo holds’ surface areas are minimized, bulk carriers store their cargo in large holds accessed by individual hatch covers. These holds are separated along the length and extend the full width of the vessel. This design is intended to transport solid granular materials (Munro and Mohajerani, 2015).

Five main subclasses of bulk carrier are identified and referenced during this research. Over this period, there have been minor changes in respect of the Dead Weight Tonnage (DWT) of each subclass of bulk carrier (United Nations Conference on Trade and Development (UNCTAD), 2011, 2014, 2016). Table 4 shows the approximate bulk carrier subclass terminology and sizes, in DWT, as of 2016 (United Nations Conference on Trade and Development (UNCTAD), 2016). Figure 16 shows a typical profile and plan view of a bulk carrier.

**Table 4 – Approximate bulk carrier subclass terminology and sizes** (United Nations Conference on Trade and Development (UNCTAD), 2016)

<table>
<thead>
<tr>
<th>Bulk Carrier Subclass</th>
<th>DWT b&lt;sup&gt;a&lt;/sup&gt; (tons)</th>
<th>Typical Number of Cargo Holds</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Bulker</td>
<td>&lt; 9,999</td>
<td>&lt; 5</td>
<td>Figure 12</td>
</tr>
<tr>
<td>Handysize</td>
<td>10,000 – 39,999</td>
<td>5</td>
<td>Figure 13</td>
</tr>
<tr>
<td>Handymax</td>
<td>40,000 – 64,999</td>
<td>5</td>
<td>Similar to Figure 13</td>
</tr>
<tr>
<td>Panamax</td>
<td>65,000 – 99,999</td>
<td>7</td>
<td>Figure 14</td>
</tr>
<tr>
<td>Capesize</td>
<td>&gt; 100,000</td>
<td>9</td>
<td>Figure 15</td>
</tr>
</tbody>
</table>

a DWT, Dead Weight Tonnage is a measure of how much mass a vessel can safely carry. It does not include the weight of the vessel, but includes things such as the cargo, crew, passengers, ballast, and fuel.

b The DWT for each subclass is based on UNCTAD’s Review of Maritime Transport (2016) (United Nations Conference on Trade and Development (UNCTAD), 2016).
Figure 12 – General bulker (ship.gr, Undated)

Figure 13 – Handysize subclass of bulk carrier (similar to Handymax subclass) (ship.gr, 2013b)

Figure 14 – Panamax subclass of bulk carrier (Imabari Shipbuilding Co. Ltd., 2016)
The terms given to bulk carriers of larger subclasses are typical names of the areas they travel. The Capesize subclass of bulk carriers are too large to traverse either the Suez Canal or Panama Canal, and, therefore, have to pass around either Cape Agulhaz, South Africa, or Cape Horn, South America. The Panamax subclass of bulk carrier, on the other hand, can traverse the Panama Canal and Suezmax; a subclass of the Panamax bulk carrier, can traverse the Suez Canal (Maritime Connector, Undated). This means that the time taken to travel from location to location can vary significantly.

A typical voyage from Australia to China can take a bulk carrier around 17 days and can take as much as 40 days from Brazil to China (Iron Ore Technical Working Group, 2013b; Munro and Mohajerani, 2016d).
2.4 LOADING AND UNLOADING TECHNIQUES

Bulk carriers of different subclasses have varying techniques to load and unload solid bulk cargoes. The smaller Handysize and Handymax subclass of bulk carriers commonly have gear on board to load and unload the cargo. These types of bulk carrier are known as Geared Bulk Carriers (Bright Hub Engineering, 2009), as shown in Figure 16. The advantage of geared bulk carriers is that they do not rely on shore-based equipment, and, due to their size, have flexibility in the routes they can travel. They are often used at smaller ports to load cargoes from barges when the depth of the vessel prohibits it from nearing shore. An example of this can be seen in Figure 27.

The larger subclass of bulk carriers, such as Panamax and Capesize, commonly use on shore equipment to load and unload cargo, such as derricks, grab cranes and conveyors; similar to that used on board geared bulk carriers. The technique used to load vessels will inevitably influence the conditions of the cargo in the hold before transportation.

Some additional details regarding loading techniques can be seen in Chapter 11. The manuscript presented in this chapter reviews and discusses the reports investigating suspected liquefaction incidents. Furthermore, information regarding the trimming of cargoes can be seen in section 2.8.4.

2.5 BULK CARRIER STABILITY

The basic understanding of the stability of bulk carriers is required to understand the result of a cargo shift in the hold of a bulk carrier. Regardless of the cause of the cargo shifting, for a bulk carrier to list or capsize, the mass of the cargo that has shifted must result in an overturning moment, $M_O$, which exceeds the restoring moment, $M_R$. These moments, which are off-centred forces, are caused by both buoyancy, which is an upward force applied by the sea that opposes the weight of the vessel, and gravity, which is the downwards force of the vessel on the sea itself. The conditions that are
considered to be unstable are shown in Figure 18 (right) in which the centre of buoyancy of the hull, B, stays inwards of the centre of gravity of the vessel, G (Munro and Mohajerani, 2017b, 2017f).

The location of the metacentre is critical to the stability of the vessel. The metacentre is considered to be the intersection between two theoretical lines, both drawn through the centres of buoyancy; one when the vessel is vertical and one when the vessel is tilted. When the resulting metacentre, M, is below the centre of gravity, as seen in Figure 18 (right), the overturning moment, $M_O$, exceeds the restoring moment, $M_R$, causing instability. Under these conditions, the bulk carrier develops a list and may capsize if preventative measures are not taken. Listing vessels can often be righted by using ballast, but due to the weight of iron ore fines it sometimes requires more ballast than what is available, and further shifting of the cargo may cause the vessel to capsize. (Munro and Mohajerani, 2017b, 2017f).

![Figure 18 – Illustrations depicting a stable (left and middle) and unstable (right) vessel (Munro and Mohajerani, 2017b, 2017f)](image)

Where: $B =$ Centre of buoyancy of hull; $F_b =$ Buoyancy force; $G =$ Centre of gravity of vessel; $M =$ Metacentre; $M_O =$ Overturning moment; $M_R =$ Restoring moment; $W =$ Vessel weight; $\alpha =$ Angle of heel.

2.6 CARGO SHIFT PHENOMENON

The phenomena listed in this section have been identified as possible causes of cargo shifts on board bulk carriers. During this research, all the phenomena listed are analysed and discussed in detail.

2.6.1 Liquefaction

Since liquefaction is the suspected cause of the cargo shifts identified during this research, this phenomenon was primarily investigated. Hence, there are many sections related to this phenomenon within the supplied manuscripts.

For information on the liquefaction of saturated and unsaturated soils, reference is made to Chapter 14 section 14.3.2.2. For further information on liquefaction of saturated soils according to the critical state framework, reference is made to Chapter 15 section 15.3.4.1. Summaries of liquefaction can also be found in Chapter 5 section 5.3.3, Chapter 9 section 9.3.4.1, Chapter 10 section 10.3.2.1, and Chapter 16 section 16.3.3.2.1.
2.6.2 Cyclic Mobility, Incremental Collapse, and Shakedown

Similar to liquefaction, cyclic mobility, incremental collapse and shakedown can occur under cyclic loading. These phenomena are similar to liquefaction and sometimes referred to as such. The differences between these phenomena are discussed in Chapter 15 section 15.3.4.1. Other mentions of cyclic mobility, incremental collapse, and shakedown are made in Chapter 10 section 10.3.4.2, and Chapter 12 section 12.3.5.

2.6.3 Shearing (Slope Stability Analysis)

During this research, two types of slope stability analysis were performed, herein referred to as rotational and translational slope failure. These failures can occur when a slip plane develops due to the internal resisting shear strength of the cargo being exceeded by the resultant stresses being applied (i.e. equilibrium being overcome) (Budhu, 2011; Das, 2013; Munro and Mohajerani, 2017f). Illustrations depicting the two phenomena can be seen in Figure 19. The two phenomena are discussed in detail in Chapter 13 section 13.3.3.2.1.

Although not analysed during this research, another similar failure mode is one where the cargo slides en-masse. This phenomenon occurs when the shear strength and friction along the stratum between the cargo and the hold is overcome by external forces and the entire cargo mass shifts as a single entity in the hold; thus en-masse (Munro and Mohajerani, 2017f). An illustration of the phenomenon can be seen in Figure 20. A previous investigation has considered a cargo of iron ore concentrate sliding en-masse (A. Kruszewski, 1988).
2.7 SUSPECTED LIQUEFACTION INCIDENTS

As a result of a cargo shifting, there have been numerous incidents where bulk carriers have listed or foundered. Two manuscripts presented in this thesis focus on incidents where liquefaction was the suspected cause of the cargo shifting. Reference is made to Chapter 10 section 10.3.3 for a review of all suspected liquefaction incidents involving iron ore, bauxite, fluorspar and nickel ore. In the same chapter, sections 10.3.6 and 10.3.7 are the manuscripts appendices, which include a table of all the incidents reviewed and charts depicting the vessels origin, route and location of the incident.

The second manuscript presented in this thesis, relating to the review of cargo shift incidents, is given in Chapter 11. This chapter provides a review of seven case studies where the incident reports were available for review. One incident that was reviewed involved the bulk carrier Trans Summer, which can be seen in Figure 21. Chapter 10 section 10.3.5, and Chapter 11 section 11.3.5 provide discussions, recommendations, and conclusions relating to these incidents.
It is noted that, recently, there has been another incident involving the bulk carrier Stellar Daisy, where speculation concerning liquefaction of the cargo abounds. On 31 March 2017, the 266,000 DWT vessel foundered off the coast of Uruguay en-route from Brazil to China. Although the cause of the foundering is currently unknown, similarities to other suspected liquefaction incidents have fuelled speculation of liquefaction (Chinoy, 2017; O’Neill, 2017; Parrish, 2017; Shipwreck Log, 2017; The Maritime Executive, 2017; 2016b; Traffic, 2017).

2.8 INTERNATIONAL MARITIME SOLID BULK CARGOES CODE (IMSBC CODE)

The International Maritime Solid Bulk Cargoes Code (IMSBC Code), which is published and frequently revised by the International Maritime Organization (IMO), is an internationally accepted code of safe practice, the implementation of which is mandatory when transporting solid bulk cargoes at sea (International Maritime Organization, 2013b; Munro and Mohajerani, 2015, 2016c). In 2011, the IMSBC Code, formally the Code of Safe Practice for Solid Bulk Cargoes (BC Code), was made mandatory under the SOLAS Convention (International Maritime Organization, 1998; International Maritime Organization MSC85/26/Add.2, 2008; Munro and Mohajerani, 2016a).

Within the IMSBC Code are schedules and procedures specific to certain hazardous solid bulk cargoes that are to be followed. Each schedule includes information, such as the characteristics of the material, hazards it poses, precautions that must be taken, and other requirements specific to the cargo. Also included in the schedule is the group classification of the cargo (International Maritime Organization, 2016). There are three groups into which a cargo can be classified:
1. Group A - cargoes that may possibly liquefy,
2. Group B - cargoes that may pose a chemical hazard, and
3. Group C - cargoes that are deemed neither able to liquefy nor pose a chemical hazard.

Included in Appendix 2 of the IMSBC Code are test methods that are to be followed when a cargo is classified as ‘Group A’ or liquefiable (International Maritime Organization, 2013b). At the time of the mandatory implementation of the IMSBC Code, there was no individual schedule listed in the IMSBC Code for iron ore fines and no test method used to prevent liquefaction of iron ore fines. All that existed was an all-encompassing schedule for iron ore, where the classification was Group C or deemed neither able to liquefy nor pose a chemical hazard (International Maritime Organization, 2012b).

At that time, iron ore fines was a cargo that had been suspected of undergoing liquefaction during transportation on bulk carriers that resulted in the listing or foundering of the transporting vessel (Munro and Mohajerani, 2017b). In October 2011, a circular was released by the IMO (DSC.1-Circ.66) where it stated:

“iron ore fines may liquefy and should be treated as such, in particular the Master should refer to section 7 of the IMSBC Code, which warns about cargoes that may liquefy” (International Maritime Organization, 2011).

Not until November 2013, was iron ore fines given an individual schedule in amendment DSC.1-Circ.71, which superseded circular DSC.1-Circ.66. From November 2013, circular DSC.1-Circ.71 could be implemented on a voluntary basis (International Maritime Organization, 2013a; Munro and Mohajerani, 2016c). The individual schedule for iron ore fines was adopted as part of amendment 03-15 to the 2015 edition of the IMSBC Code and entered into force 1 January 2017 (International Maritime Organization, 2013a; Munro and Mohajerani, 2016c). The considerations for amendment 03-15 were released in January 2015 as MSC 95/3/Add.1 (International Maritime Organization, 2015d; Munro and Mohajerani, 2016c).

Additional information, regarding the IMSBC Code, is included in many of the manuscripts presented in this thesis. Reference is made to the timeline presented in Chapter 7 section 7.3.8 for a visual portrayal of the information provided in this section.

2.8.1 Iron Ore Technical Working Group (TWG)

The Iron Ore Technical Working Group (TWG) was established by the International Maritime Organization (IMO) in late 2012 to “conduct research and coordinate recommendations and conclusions about the transportation of IOF” (Iron Ore Technical Working Group, 2013c; Munro and Mohajerani, 2014, 2016b). The TWG was assembled by the International Maritime Organization not only to develop an individual schedule for iron ore fines but “consider the adequacy of current methods for determining transportable moisture limit for iron ore fines and consider new and/or amended existing methods to be included in appendix 2 of the IMSBC Code” (Iron Ore Technical Working Group, 2013e; Munro and Mohajerani, 2016c).

The Modified Proctor/Fagerberg Test (MPFT) and individual schedule for iron ore fines was developed by the TWG over a two-year period from May 2012 (AMIRA International, 2012). The TWG was managed by AMIRA International and consisted of eight sponsors and five research providers. The
Chapter 2 - Literature Review

sponsors consisted of major industries involved in the export and transportation of iron ore fines including BHP Billiton, Cliffs Asia Pacific Iron Ore, the Chamber of Minerals and Energy Western Australia, Fortescue Metals Group, the Minerals Council of Australia, Rio Tinto, Roy Hill and Vale Australia. The five research providers from Australia and New Zealand consisted of Auckland UniServices, Creative Process Innovation, the CSIRO, and the universities of Auckland and Newcastle (AMIRA International, 2012; Munro and Mohajerani, 2016c).

The early implementation of the TWG’s research was introduced in 2013, by the IMO in the circular DSC.1/Circ.71 (International Maritime Organization, 2013a) and considerations for the implementation in the IMBSC Code in 2015 were presented in amendment 03-15 MSC 95/3/Add.1 (International Maritime Organization, 2015d; Munro and Mohajerani, 2016c). The reports produced by the TWG are currently publicly available (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e).

Additional information regarding the TWG is included in many of the manuscripts presented in this thesis. Reference is made to the timeline presented in Chapter 7 section 7.3.8 for a visual portrayal of the information provided in this section. Additionally, some of the aspects of the research performed by the TWG are described in section 2.8.3 relating to the MPFT.

2.8.2 Original TML Test Methods

The information provided in this section is related to the original Transportable Moisture Limit (TML) test methods given in Appendix 2 of the 2013 Edition of the International Maritime Solid Bulk Cargoes Code (IMSBC Code). At this time, the IMSBC Code did not include the Modified Proctor/Fagerberg Test (MPFT), which is described in detail in section 2.8.3.

Up until the implementation of the MPFT in 2015, there were only three test methods given in the IMSBC Code to determine the TML of coal and mineral concentrates (International Maritime Organization, 2013b). The tests referred to herein are the:

1. Flow Table Test (FTT),
2. Penetration Test (PT), and
3. Proctor/Fagerberg Test (PFT).

The TML, which is determined using these test methods, is inferred by the IMSBC Code as the maximum allowable moisture content that a cargo may contain while being loaded onto a bulk carrier for marine transportation without it being at risk of liquefying (International Maritime Organization, 2016).

Knowledge of the specifics of these three test methods is uncommon amongst researchers, especially in the geotechnical engineering and soil mechanics fields. Therefore, most the manuscripts referencing them were required to include a description for context. Due to this, most manuscripts included in this thesis include a description of the test methods.

Table 5 provides references to specific chapters and sections within the included manuscripts where certain information is provided regarding the test methods. Information can also be found in additional sections of the manuscripts presented in this thesis that have not been listed in this section. The most relevant chapter of this thesis when referring to the original TML test methods is Chapter 5.
Table 5 – References to information regarding the original TML test methods given in Appendix 2 of the 2013 Edition of the IMSBC Code

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Section</th>
<th>Method</th>
<th>Information Provided</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 5</td>
<td>5.3.4.1</td>
<td>Proctor/Fagerberg Test</td>
<td>- Background</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>- Procedure</td>
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<td>- Estimated Test Time</td>
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<td>- Reliability</td>
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<td>- Material Applications</td>
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<td></td>
<td></td>
<td>- Particle Density</td>
</tr>
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<td></td>
<td>- Requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Development</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>5.3.4.2</td>
<td>Flow Table Test</td>
<td>- Background</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Procedure</td>
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<td>- Reliability</td>
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<td>- Material Applications</td>
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<td></td>
<td></td>
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<td>- Sample Compaction</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>5.3.4.3</td>
<td>Penetration Test</td>
<td>- Background</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Procedure</td>
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</tr>
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<td></td>
<td></td>
<td></td>
<td>- Sample Compaction</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>5.3.6</td>
<td>Proctor/Fagerberg and Flow Table Tests</td>
<td>- Comparison Testing</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>5.3.7</td>
<td>All Methods</td>
<td>- Supporting Results</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>5.3.8</td>
<td>All Methods</td>
<td>- Discussion and Recommendations</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>5.3.9</td>
<td>All Methods</td>
<td>- Conclusion</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>5.3.10</td>
<td>All Methods</td>
<td>- Terminology</td>
</tr>
<tr>
<td>Chapter 5</td>
<td>5.3.11</td>
<td>All Methods</td>
<td>- Calculations</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.3.1</td>
<td>Proctor/Fagerberg Test</td>
<td>- Summary</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.3.2</td>
<td>Flow Table Test</td>
<td>- Summary</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.3.3</td>
<td>Penetration Test</td>
<td>- Summary</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.4.1</td>
<td>All Methods</td>
<td>- Supporting Results</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.6</td>
<td>All Methods</td>
<td>- Conclusion</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.8</td>
<td>All Methods</td>
<td>- Timeline</td>
</tr>
<tr>
<td>Chapter 9</td>
<td>9.3.2.2.1</td>
<td>Proctor/Fagerberg Test</td>
<td>- Summary</td>
</tr>
<tr>
<td>Chapter 9</td>
<td>9.3.2.2.2</td>
<td>Flow Table Test</td>
<td>- Summary</td>
</tr>
<tr>
<td>Chapter 9</td>
<td>9.3.2.2.3</td>
<td>Penetration Test</td>
<td>- Summary</td>
</tr>
<tr>
<td>Chapter 9</td>
<td>9.3.2.2.5</td>
<td>All Methods</td>
<td>- Table Summarizing Test Methods</td>
</tr>
<tr>
<td>Appendix B</td>
<td></td>
<td>All Methods</td>
<td>- TML Comparisons to Ore Concentrates</td>
</tr>
<tr>
<td>Appendix C</td>
<td></td>
<td>Proctor/Fagerberg Test</td>
<td>- Test Method Issues</td>
</tr>
</tbody>
</table>

2.8.3 Modified Proctor/Fagerberg Test (MPFT) and Schedule for Iron Ore Fines

The information provided in this section is related to the newly developed Modified Proctor/Fagerberg Test (MPFT), now given in Appendix 2 of the 2016 Edition of the International Maritime Solid Bulk Cargoes Code (IMSBC Code), which is specifically designed for use with iron ore fines (International Maritime Organization, 2016).

Similar to the methods described in section 2.8.2, knowledge of the specifics of the MPFT is uncommon amongst researchers, especially in the geotechnical engineering and soil mechanics fields. Therefore, all the manuscripts referencing the method were also required to include a description for context.

Table 6 provides references to specific chapters and sections within the included manuscripts where certain information is provided regarding the MPFT. Information can also be found in additional
sections of the manuscripts presented in this thesis that have not been listed in this section. The most relevant chapter of this thesis when referring to the MPFT is Chapter 6 and Chapter 7.

Table 6 – References to information regarding the MPFT given in Appendix 2 of the 2016 Edition of the IMSBC Code

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Section</th>
<th>Information Provided</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 5</td>
<td>5.3.10</td>
<td>- Terminology (Same as the Standard Proctor/Fagerberg Test)</td>
</tr>
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<td>Chapter 5</td>
<td>5.3.11</td>
<td>- Calculations (Same as the Standard Proctor/Fagerberg Test)</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>6.3.4.1</td>
<td>- History</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>6.3.4.2</td>
<td>- Modifications from the Standard Proctor/Fagerberg Test</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>6.3.4.3</td>
<td>- Verification</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>6.3.4.3.1</td>
<td>- Hexapod Testing for Verification</td>
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<td>Chapter 6</td>
<td>6.3.4.3.2</td>
<td>- Numerical Modelling for Verification</td>
</tr>
<tr>
<td>Chapter 6</td>
<td>6.3.5</td>
<td>- Discussion</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.4.2</td>
<td>- Summary</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.4.3</td>
<td>- Particle Size Provisions</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.4.4</td>
<td>- Goethite Content Provisions</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.4.5</td>
<td>- Hexapod Testing</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.5.3</td>
<td>- Comparison Testing to the Standard Proctor/Fagerberg Test</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.6</td>
<td>- Conclusion</td>
</tr>
<tr>
<td>Chapter 7</td>
<td>7.3.8</td>
<td>- Timeline</td>
</tr>
<tr>
<td>Chapter 9</td>
<td>9.3.2.2.4</td>
<td>- Summary</td>
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<td>Chapter 9</td>
<td>9.3.2.2.5</td>
<td>- Table Summarizing Test Methods</td>
</tr>
<tr>
<td>Chapter 14</td>
<td>14.3.2.1</td>
<td>- Summary</td>
</tr>
<tr>
<td>Appendix C</td>
<td></td>
<td>- Test Method Issues (Same as the Standard Proctor/Fagerberg Test)</td>
</tr>
</tbody>
</table>

2.8.4 Trimming

Bulk carriers transporting specific types of solid bulk cargoes are required to perform trimming according to Sections 5 and 6 of the 2013 IMSBC Code to prevent slope failure from occurring, as described in section 2.6.3 of this chapter. The cargoes that require trimming are cohesionless cargoes that are listed in Appendix 3 of the IMSBC Code. Trimming ultimately “reduces the likelihood of the cargo shifting” (International Maritime Organization, 2016; Munro and Mohajerani, 2017a, 2017f). Figure 22 shows depictions of hypothetical trimmed and untrimmed cargoes with and without an angle of heel (Munro and Mohajerani, 2017f).

Figure 22 – Depictions of hypothetical trimmed (left) and untrimmed (right) cargos with and without an angle of heel (Munro and Mohajerani, 2017f)
Trimming is commonly achieved by using crane grabs to level and press the surface of the cargo in the holds. According to Section 5 of the 2016 IMSBC Code as well as the individual schedule for iron ore fines, the Master has the right to request that a cargo of iron ore fines undergo trimming, but trimming is not mandatory as iron ore fines is considered to be a cohesive cargo (International Maritime Organization, 2016; Munro and Mohajerani, 2017a, 2017f).

During this research, computational analysis was performed on trimmed and untrimmed cargoes in relation to slope stability. The outcome of this analysis is provided in Chapter 13.

2.9 ADDITIONAL SUSCEPTIBLE SOLID BULK CARGOES

The focus of this research presented in this thesis is on iron ore fines. Iron ore fines are not the only solid bulk cargo that has been suspected of undergoing liquefaction during marine transportation. Appendix 4 of the IMSBC Code lists all solid bulk cargoes along with their group classification (International Maritime Organization, 2016; TML Testing Wiki, 2017). As of 2016, 75 solid bulk cargoes are listed as Group A or liquefiable (International Maritime Organization, 2016). Identified from the list of solid bulk cargoes are the following three:

1. bauxite,
2. fluorspar, and
3. nickel ore.

These solid bulk cargoes have been identified, as they have also been reported as being suspected of undergoing liquefaction during marine transportation and causing the bulk carrier to list or founder. The details of these incidents and material group classifications, as of 2016, can be seen in Table 7 and Figure 23. Reference is made to the manuscript presented in Chapter 10 and Chapter 11 where these incidents are discussed in detail. Although these cargoes have been linked to incidents during marine transportation, not all were identified as liquefiable or sufficiently researched at the time this research commenced.

Table 7 – Incidents and resulting casualties for individual solid bulk cargo, 1988-2016, including group classification as of 2016 (Munro and Mohajerani, 2017b)

<table>
<thead>
<tr>
<th>Solid Bulk Cargo</th>
<th>Classification as of 2016</th>
<th>Incidents</th>
<th>Casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>#</td>
<td>%</td>
</tr>
<tr>
<td>Bauxite</td>
<td>Group C</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Fluorspar</td>
<td>Group A and B</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Iron Ore (Fines)</td>
<td>Group C (Lump)</td>
<td>7</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>Group A (Fines)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel Ore</td>
<td>Group A</td>
<td>13</td>
<td>57</td>
</tr>
<tr>
<td>Undetermined Ore</td>
<td>N/A</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

*Cargoes classified ‘Group A’ in the IMSBC Code are considered to be potentially liquefiable and must undergo TML testing (International Maritime Organization, 2013b, 2015d)*
Bauxite, as seen in Figure 24, is the world’s main source of aluminium. It is extracted from open pit mines, converted to alumina then processed further to create aluminium. Alongside iron ore, it is considered integral to the global economy. Research into Bauxite by industries, in Australia and Brazil, began in 2013. It was concluded that there was a possibility of a cargo of Bauxite being able to liquefy if the properties were not that described in the individual schedule for bauxite, specifically the moisture content and particle size (International Maritime Organization, 2015a, 2015c, 2016).

In 2016, a correspondence group was set-up to produce a preliminary draft amendment for Bauxite as a Group A or liquefiable material (Lloyd’s Register, 2016). To date, there has not been sufficient research into the applicability of the current test methods given in Appendix 2 of the IMSBC Code in relation to the testing of Bauxite. It is noted that the original methods, given in the 2013 Edition of the IMSBC Code, were considered unsuitable for the testing of solid bulk cargoes unlike mineral...
concentrates. These included iron ore fines, coal and certain nickel ores (International Maritime Organization, 2013a; Lloyd's Register, 2016).

Nickel ore, as a solid bulk cargo, was given the infamous title of “the world’s most dangerous cargo” after three successive incidents occurred in 2010 while the material was being transported at sea (Munro and Mohajerani, 2017b; Wilson, 2017). Since then, the cargo has been at the forefront of investigations to determine its potential to liquefy and the application of the current test methods given in the IMSBC Code (Britannia - The Britannia Steam Ship Insurance Association Limited, 2015; Chan, 2015; “ClassNK’s Initiatives for the Safe Carriage of Nickel Ore,” 2012; Jian-Ping, 2011; Wilson, 2017; Zou et al., 2013).

Incidents involving vessels transporting nickel ore have significantly increased over the past decade (Munro and Mohajerani, 2017b). This increase in incidents has been attributed to the increase in exports from countries, such as Indonesia, New Caledonia, and the Philippines. Figure 25 shows the combined nickel ore production of Indonesia, New Caledonia and the Philippines alongside the suspected liquefaction incidents involving nickel ore (Munro and Mohajerani, 2017b; United States Geological Survey).

Figure 25 – Combined nickel ore production from Indonesia, New Caledonia and the Philippines alongside suspected liquefaction incidents involving bulk carriers transporting nickel ore (Munro and Mohajerani, 2017b; United States Geological Survey)

These countries have an increased incident rate as many mines where ores are extracted are very basic and situated in remote locations. This makes it hard for surveyors and experts to attend them (Munro and Mohajerani, 2016a). Additionally, there is a significantly increased ability for the moisture within the humid climate of these areas to be taken in by the cargo during extraction, transport, storage, and loading. To date, there have been many warnings regarding the perils of transporting
nickel ore on bulk carriers, which has contributed to the reduction in incidents (Britannia - The Britannia Steam Ship Insurance Association Limited, 2015; Chan, 2015; Jian-Ping, 2011; The American Club, 2010; Wilson, 2017).

Fluorspar, also called fluorite, is directly or indirectly used in the making of products, such as aluminium, gasoline, and steel (United States Geological Survey) and was involved in an incident back in 2005 (Munro and Mohajerani, 2016a, 2017b). Fluorspar was, and still is, classified as a Group A or liquefiable solid bulk cargo from at least the 2008 Edition of the IMSBC Code (International Maritime Organization, 2013b). Unlike bauxite and nickel ore, the typical physical properties of fluorspar are closer to those of mineral concentrates than ores (International Maritime Organization, 2016).

Table 8 and Figure 26 show the worldwide production of bauxite, fluorspar and nickel ore in relation to the worldwide production of iron ore for the year 2015 (United States Geological Survey, Undated-d). These cargoes combined make up only approximately 11% of the total worldwide production when including iron ore. This significant difference in production and recent incidents is why this research focusses on iron ore fines rather than bauxite, fluorspar or nickel ore.

Table 8 – Worldwide production of bauxite, fluorspar and nickel ore in relation to the worldwide production of iron ore in 2015 (United States Geological Survey, Undated-d)

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Major Producers</th>
<th>2015 Worldwide Production</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Ore</td>
<td>Australia, Brazil, China, India, and Russia.</td>
<td>2,280,000,000</td>
<td>88.31</td>
</tr>
<tr>
<td>Bauxite</td>
<td>Australia, China, Malaysia, Brazil, and India.</td>
<td>293,000,000</td>
<td>11.35</td>
</tr>
<tr>
<td>Fluorspar</td>
<td>China, Mexico, Mongolia, Vietnam, and South Africa.</td>
<td>6,670,000</td>
<td>0.26</td>
</tr>
<tr>
<td>Nickel Ore</td>
<td>Philippines, Russia, Canada, Australia, and New Caledonia.</td>
<td>2,280,000</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Figure 26 – Worldwide production of bauxite, fluorspar and nickel ore in relation to the worldwide production of iron ore in 2015 (United States Geological Survey, Undated-d)
CHAPTER 3 EXPERIMENTAL MATERIALS

3.1 INTRODUCTION

It is noted that a request was made that the specific origin of the samples tested during this research was not made public. Furthermore, the numerous samples initially tested and used to determine the typical properties of iron ore fines are not provided in this chapter. For details on the range of physical properties for the samples of iron ore fines initially tested, please refer to Chapter 5 Section 5.3.5.

In this chapter, a description is given of the three samples of iron ore fines that the majority of testing was performed upon during this research. The samples obtained for this research were from Australia’s Pilbara region located in central-western Western Australia seen inset in Appendix A. All samples obtained were from cargoes that were transported by sea in the holds of bulk carriers. The Pilbara region contributes significantly to Western Australia’s Economic Demonstrated Resources (EDR) of iron ore in 2015, as seen in Figure 27 (Geoscience Australia, 2016).

Figure 27 – Australia’s Economic Demonstrated Resources (EDR) of iron ore in 2015 (Geoscience Australia, 2016)

In the same year, Australia’s EDR was the world’s largest at 28%, followed by Russia at 14%, then Brazil and China at 13%. Considering Australia’s demonstrated iron ore resources along with the countries high export quantities to places, such as China, Japan, and the Republic of Korea, described in Chapter 2 Section 2.2, it was determined that this cargo is one that could be considered typical at the time of procurement and most likely will be a typical cargo undergoing marine transportation well into the future.
3.2 PROPERTIES OF RESEARCH MATERIALS

Sample MA002 was tested alongside MA003 during the early stages of this research to both determine the potential issues that may arise when performing the chosen tests that would be utilized during this research and determine if the results produced would assist in achieving the overall objective set out in 1.2. Sample MA004 was used during the latter part of this research. Due to the amount of material able to be obtained, sample MA004 was utilized for the major tests, including cyclic triaxial and scale model in order for a comparison to be made between methods. Table 9 shows the physical properties of the three samples of iron ore fines utilized during this study alongside images of the materials given in Figure 28 to Figure 30. It is noted that the samples of iron ore fines vary in colour due to the strata they were extracted, hence variable mineral compositions.

![Sample MA002](image1.png)  ![Sample MA003](image2.png)  ![Sample MA004](image3.png)

**Figure 28 – Sample MA002**  **Figure 29 – Sample MA003**  **Figure 30 – Sample MA004**

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard/ Apparatus</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen Identification</td>
<td>N/A</td>
<td>MA002</td>
</tr>
<tr>
<td>* Flow Table TML (35kg.f)</td>
<td>2016 IMSBC Code (International Maritime Organization, 2016)</td>
<td>10.2% GWC or 11.4% NWC</td>
</tr>
<tr>
<td>* Proctor/Fagerberg TML</td>
<td>2016 IMSBC Code (International Maritime Organization, 2016)</td>
<td>11.1% GWC or 12.5% NWC</td>
</tr>
<tr>
<td></td>
<td>MA003</td>
<td>10.3% GWC or 11.5% NWC</td>
</tr>
<tr>
<td></td>
<td>MA004</td>
<td>9.6% GWC or 10.6% NWC</td>
</tr>
</tbody>
</table>

* See Figure 31
* See Figure 32
* See Figure 33

Michael Colin Munro – July 2017
### Experimental Materials

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Method/Standard/Code</th>
<th>Value (Note(s))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modified Proctor/Fagerberg</strong> TML</td>
<td>2016 IMSBC Code (International Maritime Organization, 2016)</td>
<td>12.6% GWC or 14.4% NWC at 80% Saturation (OMC occurring at 93% Saturation)</td>
</tr>
<tr>
<td><strong>Maximum Dry Density</strong></td>
<td>AS1289 5.2.1 (Standards Australia, 2003c)</td>
<td>2.67 t/m³ (e = 0.46)</td>
</tr>
<tr>
<td><strong>Minimum Dry Density</strong></td>
<td>AS1289.5.1 (Standards Australia, 1998)</td>
<td>2.00 t/m³ (e = 0.95)</td>
</tr>
<tr>
<td><strong>Atterberg Limits</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Liquid Limit</strong></td>
<td>AS1289.3.1.2 (Standards Australia, 2009a)</td>
<td>18% NWC or 15.3% GWC</td>
</tr>
<tr>
<td><strong>Plastic Limit</strong></td>
<td>AS1289.3.2.1 (Standards Australia, 2009b)</td>
<td>17% NWC or 14.5% GWC</td>
</tr>
<tr>
<td><strong>Plasticity Index</strong></td>
<td>AS1289.3.3.1 (Standards Australia, 2009c)</td>
<td>1% NWC or 1% GWC</td>
</tr>
<tr>
<td><strong>Standard Proctor Compaction</strong></td>
<td>AS1289 5.1.1 (Standards Australia, 2003b)</td>
<td>2.55 t/m³ at 12.5% NWC or 11.1% GWC OMC</td>
</tr>
<tr>
<td><strong>Modified Proctor Compaction</strong></td>
<td>AS1289 5.2.1 (Standards Australia, 2003c)</td>
<td>2.67 t/m³ at 11.0% NWC or 9.9% GWC OMC</td>
</tr>
<tr>
<td><strong>Particle Size Distribution</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel (&gt;2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>45%</td>
</tr>
<tr>
<td>Sand (75 μm – 2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>43%</td>
</tr>
<tr>
<td>Silt and Clay (&lt;75 μm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>12%</td>
</tr>
<tr>
<td>Silt (2 μm – 75 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>N/A</td>
</tr>
<tr>
<td>Clay (&lt;2 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>N/A</td>
</tr>
<tr>
<td>Classification</td>
<td>AS1726 (Standards Australia, 1993)</td>
<td>Silty gravel (GM)</td>
</tr>
<tr>
<td><strong>Coefficient of Uniformity, C_u</strong></td>
<td>N/A</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>Coefficient of Curvature, C_c</strong></td>
<td>N/A</td>
<td>0.3</td>
</tr>
<tr>
<td>Figure</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d); Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>See Figure 38</td>
</tr>
<tr>
<td><strong>Particle Density, G_s</strong></td>
<td>AS1289.3.5.1 (Standards Australia, 2006)</td>
<td>3.90 t/m³</td>
</tr>
<tr>
<td><strong>Hydraulic Conductivity, K</strong></td>
<td>AS1289.6.7.1 (Standards Australia, 2001b)</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Quantitative X-Ray Diffraction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hematite (Fe₂O₃)</td>
<td>X’Pert Pro PW3040</td>
<td>N/A</td>
</tr>
<tr>
<td>Goethite (FeOOH)</td>
<td>X’Pert Pro PW3040</td>
<td>N/A</td>
</tr>
<tr>
<td>Shrinkage Limit Density</td>
<td>In-House Method</td>
<td>N/A</td>
</tr>
<tr>
<td>Soil-Water Characteristic Curve</td>
<td>In-House Method</td>
<td>N/A</td>
</tr>
</tbody>
</table>
The percentage of moisture is reported according to the relevant standard first (i.e. Net Water Content (NWC) or Gross Water Content (GWC)). In geotechnical engineering and soil mechanics, the NWC is commonly used, whereas, in most other cases, including metallurgy and marine transportation, the GWC is favoured. NWC is referred to as the percentage of moisture to dry material, while GWC is the percentage of moisture to wet material; hence, net and gross.

According to MSC 95/22/Add.2, if a cargo of iron ore fines has more than 35% goethite total weight, then the schedule for iron ore must be followed but the cargo does not need to undergo testing using the Modified Proctor/Fagerberg method, as it is considered unable to liquefy (International Maritime Organization, 2016).

Due to the high fines content of the specimens, the maximum density was determined using the Modified Proctor Compaction method specified in AS1289 5.2.1 (Standards Australia, 2003c) instead of the vibratory method given in AS1289.5.5.1 (Standards Australia, 1998).
3.3 FIGURES

**Figure 31 – Standard (PFT) and Modified Proctor/Fagerberg (MPFT) compaction curves and resulting TML values for sample MA002**

**Figure 32 – Standard (PFT) and Modified Proctor/Fagerberg (MPFT) compaction curves and resulting TML values for sample MA003**
Figure 33 – Standard (PFT) and Modified Proctor/Fagerberg (MPFT) compaction curves and resulting TML values for sample MA004

Figure 34 – Standard and modified Proctor compaction curves for sample MA002
Figure 35 – Standard and modified Proctor compaction curves for sample MA003

Figure 36 – Shrinkage limit density curve for sample MA004
Figure 37 – Soil-Water Characteristic Curve for sample MA004

Figure 38 – Particle size distributions of the samples of iron ore fines utilized during this research
CHAPTER 4 EXPERIMENTAL METHODS

4.1 INTRODUCTION

The following chapter explains the experimental methods used throughout this research. Although the majority of the experimental methods are given in the relevant manuscripts provided later, this chapter delivers a structure so that readers can easily navigate the information provided within the manuscripts. This chapter also provides some additional information not included in the manuscripts.

Similar to the literature review given in Chapter 2, parts of this chapter are covered in detail in publications included within this thesis. To reduce duplication of information, where it was deemed necessary, references have been made to the sections within those publications where the relevant information is provided.

If information was spread amongst many publications regarding a single topic, it might have been considered appropriate to collect that information and combine it in this chapter with additional information. If this is the case, reference will be made to the manuscript in which the information was sourced.

4.2 PARTICLE SIZE DISTRIBUTION AND HYDRAULIC CONDUCTIVITY

As previously mentioned, the particle size distribution of a material is considered to be a major factor of the liquefiability of a soil due to the controlling influences it has on the moisture-holding ability and hydraulic conductivity of a soil (Ishihara, 1985; Munro and Mohajerani, 2015, 2017c, 2017d). The hydraulic conductivity of a soil during cyclic loading is directly related to the ability the material has to expel excess pore pressure that contributes to the loss of shear strength, see section 2.6. In order to understand the ability for iron ore fines to dissipate excess pore pressure, the particle size distribution and hydraulic conductivity of specimens were measured at varying stages throughout this research.

4.2.1 Particle Size Distribution

During the initial stages of this research, the particle size distributions of 45 samples of iron ore fines were determined using the standard sieving method along with the hydrometer method (Standards Australia, 2003a, 2009d). The results, shown in detail in Appendix B Figure 371, provided a range of expected particle size distributions for iron ore fines. These particle size distributions were compared alongside the widely accepted boundaries for liquefiable materials to determine the likelihood that the material had particles with sizes consistent with those with the ability to increase the potential to liquefy.

Throughout the research, it was decided to use a Mastersizer Aero 3000 and related procedure (International Standards Organization, 2009) to determine the range of the particle size distributions < 75 μm for the two specimens that were predominantly tested during this research. The Mastersizer Aero 3000, as seen in Figure 39, uses particle dispersion and laser diffraction in order to achieve this. Although testing using the hydrometer method (Standards Australia, 2003a) could produce similar results, using this method was considered to be significantly more accurate. The results from testing using the Mastersizer Aero 3000 can be seen in Chapter 3 section 3.2, and section 3.3 Figure 38.
The final aspect of this research, in relation to particle size distribution, was determining the likelihood of segregation occurring during cyclic loading and producing a change in the distribution of particles within specific areas within a cargo. Reference is made to Chapter 16 where a detailed manuscript is presented on the topic. The manuscript details the cyclic loading of iron ore fines inside a scale model designed and developed specifically for this research. Additional details regarding the scale model are given in sections 4.7 and 4.10 of this chapter.

4.2.2 Hydraulic Conductivity
Using a Rowe Cell, the hydraulic conductivity of a typical sample of iron ore fines was determined under varying confining pressures up to 600 kPa. The identification of a range of hydraulic conductivities expected under varying pressures identified the ability the material may have to dissipate pore pressures, reducing or increasing the liquefaction potential of the material. Reference is made to Chapter 9 section 9.3.4.2, and section 9.3.5.3 for details on the method and results, respectively. Discussions ensuing from the results are given in Chapter 9 section 9.3.6.

During the advanced cyclic triaxial tests discussed in detail in section 4.9 of this chapter, the hydraulic conductivity of sample MA004 was determined at the compacted density prior to loading. Although the relationship between the hydraulic conductivity and void ratio was considered insignificant, as discussed alongside the results in Appendix F, the consistently high hydraulic conductivity exhibited by the samples, at the range of void ratios tested, showed the increased ability cargoes of iron ore fines are likely to have to dissipate pore pressures.

4.3 PRELIMINARY RESISTIVITY TESTING
During the initial stages of research, the idea of correlating results to the resistivity measured through a sample of iron ore fines was formed. It was hypothesized that due to the conductivity of iron ore fines, a reduction in shear strength, caused by particle separation could be determined by measuring
the resistivity through the samples. Although not a major aspect of this research, the concept, which was further built upon and discussed in relation to the advanced scale model testing is one that may be of future use if shown to produce reliable results.

Initially, a mould was designed and developed in order to test the concept and produce a draft procedure. This initial design can be seen in Figure 40 and Figure 41. The mould designed and developed was constructed from PVC and included two internal resistivity probes, which extended the entire height of the sample once compacted within the mould. These resistivity probes can be clearly seen in Figure 42. The mould included holes placed around the base in order for it to be attached to a vibrating table.

Figure 40 – Preliminary resistivity mould design with compaction collar removed
4.3.1 Experimental Procedure

The procedure used during the early stages of the resistivity testing involved the following:

1. initially, the sample was compacted into the resistivity mould using the same method used to compact the sample during the standard Proctor/Fagerberg test given in Appendix 2 of the IMSBC Code (International Maritime Organization, 2016),
2. after compaction was complete, the collar was removed, and the sample was levelled,
3. the mould was then weighed to determine the dry density after testing was complete,
4. A multimeter was then hooked up to the mould and the mould attached to the vibrating table,
5. the mould was then vibrated at a frequency of 50 Hz at a double amplitude (peak to peak) setting of 0.5 ± 0.05 mm for 2 minutes,
6. during vibration, the multimeter recorded the resistivity measured throughout the sample,
7. once vibration was complete, the change in volume was recorded along with the moisture content to calculate the change in density.

4.3.2 Experimental Outcome
The experimental results proved that the method is feasible and may produce significant results with some modifications. The major modification needed was in regards to the data logging device. The multimeter used was not sensitive enough to record the results as precisely as required. A new design of probe was needed in order to achieve this.

Additionally, the resistivity reading could only be compared to simple parameters, including changes in density and moisture content, along with the TML of the sample. It was not enough just to have these comparisons. It was required that other parameters be recorded in order to determine if liquefaction or another phenomenon was occurring and if the onset of the phenomenon was related to the changes in resistivity that was recorded.

The results from the preliminary resistivity study were inconclusive; therefore, they are not included in this document. Further on in this research, the design of the apparatus was modified along with the procedure to improve the accuracy and relevance of the results. These modifications are discussed further in section 4.10 of this chapter in relation to the advanced scale model testing.

4.4 PRELIMINARY VIBRATORY TESTING
In order to design the scale model, described in sections 4.7 and 4.10 as well as in the manuscripts presented in Chapter 14 and Chapter 16, preliminary vibratory testing was performed to understand the parameters that could and should be monitored in relation to the cyclic loading of iron ore fines.

A specific manuscript was written and published presenting the results from these tests. Chapter 9 sections 9.3.4.3, and 9.3.5.1 include the methods and results used during the preliminary vibratory testing stage of this research, and conclusions are given in section 9.3.6. Additional figures not presented in the manuscript are shown in Figure 43 and Figure 44.
4.5 PRELIMINARY REPEATED LOAD TRIAXIAL (RLT) TESTING

It was identified early on in this research that the analysis of the behaviour of iron ore fines under cyclic loading would be incomplete without utilizing the most versatile geotechnical laboratory testing apparatus, the cyclic triaxial.

To understand and improve the procedures and methods used in order to test iron ore fines under cyclic loading, the repeated load triaxial apparatus, described in Chapter 12, and seen in Figure 45 and

Figure 43 – sample of iron ore fines after vibratory testing

Figure 44 – sample of iron ore fines after vibratory testing and removal from mould
Figure 46 was used. This triaxial was not the advanced triaxial system that was utilized further on in this research because, at that time, the new apparatus had yet to be installed.

Figure 45 – Repeated load cyclic triaxial apparatus utilized during this research (1)
Reference is made to Chapter 12 section 12.3.4.2 where the apparatus, method, and procedure used is described. The results from this aspect of testing are given alongside the conclusion in Chapter 12 sections 12.3.5 and 12.3.6, respectively.

4.6 PRELIMINARY MONOTONIC TRIAXIAL TESTING

Using the same repeated load triaxial apparatus described in Section 4.5, monotonic shear tests were also performed. The tests were used to determine the cohesion factors and internal friction angles of samples at varying moisture contents and densities to complete future computational analysis.

Reference is firstly made to Chapter 12 Section 12.3.4.2 where a description of the apparatus is given. Reference is then made to Chapter 13 Section 13.3.3.2.1 where an additional description of the apparatus is given alongside the method used. Section 13.3.4.1 provides the results from the monotonic tests in relation to the shear parameters of the materials.
4.6.1 Computational Modelling
The results from the monotonic tests were used to complete the computational analysis of slope stability and are briefly described in Chapter 2 section 2.6.3. The bulk of the computational analysis performed was used to form the publication presented in Chapter 13.

Reference is made to Chapter 13 sections 13.3.3.2.2 and 13.3.4.2 for the methods used for computational analysis and the results produced, respectively. Section 13.3.5 of the same chapter provides a conclusion based on the results of the analysis.

4.7 PRELIMINARY SCALE MODEL TESTING

Similar to the triaxial testing, preliminary scale model testing was required to develop, understand and improve the procedures, method, and apparatus used in order to test iron ore fines under cyclic loading within the model.

Based upon the preliminary vibratory testing, described in section 4.4 of this chapter, the design and development of the scale model began. Initially, CAD software was used to design major aspects of the model required in order to achieve the objectives set out by this research. The development of the design concept of the model can be seen in Figure 47 through Figure 50 and the final design, at this stage of research, is shown in Figure 51.

Figure 47 – Preliminary scale model design concept (sketch 1)
Figure 48 – Preliminary scale model design concept (sketch 2)

Figure 49 – Preliminary scale model design concept (sketch 3)
Chapter 4 - Experimental Methods

Figure 50 – Preliminary scale model design concept (sketch 4)

Figure 51 – Final dimensions and features of the scale model designed, developed and utilized during the preliminary stages of this research (Munro and Mohajerani, 2017c)
Once the aspects required for the design were fulfilled, construction began on the apparatus. Firstly, the acrylic mould was constructed, as seen in Figure 52. The acrylic mould then came together with the steel base, as seen in Figure 53. The steel base was required to attach the mould securely to a vibrating table to ensure that all loading was transferred from the table to the mould, and, therefore, the sample.

Figure 52 – Completed construction of part of the scale model, the acrylic mould

Figure 53 – Coming together of the acrylic mould and steel base plate
The testing performed using the preliminary scale model design, shown in Figure 54, was presented in the manuscript given in Chapter 14. Reference is made to section 14.3.4.2.1 where the features and design aspects of the apparatus are described in further detail. The procedure used along with the apparatus and results from its use are given in sections 14.3.4.3 and 14.3.5, respectively.

Although the conclusions made in Chapter 14 section 14.3.6, in regards to the preliminary scale model testing, were important aspects of this research, it was acknowledged that further modifications were needed to improve upon the research. These improvements made to the apparatus are described in more detail in section 4.10 of this chapter.

### 4.8 IRON ORE FINES PLUNGER (IOFP) TESTING

The preliminary scale model described in section 4.7 of this chapter also included what was considered to be a separate apparatus that was attached to enhance the results and analyse another method to determine the strength of iron ore fines under cyclic loading.

The apparatus, shown in Figure 55, which we refer to as the Iron Ore Fines Plunger (IOFP), is a revised version of the Penetration Test (PT), which is given in Appendix 2 of the International Maritime Solid Bulk Cargoes Code (IMSBC Code) to determine the Transportable Moisture Limit (TML) of ore concentrates. More details regarding the PT can be found in references provided in Chapter 2 section 2.8.2.
In regards to the IOFP test, designed and developed for this research, information can be found in Chapter 9, Chapter 10, and Chapter 14. Specifically, reference is made to sections 9.3.4.4, 10.3.4.1.2 14.3.4.2.2 and 14.3.4.3, in the respective chapters, for summaries of the apparatus and procedure used. Additionally, sections 9.3.5.2, 10.3.4.2 and 14.3.5.4 provide the results from the tests alongside conclusions provided in sections 9.3.6, 10.3.4.2 and 14.3.6.
4.9 ADVANCED CYCLIC AND MONOTONIC TRIAXIAL TESTING

Moving on from the preliminary repeated load triaxial testing described in section 4.5 of this chapter is the advanced cyclic and monotonic triaxial testing. Up to this stage, due to unforeseen circumstances, the apparatus described herein was not available. This research relied on relocating, installing and creating procedures for the apparatus in order for it to be utilized for the testing of iron ore fines. During this research, successful relocation and installation of this apparatus was achieved.

The main difference between the preliminary repeated load triaxial testing, described in section 4.5 of this chapter, and the advanced cyclic triaxial, shown in Figure 56 and Figure 57, is the introduction of back pressure control, volume change measurement, and pore pressure monitoring.

Figure 56 – Advanced cyclic triaxial utilized during this study, after successful relocation and installation (1)
4.9.1 Critical State Framework

The method used to analyse the cyclic and monotonic results from the advanced triaxial involved the critical state framework. Critical state soil mechanics describes the strength and compressibility response of soils and other materials used in engineering designs. The framework under which the critical state is defined is employed to understand the response of soils negotiating the specified stress paths that the material is expected to experience (Munro and Mohajerani, 2017e).

Reference is made to the same chapter, Chapter 15, of this thesis where the advanced cyclic triaxial results are presented. Section 15.3.4.1 describes in detail the critical state framework in relation to liquefaction, cyclic mobility, incremental collapse, and shakedown. Section 15.3.5 includes the monotonic and cyclic results in relation to the critical state framework, and, finally, sections 15.3.6 and 15.3.7 include discussions and conclusions regarding the testing and analysis.

4.10 ADVANCED SCALE MODEL TESTING

As mentioned in section 4.7, when discussing the preliminary scale model testing, it was identified that further modifications to the scale model were needed to improve upon the research. The improvements made to the apparatus and references to the manuscript, where the results and analysis are presented, are given herein.

After the final preliminary scale model test was performed, the scale model went back to the drawing board to be further modified, stages of which can be seen in Figure 58 and Figure 59. In order for the
phenomena causing cargo shift to be correctly identified, there was a need to monitor both the pore air and water pressures within the samples while under vibration.

Additionally, further testing using resistivity probes, to assess the hypothesis given in section 4.3 of this chapter, was required. There were two types of resistivity probe installed on the scale model to assess the hypothesis. One method used full-length probes on the side to measure throughout the
entire sample and the other used local probes to measure resistivity at specific locations within the samples.

It is noted here that the two additions to the scale model that are shown in Figure 59 were not utilized during this research. One addition included the full-length resistivity probes and the other was the modified Iron Ore Fines Plunger (IOFP). These two aspects of the test were not used or described during this research as they needed further improvement in order for them to produce reliable results. With this said, although the full-length resistivity probes were not used, the local resistivity probes were used to determine the resistivity change during vibration.

Figure 60 – Computer, data loggers, breakout boards, tensiometers and transducers along with vibrating table controls all attached to the mould to monitor and record data during vibration (Munro and Mohajerani, 2017d)
Figure 60 and Figure 61 show the scale model with all the modifications made. Reference is made to Chapter 16 sections 16.3.3.2.2 and 16.3.3.2.3 for further details regarding the aforementioned modifications and the alterations made to the procedure used during the scale model testing. Also, given in Chapter 16 in section 16.3.4, are the results produced from the utilization of the scale model with the aforementioned modifications. The advanced scale model testing is summarized in the discussions and conclusions given in sections 16.3.5 and 16.3.6, similar to the structure of all the additional manuscripts presented from herein.
CHAPTER 5  DETERMINATION OF TRANSPORTABLE MOISTURE LIMIT OF IRON ORE FINES FOR THE PREVENTION OF LIQUEFACTION IN BULK CARRIERS

5.1  INTRODUCTION

This peer-reviewed manuscript was the first published document pertaining to this research. This manuscript introduces the concept of liquefaction of iron ore fines alongside the three test methods given in Appendix 2 of the 2012 edition of the IMSBC Code (International Maritime Organization, 2012b).

In this manuscript, specific insights into the background, development, suitability, reliability and other aspects of the tests are given and the resulting correlations to one another in respect of the testing of cargoes of iron ore fines. This manuscript also provides the range of physical properties expected of a cargo iron ore fines as well as the range of Transportable Moisture Limit (TML) values that may be obtained from performing the three test methods given in Appendix 2 of the 2012 edition of the IMSBC Code (International Maritime Organization, 2012b). This was achieved by performing tests on numerous samples obtained from various locations worldwide.

Also touched upon are the inconsistencies and misconceptions in the 2012 edition of the IMSBC Code concerning the terminology used and calculations provided. In the appendix of this manuscript, both the terminology and calculations given in the IMSBC Code are discussed (International Maritime Organization, 2012b).

Exclusions made from this manuscript and not included in this chapter are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made made continuous throughout this document.

5.2  CITATION

5.3 MANUSCRIPT CONTENTS

5.3.1 Abstract
In 2013, over 500 million metric tons of Iron Ore Fines (IOF) were transported around the world using bulk carriers. Under certain conditions IOF, while being transported, can possibly undergo liquefaction. Since 2006, there has been eight reported bulk carrier casualties possibly caused by the liquefaction of IOF. The objective of this study is to evaluate, compare and verify the limitations and relevance of the Proctor/Fagerberg, Flow Table and Penetration test methods that are used to determine the Transportable Moisture Limit (TML) of IOF. The TML is the maximum gross water content that bulk cargoes, including IOF, may contain while being transported at sea without being at risk of liquefying. A thorough literature review, along with laboratory research, was carried out to compare the TML results from the three leading test methods to determine whether they produce reliable results when testing IOF. The study concludes that the three test methods, as stated in the 2012 International Maritime Solid Bulk Cargoes Code, are unverified and therefore not appropriate for testing IOF. This is due to the variation in the results produced by the three test methods and also due to the difference in the physical properties of IOF when compared with the materials that were originally intended for testing. It is noted that the TML alone may not control the potential liquefaction of IOF and further studies, regarding the physical properties and system variables, which cause the material to liquefy, are required to determine the liquefaction potential of IOF.

5.3.2 Introduction
In 2011, over 2.8 billion metric tons of iron ore was produced worldwide (United States Geological Survey, Undated-b). After its extraction, the iron ore is mechanically divided to produce three different qualities; fines (<6.3mm), lump (6.3-30mm) and pellets (9.5-16mm) (“Fact Sheet: Iron Ore,” 2012). Since 98% of the iron ore produced is used to make steel, it is said to be "more integral to the global economy than any other commodity, except perhaps oil" (Blas, 2009). Iron Ore Fines (IOF) make up approximately 48% of the iron ore trade, which in 2011, was approximately 1.3 billion metric tons (Kogel et al., 2006).

In 2004, approximately 400 million metric tons of IOF were transported around the world using bulk carriers, with Australia and Brazil dominating the seaborne trade. The vessels used to transport IOF vary in size, with the largest being Capesize bulk carriers (Blas et al., 2009). Unlike a tanker, where the cargo holds surface areas are minimized, bulk carriers store their cargo in large holds accessed by individual hatch covers. These holds are separated along the length and extend the full width of the vessel. This design is intended to transport solid granular materials.

Since the holds of bulk carriers are not designed to carry liquid, if liquefaction of IOF or other materials occur, while being transported, it can cause the vessel to list or even capsize. This is due to the material shifting from one side of the hold to the other and causing the vessel to become unbalanced. If a vessel begins to list, ballast is used to try to correct the problem. Due to the weight of iron ore, and similar materials, this can sometimes be very difficult to correct. If the vessel continues unbalanced the list can become more pronounced and the vessel can capsize. Since 2006, there has been eight reported bulk carrier casualties possibly caused by liquefaction of IOF (Devaney, Undated; International Maritime Organization - Intercargo, 2007; "Marine Casualty Information (2011-2013),” 2013; Maritime Bulletin, 2013a; Roberts, 2012). Seen in Figure 62 and Figure 63 are two bulk carriers that were lost due to possible liquefaction of the cargo of IOF.
Although liquefaction has been known to cause vessels to capsize, since the loss of the Bengal in 1910 (Sandvik and Rein, 1992), up until 2011, owners have been able to apply the International Maritime Solid Bulk Cargoes Code, hereafter called the IMSBC Code (International Maritime Organization, 2012b), on a voluntary basis (Laudal, 2010). The IMSBC Code, formally the Code of Safe Practice for Solid Bulk Cargoes (BC Code) (International Maritime Organization, 1998), is an internationally accepted code of safe practice created to address the problems involved in the transportation of bulk cargos, including IOF. In January 2011, the IMSBC Code became part of a mandatory requirement that is to be followed by all owners of vessels carrying solid bulk cargos (Gossett, 2012).

The IMSBC Code outlines dangers associated with certain types of solid bulk cargos and provides procedures to be followed when transporting these materials. Included in the code are test methods used to determine the Transportable Moisture Limit (TML) of ‘Group A’ cargoes. ‘Group A’ cargoes are those that have the potential to liquefy due to the proportion of fine particles and moisture they contain. Before 2011, IOF were not specifically listed in the IMSBC Code (International Maritime Organization, 2011). The 2012 IMSBC Code now classifies IOF as a, ‘Group A’, liquefiable cargo.

The three test methods used to determine the TML of liquefiable materials were created, and incorporated, in the IMSBC code a considerable time before the addition of IOF to the list of liquefiable cargos within. Due to IOF now being a ‘Group A’ liquefiable cargo, they are now required to undergo TML testing using these predetermined and unmodified methods. The TML is the maximum gross water content that bulk cargoes, including IOF, may contain while being transported at sea without being at risk of liquefying. Additional information on terminology used in this study can be seen in Section 5.3.10.

When determining the TML of a material, the IMSBC Code provides three test methods that can be used. They are the Flow Table test, Penetration test and Proctor/Fagerberg test. These three test methods are discussed in Section 5.3.4 of this paper. Other tests that have been used to determine the TML of a material, but not mentioned in the IMSBC Code, are tests such as the vibrating platform method, developed by British Coal (A Kruszewski, 1989), a drainage method, produced by Norway (International Maritime Organization, 1984), and a method using a concrete tester developed in Finland (Sandvik and Rein, 1992).
The main objective of this study is to evaluate, compare and determine the limitations and relevance of the three leading test methods used to determine the TML of IOF. This study will also deliver examples why the 2012 IMSBC Code, in regards to TML testing, can at sometimes be misleading when testing IOF.

5.3.3 Liquefaction

This Section includes the basic principles of liquefaction and is included in this study to illustrate that the underlying factors why IOF potential to liquefy may be much more complex than initially perceived. Liquefaction is a description of the follow-on effect of a static or dynamic load being applied to a material, usually a fine sand or silt, resulting in the material acting like a liquid. “Liquefies” was first termed in 1920 when referring to the failure of the Calaveras Dam in 1918 (Hazen, 1920). Since then, there have been numerous studies done on the subject. Although the subject is particularly complex, there have been found to be two common types of liquefaction, they are static and dynamic liquefaction.

Static liquefaction occurs less regularly than dynamic liquefaction. It is caused by increasing the shear stress in a material, usually by applying a monotonic load, until such a point is reached that one point of the material liquefies and propagates rapidly, from that point, to produce total liquefaction of the material. This can be seen graphically in Figure 64. Static liquefaction most commonly occurs in undrained or saturated conditions.

![Figure 64](image)

*Figure 64 – Idealized response of saturated cohesionless tailings under monotonic and cyclic loading (Davies et al., 2002)*

Dynamic liquefaction occurs more frequently than static liquefaction. This is because it is produced regularly by nature, in the form of earthquakes. Dynamic liquefaction occurs when a cyclic or dynamic load is applied to a material causing parameters within the material to change and therefore liquefy (Davies et al., 2002). Dynamic liquefaction propagates throughout the material from a single point, like static liquefaction, to cause total liquefaction of the material. This phenomenon can occur in saturated or unsaturated materials.

Eq. 3 show the relationship between the effective stress ($\sigma'$), normal stress ($\sigma$) and pore water pressure ($u_w$) of a saturated material (Bishop and Eldin, 1950). Referring to basic soil mechanics, the
effective stress directly affects the resulting shear stress ($\tau$), and Eq. 3 show that increasing pore water pressure reduces the effective stress. The pore water pressure can be suddenly increased by applying dynamic energy or a monotonic load. If the effective stress of a cohesionless material is reduced to zero, the shear stress is also reduced to zero and the material has the potential to liquefy.

$$\sigma' = \sigma - u_w$$  \hspace{1cm} (Eq. 1)

Likewise, in partially saturated cohesionless materials, when the effective stress is reduced to zero, the shear stress is also reduced to zero. The difference between the resulting effective stress of a saturated verses partially saturated material is the presence of pore air pressure ($u_a$) and a factor of the degree of saturation ($\chi$), as seen in Eq. 3 (Bishop, 1959).

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w)$$  \hspace{1cm} (Eq. 2)

When static, the pore water pressure is negative and this suction force has a tendency to hold the particles together, as seen in Figure 65, but when a monotonic load or dynamic energy is applied the pore air pressure and pore water pressure will increase and force the particles apart, as seen in Figure 66. Since air compresses and water does not, the pores filled with air will reduce causing a decrease in the void ratio and an increase in the degree of saturation. Under certain conditions this can cause the effective stress of a material to reduce to zero causing the material to become potentially liquefiable.

The complex behaviour IOF exhibit when it undergoes liquefaction is dissimilar from that of soils and tailings. As IOF are transported in bulk carriers, the energy transmitted from the waves and the vessels engine varies from the energy produced from more common causes of liquefaction, such as earthquakes. This input of energy consolidates the IOF, as it is being transported, reducing the void ratio of the material closer to the bottom of the hold as well as increasing its degree of saturation. The extraction, refining and storage of IOF contribute to the moisture that the material contains when it is loaded onto bulk carriers. IOF are commonly loaded as dry as possible, as seen in Figure 67, but sometimes contain significant moisture, as seen in Figure 68. A combination of the moisture content, dynamic energy produced by the waves and the vessels engine along with the weight of the material itself leads us to believe that the material may be undergoing a combination of both static and dynamic liquefaction.
Chapter 5 - Determination of Transportable Moisture Limit of Iron Ore Fines for the Prevention of Liquefaction in Bulk Carriers

Figure 67 – Dry IOF being loaded onto a bulk carrier (Crouch and Aamlid, 2009)

Figure 68 – Partially saturated IOF in the hold of a bulk carrier in India (Crouch and Aamlid, 2009)

Although all IOF may not be potentially liquefiable, the risk that IOF pose, when being transported, is significant. Further studies need to be completed to determine what physical properties of IOF determine the resulting TML and if there are limits on the physical properties, which could indicate that a sample does not have the potential to liquefy.

5.3.4 TML Test Procedures

5.3.4.1 Proctor/Fagerberg Test

5.3.4.1.1 Background

The Proctor/Fagerberg test was first published in Stockholm in 1962 by Bengt Fagerberg and Kjell Eriksson as part of a committee established by the Swedish Mining Association and several Scandinavian mining companies. The committee was given the task to develop a simple method for determining the critical moisture content (CMC) of individual cargos (Fagerberg and Stavang, 1971). The test method is based upon use of the Proctor apparatus developed in soil mechanics (American Society for Testing and Materials, 2012) and was adopted by the International Maritime Organization, for use in the BC Code (International Maritime Organization, 1998), between 1991 and 1998. The critical moisture content in the Proctor/Fagerberg test is also known as the TML.

5.3.4.1.2 Procedure

The procedure to determine the TML of a material, according to the Proctor/Fagerberg test, begins by drying out enough material, at approximately 100°C, to fill a one litre mould 5-10 times. Once dry, a suitable amount of water is added to the first test portion and mixed thoroughly for five minutes. The mould is then filled to approximately one fifth of the height, levelled off then the material is compacted uniformly with a compaction hammer. Compacting is executed by dropping a 350g hammer, 25 times, though a guided pipe from a height of 0.2m. This procedure is repeated for all five layers. The compaction energy specified is from compaction “Method C” obtained by research carried out by Fagerberg and Stavang. More details on the compaction of the sample and energy can be seen in Section 5.3.4.1.7.

After compaction is complete, the collar is removed and the sample is levelled along the brim with a straightedge, as seen in Figure 69. The weight of the mould and the sample is determined then the mould is emptied, as seen in Figure 70, and the sample dried and weighed again. This procedure is then repeated at different moisture contents.
After 5-10 compactions at varying moisture contents have been performed and the gross water contents determined, standard soil mechanic equations are used to create a graphical representation of the samples compaction curve. A typical compaction curve, along with the resulting TML, that is produced during a Proctor/Fagerberg test can be seen in Figure 71.

![Figure 71 – Typical graphical representation of the compaction curve and resulting TML from the Proctor/Fagerberg test](image)

The TML of the material is taken as equal to the gross water content when the material is 70% saturated. More details on why 70% saturation is used during this procedure can be seen in Section
5.3.4.1.7. The calculations used for the Proctor/Fagerberg test can be seen in Section 5.3.11.1 and typical IOF TML values for this test can be seen in Table 22 in Section 5.3.12.

The Proctor/Fagerberg test may require 20-40kg of IOF depending on how many compaction points are needed to complete the compaction curve. To complete the minimum of 5 points, covering the correct range of moisture contents, approximately 20kg of material will be needed. The 2012 IMSBC Code states that the Proctor/Fagerberg test is only suitable for samples with a maximum particle size of 5mm.

5.3.4.1.3 Estimated Test Time
According to the procedure in the 2012 IMSBC Code, the Proctor/Fagerberg test can be completed in two days, one day for completing the compaction points, then the second to weigh the dry samples and create a graphical representation of the compaction curve. To calculate the saturation lines and void ratios needed for the graphical representation, the particle density must also be obtained. The determination of particle density can be completed, separately, in the same amount of time as the Proctor/Fagerberg test, therefore a sample can still be tested within two days although it will require additional labour. See Section 5.3.4.1.6 for information regarding the determination of particle density for the Proctor/Fagerberg test.

5.3.4.1.4 Reliability
The Proctor/Fagerberg test uses set measurements to determine whether the TML has been reached and does not need the operator to interpret visually, or otherwise, the TML during the test. Since this test is based upon the widely used Proctor apparatus, developed in soil mechanics (American Society for Testing and Materials, 2012), it is easy for an operator familiar with the Proctor apparatus to perform the test. Compared with the Proctor compaction procedure, there are only slight differences in the compaction effort, number of layers and reporting requirements (International Maritime Organization, 2012b). The Proctor/Fagerberg test has been widely accepted to have great repeatability and reproducibility when comparing against multiple operators and laboratories because of its similarity to the Proctor compaction procedure (American Society for Testing and Materials, 2012). The preparation procedures are discussed in more detail in Section 5.3.8.

5.3.4.1.5 Application of Materials
Fagerberg and Stavang wrote in their 1971 paper, which is regarding the development of the Proctor/Fagerberg test, that the aim of the committee, appointed by the Swedish Mining Association, was to “develop a simple method for determining the critical moisture content of individual concentrates” (Fagerberg and Stavang, 1971). There were no additional studies completed, up to the time the Proctor/Fagerberg test was introduced into the IMSBC Code, to determine if the test was valid for determining the TML of IOF.

5.3.4.1.6 Particle Density (Specific Gravity)
The importance of determining the particle density, of samples tested using the Proctor/Fagerberg method, is not emphasized in the 2012 IMSBC Code. If the particle density has not been determined correctly, determined using an incorrect standard or simply assumed, the TML obtained from the point at which the material reaches 70% saturation will be incorrect. This is because the saturation lines are calculated using the particle density of the sample being tested.
Because ore concentrates have been refined, the particle densities can be predictable and fairly consistent, but in contrast, the particle density of the IOF can vary significantly. During this study, the particle density of samples of IOF ranged from 3.8 - 4.8t/m$^3$. It is critical that the particle density is measured correctly for use during the Proctor/Fagerberg test to obtain an accurate TML.

5.3.4.1.7 Development of the Proctor/Fagerberg Test

During research into the development of the Proctor/Fagerberg test in 1971, Fagerberg and Stavang compacted samples to different densities with hammers of different weights and drop heights, as seen in Table 10 (Fagerberg and Stavang, 1971).

Table 10 – Hammer weights and drop heights used during the development of the Proctor/Fagerberg test (Fagerberg and Stavang, 1971)

<table>
<thead>
<tr>
<th>Methods Tested</th>
<th>Hammer Weight (g)</th>
<th>Height of Drop (cm)</th>
<th>Number of Blows per Layer</th>
<th>Number of Layers</th>
<th>Compaction Energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2498</td>
<td>30.5</td>
<td>25</td>
<td>5</td>
<td>747.16</td>
</tr>
<tr>
<td>B</td>
<td>1000</td>
<td>20.0</td>
<td>25</td>
<td>5</td>
<td>196.13</td>
</tr>
<tr>
<td>C</td>
<td>350</td>
<td>20.0</td>
<td>25</td>
<td>5</td>
<td>68.65</td>
</tr>
<tr>
<td>D</td>
<td>150</td>
<td>15.0</td>
<td>25</td>
<td>5</td>
<td>22.06</td>
</tr>
<tr>
<td>E</td>
<td>50</td>
<td>4.0</td>
<td>25</td>
<td>5</td>
<td>1.96</td>
</tr>
</tbody>
</table>

To determine the compaction effort to be used, Fagerberg and Stavang obtained core samples from 85 vessels, containing different types of ore concentrates. The samples were obtained by inserting small brass cylinders in the cargo during unloading. The undisturbed samples were then sent off to a laboratory for the determination of void ratio and moisture content. These samples were taken from different depths, with the deepest being 8m. They examined the results and discovered that the density produced by compaction “Method C” and “Method D” was the same density of the cargo in the vessels (Fagerberg and Stavang, 1971).

Figure 72 show these two compaction curves produced by Fagerberg and Stavang along with the void ratios from one of the 85 cargo vessels. Compaction “Method D” produced the most similar densities to what were measured on board the vessels, but compaction “Method C” was chosen as the preferred method because it provided an inbuilt safety factor (Fagerberg and Stavang, 1971).
The materials that Fagerberg and Stavang tested were ore concentrates which had an optimum moisture contents of around 70% saturation. The optimum moisture content is the moisture content at which a compaction curve reaches the minimum void ratio or maximum density. Fagerberg and Stavang considered the optimum moisture content, of the ore concentrates, as the most probable point at which they would become potentially liquefiable. This is the reason behind Fagerberg and Stavang selecting 70% saturation as the point where the TML would be obtained. In the 2012 IMSBC Code, compaction “Method C” along with selecting the TML from where the compaction curve intersects 70% saturation is known as the Proctor/Fagerberg test, which is currently used to determine the TML of potentially liquefiable cargoes (International Maritime Organization, 2012b).
5.3.4.2  Flow Table Test

5.3.4.2.1  Background
The Flow Table test has been widely used in the cement industry to test hydraulic cement since 1983 with the release of ASTM C230 / C230M Standard Specification for Flow Table for Use in Tests of Hydraulic Cement (American Society for Testing and Materials, 2008). It can be traced back to 1971 when it was used to test Portland-Cement (American Society for Testing and Materials, 1971) and as far back as 1952 when it was used to test Magnesium Oxychloride Cements (American Society for Testing and Materials, 1952). The early BC Code included a modified procedure, created by the Department of Mines and Technical Services in Canada that can be used to determine the TML of bulk cargos using the Flow Table apparatus. In 2000, this method also branched out into the ISO Guide 12742 (International Standards Organization, 2007). The following is a brief description of the Flow Table test procedure as given in the 2012 IMSBC Code (International Maritime Organization, 2012b), which also references apparatus used in ASTM C230 / C230M - 08 Standard Specification for Flow Table for Use in Tests of Hydraulic Cement (American Society for Testing and Materials, 2008).

5.3.4.2.2  Procedure
The Flow Table test is performed by placing a conical shaped mould on the centre of the Flow Table, as seen in Figure 73. The mould is filled and the material is compacted in three stages. In the first stage, the mould is filled to one third its height then compacted uniformly, with 35 tamping actions, by means of an adjustable tamper, as seen in Figure 74. The second and third stages are similar except 25 and 20 tamping actions are performed, respectively. The predetermined force used for tamping is discussed in more detail in Section 5.3.4.2.6.

After compaction is complete, and the excess material has been struck off with a straightedge, the mould is then carefully removed. Immediately after the mould is removed, the Flow Table is raised and dropped up to 50 times through a height of 12.5mm at a rate of 25 times per minute. This procedure is then repeated at different moisture contents.
Initially, the required amount of material is mixed in a bowl and three subsamples are taken. One subsample is used to obtain the initial moisture content and the other two for the preliminary and the main Flow Table tests. The preliminary test should be performed determine the approximate moisture content at which the material will start to show plastic deformation. This point is called the flow moisture point (FMP) and in the Flow Table test it is considered to be reached when with the correct moisture content, the dropping of the table produces plastic deformation of the sample, as seen in Figure 75. If the material is under the FMP the material will crumble, as seen in Figure 76.
There are two preliminary test methods that can be used to determine the approximate moisture content at which the material will start to show plastic deformation. The first method is to wet the material, in the mixing bowl, until it is determined that the sample is over the FMP. A test is then performed on the Flow Table at this moisture content then another increment of water is added and the test is performed again. The FMP can then be estimated by plotting the moisture content against the increase in diameter. This can be seen in Figure 77. The diameter of the sample is to be measured at the end of each of the two tests and is approximately linear.

The second preliminary test method involves performing the test at an initial moisture content, return the material to the mixing bowl, then mixing in 5-10ml of water, then repeat testing and adding known increments of water until the FMP has been reached.

After the preliminary test, the main test is then performed by performing the Flow Table test on the sample at 1-2% below the assumed FMP then adding water in increments of 0.5% of the mass of the test material. The material is retained after each test in case the FMP is reached in the subsequent test. After the FMP has been reached, the gross water content is determined on the samples just below and just above the FMP. The difference between these two gross water contents should be 0.5% or less to be in accordance with the code. The FMP is then taken as the mean of these two values and the TML is taken as 90% of the FMP. The calculations used in this test method can be seen in Section 5.3.11.2 and typical IOF TML values for this test can be seen in Table 23 in Section 5.3.12.

The Flow Table test uses the least amount of material of the three tests. It needs a minimum sample size of 5-10kg for testing a sample of IOF. The use of approximately 1kg of IOF per compaction point is sufficient for filling the mould with a small amount sample to spare. The 2012 IMSBC Code (International Maritime Organization, 2012b) states the Flow Table test is applicable for materials with a maximum particle size of 1mm, but may be applicable for materials with a maximum particle size of 7mm. It is not suitable for materials coarser than this or for materials with high clay content.
5.3.4.2.3 Estimated Test Time
According to the procedure in the 2012 IMSBC Code, if the Flow Table test is performed by an experienced operator it can be completed in three days. One day is needed to complete the preliminary test, the second to estimate the FMP from the preliminary moisture contents and then perform the main test, and the third to determine the gross water contents of the main test samples and determine the TML.

Determining the bulk density using the Proctor compaction test described in ASTM D-698 (American Society for Testing and Materials, 2012) or JIS-A1210 (Japanese Standards Association, 2009), which is needed to determine the tamping pressure used during the Flow Table test, can be performed on the first day prior to the preliminary test. This is because determining the moisture content for the Proctor compaction can be avoided as it is not needed to calculate the bulk density. See Section 5.3.4.2.6 for more details on the compaction of the sample.

5.3.4.2.4 Reliability
Determining the TML of a material using the Flow Table test is the most demanding test on the operator. The operator has to visually determine whether or not the sample is above or below the FMP. Visually being able to determine the FMP of coarser samples can be difficult as coarse particles breaking off can obscure the operator’s view when trying to observe plastic deformation of the sample. Although with the same laboratory and same operator the repeatability of the test is excellent, when comparing against other laboratories and operators the repeatability is not as good as the other two methods. The repeatability and reproducibility of the test can be improved with a more detailed test procedure.

5.3.4.2.5 Application of Materials
The Flow Table test, as seen in the 2012 IMSBC Code (International Maritime Organization, 2012b) and ISO-12742 (International Standards Organization, 2007), is only used for determining the TML of ore concentrates and coals. Since both standards are near identical, it can be assumed that they are used to test the same materials. In table 1.1.4.1, p. 306, of the 2012 IMSBC Code, it lists coal, metal ore, iron ore concentrate and lead ore concentrate. In the scope of ISO-12742 it states “This International Standard specifies a flow-table method for the determination of the TML of copper, lead and zinc sulfide concentrates, which may liquefy during transport”. Nowhere does it refer to the TML testing of other materials, such as IOF. Further investigation is needed to determine if the Flow Table test gives accurate results when determining the TML of IOF.

5.3.4.2.6 Compaction of the Sample
In the Flow Table and Penetration test procedures, the 2012 IMSBC Code gives options for determining the pressure that should be used when compacting samples into the mould using the tamping rod. To determine the pressure either paragraph 1.1.4.1.2, pp. 305 (see Eq. 3) or table 1.1.4.1, pp. 306 (see Table 11) of the 2012 IMSBC Code should be used (International Maritime Organization, 2012b). IOF are not mentioned in Table 11 therefore Eq. 3 must be used utilizing the bulk density determined using either ASTM D-698 (American Society for Testing and Materials, 2012) or JIS-A1210 (Japanese Standards Association, 2009).
Tamping Pressure (Pa) = Bulk Density (kg/m$^3$) x Maximum Depth of Cargo (m) x Acceleration of Gravity (m/s$^2$)  
(Eq. 3)


### Table 11 – Standard tamping pressures for the Flow Table and Penetration tests according to the 2012 IMSBC Code (International Maritime Organization, 2012b)

<table>
<thead>
<tr>
<th>Cargo</th>
<th>Bulk Density (kg/m$^3$)</th>
<th>Maximum Cargo Depth (m)</th>
<th>Tamping Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2m</td>
<td>5m</td>
</tr>
<tr>
<td>Coal</td>
<td>1000</td>
<td>20 (1.4)</td>
<td>50 (3.5)</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>40 (2.8)</td>
<td>100 (7.1)</td>
</tr>
<tr>
<td>Metal Ore</td>
<td>3000</td>
<td>60 (4.2)</td>
<td>150 (10.6)</td>
</tr>
<tr>
<td>Iron Ore Conc.</td>
<td>4000</td>
<td>80 (5.7)</td>
<td>200 (14.1)</td>
</tr>
<tr>
<td>Lead Ore Conc.</td>
<td>5000</td>
<td>100 (7.1)</td>
<td>250 (17.7)</td>
</tr>
</tbody>
</table>

(Values in parenthesis are equivalent kg.f when applied via a 30mm diameter tamping head.)

Table reproduced from Table 1.1.4.1, pp.306 of the 2012 IMSBC Code (International Maritime Organization, 2012b).

**Note:** The standard Proctor compaction method in ASTM D-698 (American Society for Testing and Materials, 2012), also known as the “Proctor C Method”, is not to be confused with the Proctor/Fagerberg test, also called “Method C” by Fagerberg and Stavang during their research (Fagerberg and Stavang, 1971). This is described in more detail in Section 5.3.4.1.7.

Eq. 3 and Table 11, from the 2012 IMSBC Code assumes that the cargoes have a uniform density from top to bottom therefore the tamping pressure may not be accurately reproducing the density of the cargoes in the holds of bulk carriers. As an example of this, Eq. 4 shows iron ore concentrate’s calculated tamping pressure for a depth of 20m. The values used are from Table 11 (i.e. 4000kg/m$^3$).

\[ Tamping \ Pressure \ (Pa) = 4000 \ (kg/m^3) \times 20 \ (m) \times 9.81 \ (m/s^2) = 785kPa \]  
(Eq. 4)

Eq. 4 illustrates the value in Table 11 of 800kPa (~785kPa) is assuming a uniform density of 4000kg/m$^3$ through the total height of the cargo. In reality a well graded material, such as IOF, will increase in density, from the top to the bottom of the material. This is caused by the increasing pressure, on the material below, from the material above.

One of the main contributing factors, to the resulting TML value, is the density that a sample is compacted. Based on the information obtained, the 2012 IMSBC Code (International Maritime Organization, 2012b) does not reasonably describe to what density a sample of IOF should be compacted or what tamping pressure should be used. This is true for both the Flow Table test and the Penetration test as they both utilise the same method. See Section 5.3.4.3.6 for more details on the compaction method used for the Penetration test.

5.3.4.3 **Penetration Test**

5.3.4.3.1 **Background**

The Penetration test was developed in Japan at the Research Institute of Marine Engineering for determining the TML of coal (Tanaka and Ura, 1989). It was adopted by the International Maritime Organization, between 1991 and 1998, for determining the TML of ore concentrates and coal.
5.3.4.3.2 Procedure

The Penetration test is performed by placing a sample, in four layers, into a cylindrical mould, as seen in Figure 78. The mould is either 1700cm³ or 4700cm³ in size depending on the maximum particle of the sample. For each layer, the sample is compacted with an adjustable tamper so that the sample is flat and level. It is stated by the creators of the test that regardless of the tamping pressure used, prior to vibrating, it will not affect the result because the sample is quickly consolidated by the vibrating table (Tanaka and Ura, 1989). After compaction is complete the mould is attached to a vibrating table and a Penetration bit, that weighs 5kPa for coals or 10kPa for ore concentrates, is placed on the surface of the material, as seen in Figure 79. The vibrating table is then operated at a frequency of 50-60Hz with an acceleration of 2g RMS ± 10% for 6 minutes. After 6 minutes the depth of Penetration, by the Penetration bit, is recorded.

Initially, the required amount of material is mixed in a bowl and three subsamples are taken. One subsample is used to obtain the initial moisture content and the other two for the preliminary and the main Penetration tests. The preliminary test is performed to determine the approximate moisture content at which the depth of penetration, by the penetration bits, will be greater than 50mm. During the Penetration test, the point at which the depth of Penetration is greater than 50mm is called the flow moisture point (FMP).

The preliminary test procedure involves mixing water into the material, in increments of 1% of the mass of the subsample then performing the procedure described above. When the depth of Penetration is less than 50mm, it is judged that the FMP has not been reached. If this is so, the material is removed from the mould and recombined with the initial sample and an additional increment of water is added. These steps are repeated until the depth of Penetration is greater than 50mm. The
material is then removed from the mould and the gross water content determined. This will be the gross water content of the sample above the FMP. The gross water content just below the FMP is then calculated based on the amount of water added. The average of these two values is the assumed FMP of the sample and this value is used to perform the main test.

The main test is similar to the preliminary test but is intended to be more accurate. Water is added to the remaining subsample until the moisture content just below the assumed FMP. The first main test is performed on the material at this moisture content then additional water is added in increments of no more than 0.5% of the mass of the test material, retaining the material that was tested each time in case the FMP is reached in the subsequent test. When the depth of Penetration is greater than 50mm the FMP has been reached and the gross water content is determined on this sample and the preceding sample. These two samples should be just below and just above the FMP and the difference between the two sample’s gross water contents should be no more than 0.5%. The FMP is then taken as the mean of these two values and the TML is taken as 90% of the FMP. The calculations used for the Penetration test are the same as the Flow Table test and can be seen in Section 5.3.11.2 and typical IOF TML values for this test, reported by Brazil, can be seen in Table 24 in Section 5.3.12 (International Maritime Organization, 2012a).

The sample size needed to complete a Penetration test can vary significantly depending on the mould size that is needed. 25kg of IOF are needed if the maximum particle size of the material is 10mm (1700cm$^3$ mould) or 70kg is needed if the maximum particle size of the material is 25mm (4700cm$^3$ mould). The Penetration test can be performed on materials with a maximum particle size of 25mm.

5.3.4.3.3 Estimated Test Time
According to the procedure in the 2012 IMSBC Code, the Penetration test can be completed in two days. This is if the test is performed by an experienced operator and the preliminary test’s FMP is calculated based on moisture added instead of oven drying the samples to determine the moisture contents. One day is needed to complete the preliminary test, estimate FMP and then perform the main test. The second day is needed to weigh up the samples that were dried out during the main test and then calculate the TML.

Determining the bulk density using the Proctor compaction test described in ASTM D-698 (American Society for Testing and Materials, 2012) or JIS-A1210 (Japanese Standards Association, 2009), which is needed to determine the tamping pressure used during the Penetration test, can be performed on the first day prior to the preliminary test. This is because determining the moisture content for the Proctor compaction can be avoided as it is not needed to calculate the bulk density. See Section 5.3.4.3.6 for more details on the compaction of the sample.

5.3.4.3.4 Reliability
The Penetration test uses measurements to determine whether the FMP has been reached and does not need the operator to interpret visually whether this point has been reached. The test is repeatable between operators and laboratories as long as the same procedure is used. Varying the settings on the vibrating table can cause significant differences in the results and more investigation is needed to determine if the initial compacted density, produced by the tamper, effects the resulting TML. More information regarding compaction of the sample can be seen in Section 5.3.4.3.6.
5.3.4.3.5 Application of Materials
The Penetration test was developed in Japan at the Research Institute of Marine Engineering (Tanaka and Ura, 1989) and is stated as being “applicable to coals and similar materials” (T Ura, 1992). When the test was incorporated into the 2012 IMSBC Code (International Maritime Organization, 2012b), there were no studies completed to see if it is reliable for determining the TML of IOF.

5.3.4.3.6 Compaction of the Sample
The Penetration test refers to the compaction effort performed in the Flow Table test. The 2012 IMSBC Code states to “tamp to a pressure denoted in 1.1.4.1 (Flow table preparation procedure) for mineral concentrates or to 40 kPa for coals, and apply the pressure evenly over the whole surface area of the material until a uniformly flat surface is obtained” (International Maritime Organization, 2012b). The 2012 IMSBC Code does not state the number of tamping actions required.

Furthermore, during initial studies, it was stated that “the tamping does not affect the result of the Penetration test, because the sample is quickly consolidated by vibration regardless of the pressure of tamping conducted prior to the test. In order to get a smooth surface, 0.42 kg.f/cm² in tamping pressure is recommendable.” (Tanaka and Ura, 1989). For the testing of IOF, further studies are required to determine if the density achieved by vibration in the Penetration test is representative of that in a bulk carrier’s hold and if the tamping pressure affects the resulting TML.

5.3.5 Materials
The typical properties of IOF that were tested during this study can be seen in Table 12 to Table 14. The IOF that were tested were obtained from various locations around Australia.

Table 12 – Typical properties of IOF tested during this study

<table>
<thead>
<tr>
<th>Property</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Moisture Content (%)</td>
<td>3.42</td>
<td>10.30</td>
<td>7.86</td>
<td>AS1289.2.1.1</td>
</tr>
<tr>
<td>Particle Density (t/m³)</td>
<td>3.78</td>
<td>4.91</td>
<td>4.27</td>
<td>AS1289.3.5.1</td>
</tr>
</tbody>
</table>

Table 13 – Typical properties of a sample of IOF that were tested during this study

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Dry Density (t/m³)</td>
<td>2.12</td>
</tr>
<tr>
<td>Maximum Dry Density (t/m³)</td>
<td>3.08</td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>18.00</td>
</tr>
<tr>
<td>Plastic Limit (%)</td>
<td>16.00</td>
</tr>
<tr>
<td>Plasticity Index (%)</td>
<td>2.00</td>
</tr>
<tr>
<td>Standard Proctor Compaction - Optimum Moisture Content (%)</td>
<td>12.00</td>
</tr>
<tr>
<td>Standard Proctor Compaction - Maximum Dry Density (t/m³)</td>
<td>2.73</td>
</tr>
</tbody>
</table>

Table 14 – Typical particle size distribution data, obtained using AS1289.3.6.1, of IOF tested during this study

<table>
<thead>
<tr>
<th>Property</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Clay (&lt;75µm)</td>
<td>2.60</td>
<td>6.50</td>
<td>4.74</td>
</tr>
<tr>
<td>% Silt (2-60µm)</td>
<td>4.70</td>
<td>19.10</td>
<td>14.33</td>
</tr>
<tr>
<td>% Sand (0.06-2mm)</td>
<td>42.00</td>
<td>58.70</td>
<td>48.36</td>
</tr>
<tr>
<td>% Gravel (2-60mm)</td>
<td>21.10</td>
<td>45.50</td>
<td>33.30</td>
</tr>
<tr>
<td>Nominal Particle Size (mm)</td>
<td>0.075</td>
<td>2.36</td>
<td>2.36</td>
</tr>
<tr>
<td>Maximum Particle Size (mm)</td>
<td>4.75</td>
<td>13.20</td>
<td>9.50</td>
</tr>
<tr>
<td>Coefficient of Uniformity (C_u)</td>
<td>24.86</td>
<td>273.16</td>
<td>119.30</td>
</tr>
<tr>
<td>Coefficient of Curvature (C_c)</td>
<td>0.65</td>
<td>7.44</td>
<td>1.72</td>
</tr>
</tbody>
</table>
Chapter 5 - Determination of Transportable Moisture Limit of Iron Ore Fines for the Prevention of Liquefaction in Bulk Carriers

Note 1: The boundaries of the IOF particle size distributions tested during this study can be seen in Figure 80.

Note 2: All properties listed in Table 12 to Table 14 were performed in accordance with AS1289.0-2000 – Method of testing soils for engineering purposes (Standards Australia, 2000).

Note 3: Not all of the samples used to obtain the typical physical properties of IOF provided in Table 12 to Table 14 were tested during this study.

From the IOF tested, a significant variation in the physical properties was noticed depending on the location from where it was extracted. One main property of IOF which determine the moisture content at which it may become potentially liquefiable is the particle size distribution. Some samples of IOF contain significant amounts of large particles which, according to Ishihara (Ishihara, 1985), reduce the potential to liquefy. Shown in Figure 80 are the boundaries of potentially liquefiable materials when compared with their particle size distributions. By overlaying the particle size distributions of the IOF tested during this study, it shows that some samples tested may have more of a potential to liquefy than others.

Figure 80 – Particle size distribution boundaries of liquefiable materials, determined by Ishihara (Ishihara, 1985), and boundaries of IOF determined during this study

During this study the samples of IOF tested were not modified to reduce the particle size to be in accordance with the maximum particle sizes listed for the TML test procedures in the 2012 IMSBC Code (International Maritime Organization, 2012b). Reducing the particle size will change the total particle surface area and therefore the moisture-holding abilities of the sample will increase.

The 2012 IMSBC Code states the maximum particle size permissible for each of the three test methods (International Maritime Organization, 2012b). The Penetration test can be performed on materials with a maximum particle size of 25mm. As part of this study, the particle size distributions of the samples of IOF were tested and the maximum particle size overall was found to be 13.2mm, therefore less than the 2012 IMSBC Code’s limitation of 25mm.
The 2012 IMSBC Code states that the Proctor/Fagerberg test is only suitable for samples with a maximum particle size of 5mm. All the samples of IOF tested during this study contain particles greater than 5mm with the average being 15% retained on the 4.75mm (No. 4) sieve. This said, the results from testing IOF, with 15-20% greater than 4.75mm, using the Proctor/Fagerberg test method, correlates with the results from the Flow Table and Penetration test methods, as seen in Figure 82, Figure 88 and Figure 89, therefore the small amount of large particles do not seem to affect the results of the test. Further investigation into the effects of particle size on the Proctor/Fagerberg test is needed when testing coarse materials, such as IOF.

The 2012 IMSBC Code states that the Flow Table test is applicable for materials with a maximum particle size of 1mm, but may be applicable for materials with a maximum particle size of 7mm. It also states that it is not suitable for materials with high clay content. From the samples of IOF tested the average material retained on the 6.7mm (0.265") sieve was approximately 7%. This small amount of coarse material does not seem to affect the matrix of the finer particles in the samples during testing on the Flow Table. The problem with the coarser material is that it interferes with the operator’s interpretation of the FMP.

There is a limitation to the TML testing of IOF using the Flow Table and Proctor/Fagerberg test methods based on the particle size of the material and the limiting size stated in the 2012 IMSBC Code (International Maritime Organization, 2012b). Further studies are required to determine the effect of particle size while performing the Flow Table and Proctor/Fagerberg tests.

5.3.6 Experimental Results from this Study
During this research, we performed testing to determine the TML of IOF using the Proctor/Fagerberg and Flow Table test methods. The Penetration test was not able to be performed due to not having the available apparatus. For this reason, we have included results for the Penetration test in Section 5.3.7 where supporting results are compared with the experimental results from this study.

5.3.6.1 Proctor/Fagerberg and Flow Table TML Results
When comparing the TML values, of IOF, obtained using the Proctor/Fagerberg and Flow Table test methods we can clearly see a variation in the results. The Proctor/Fagerberg test produces a higher TML value when compared with the Flow Table TML. Figure 81 and Table 15 show the Proctor/Fagerberg TML value can be up to 16% greater than the Flow Table TML. Another representation of the data in Table 15 can be seen in Figure 82. The results correlate well ($R^2 = 0.97$), but vary from the equality line significantly ($Y_{FT} = 0.71X_{PF} + 1.98$).
Figure 81 – Comparison of IOF TML values using the Proctor/Fagerberg and Flow Table tests

Table 15 – Comparison of IOF TML values using the Proctor/Fagerberg and Flow Table tests

<table>
<thead>
<tr>
<th>Sample</th>
<th>Proctor/Fagerberg TML (GW%)</th>
<th>Flow Table TML (35kg.f) (GW%)</th>
<th>Difference between PF and FT TML Values (GW%)</th>
<th>Percent Difference between PF and FT TML Values (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.7</td>
<td>9.7</td>
<td>1.0</td>
<td>10.3</td>
</tr>
<tr>
<td>2</td>
<td>11.3</td>
<td>10.1</td>
<td>1.2</td>
<td>11.9</td>
</tr>
<tr>
<td>3</td>
<td>11.1</td>
<td>10.0</td>
<td>1.1</td>
<td>11.0</td>
</tr>
<tr>
<td>4</td>
<td>11.6</td>
<td>10.2</td>
<td>1.4</td>
<td>13.7</td>
</tr>
<tr>
<td>5</td>
<td>11.8</td>
<td>10.4</td>
<td>1.4</td>
<td>13.5</td>
</tr>
<tr>
<td>6</td>
<td>11.8</td>
<td>10.4</td>
<td>1.4</td>
<td>13.5</td>
</tr>
<tr>
<td>7</td>
<td>12.3</td>
<td>10.6</td>
<td>1.7</td>
<td>16.0</td>
</tr>
<tr>
<td>8</td>
<td>11.0</td>
<td>9.9</td>
<td>1.1</td>
<td>11.1</td>
</tr>
<tr>
<td>9</td>
<td>10.8</td>
<td>9.9</td>
<td>0.9</td>
<td>9.1</td>
</tr>
<tr>
<td>10</td>
<td>9.3</td>
<td>8.4</td>
<td>0.9</td>
<td>10.7</td>
</tr>
<tr>
<td>11</td>
<td>13.1</td>
<td>11.3</td>
<td>1.8</td>
<td>15.9</td>
</tr>
<tr>
<td>Average</td>
<td>11.4</td>
<td>10.1</td>
<td>1.3</td>
<td>12.4</td>
</tr>
</tbody>
</table>
Based on the data obtained during this study the Proctor/Fagerberg test will produce a higher TML value than the Flow Table test when testing samples of IOF.

5.3.6.2 Proctor/Fagerberg and Flow Table Compaction Comparisons

The IMSBC Code states, in the Proctor/Fagerberg test, that “the critical moisture content is indicated by the intersection of the compaction curve and the line $S = 70\%$ degree of saturation. The TML is the critical moisture content” (International Maritime Organization, 2012b). Fagerberg and Stavang note that during compaction “it is a characteristic of all concentrates investigated that the voids are then filled by water to 70-75\% by volume” (Fagerberg and Stavang, 1971). Figure 83 show a typical Proctor/Fagerberg compaction curve of a sample of IOF. The characteristics of IOF investigated were that the voids are filled by water to 90-95\% by volume and not 70-75\%. This characteristic of IOF can be attributed to the material being well graded when compared with the materials tested by Fagerberg and Stavang, seen in Figure 72 (section 5.3.4.1.7), and therefore can reach higher degrees of saturation.

Figure 83 also show a compaction curve produced by the Flow Table test. The flow Table test was performed at a tamping pressure to replicate the density produced by the Proctor/Fagerberg test (10kg.f). When comparing the Flow Table TML and the Proctor/Fagerberg FMP, where the FMP is the point at which the material on the Flow Table begins to show plastic deformation, the Flow Table FMP is significantly higher, as seen in Figure 83 and Table 16. The comparison between the Flow Table FMP and the Proctor/Fagerberg TML is being used to eliminate the Flow Table safety factor, where 90\% of the Flow Table FMP is the Flow Table TML. This is described in more detail in Section 5.3.6.3.
To determine the actual tamping pressure needed to perform the Flow Table test, the maximum bulk density was determined on the sample of IOF and was found to be 3075kg/m³ (section 5.3.5, Table 13). The tamping pressure, seen in Eq. 5, was obtained using the equation given in the 2012 IMSBC Code (paragraph 1.1.4.1.2, pp. 305) (International Maritime Organization, 2012b).

\[
Tamping\ Pressure\ (Pa) = 3075\ (kg/m^3) \times 20\ (m) \times 9.81\ (m/s^2) = 603kPa
\]  

(Eq. 5)

According to table 1.1.4.1 of the 2012 IMSBC Code, 603kPa is approximately 42kg.f when applied to a sample in the Flow Table test through a tamper with a 30mm diameter head (International Maritime Organization, 2012b). To compare the TML using the calculated tamping effort, the same sample used in Figure 83 was again compacted except this time using 35kg.f. 35kg.f was used instead of 42kg.f due to this being the maximum tamping effort the tamper rod we had could apply. Figure 84 and Table 17 show the difference in densities between the calculated tamping effort (~35kg.f) and the tamping effort equivalent to the Proctor/Fagerberg test (10kg.f).
Note 1: One point compacted at 30kg.f and 20kg.f is also shown.

Note 2: The different shaped compaction curves, created by the Proctor/Fagerberg and Flow Table tests, are attributed to the different types of compaction energies being applied (i.e. Flow Table using a tamping rod and Proctor/Fagerberg using a compaction hammer).

Table 17 – IOF Proctor/Fagerberg TML value compared with the Flow Table FMP values at 35kg.f and 10kg.f

| Proctor/Fagerberg TML | 11.9% |
| Flow Table (10kg.f) FMP | 12.8% |
| Flow Table (35kg.f) FMP | 11.8% |

From the 1971 paper written by Fagerberg and Stavang (Fagerberg and Stavang, 1971), it has been determined that the Proctor/Fagerberg test was initially designed for determining the TML of ore concentrates and not for use with IOF. The Proctor/Fagerberg test, as stated in the 2012 IMSBC Code (International Maritime Organization, 2012b), does not seem to portray the methodology behind the procedure created by Fagerberg and Stavang. In their paper, it does not state that at 70% saturation the moisture content is equal to the TML for all materials. They state that at 70-75% saturation the ore concentrates that they tested reached minimum void ratio or maximum density and therefore this is the point at which they will be most likely to liquefy (Fagerberg and Stavang, 1971). IOF reach minimum void ratio or maximum density at approximately 90-95% saturation. If comparing to the Flow Table test, a sample of IOF shows no plastic deformation at 70% saturation as seen by the Flow Table FMP results see in Figure 84. If the 2012 IMSBC Code Flow Table procedure is followed, at 80-85% saturation the samples of IOF start to show plastic deformation. Further studies are required to determine what combination of degree of saturation and density govern IOF’s potential to liquefy.
5.3.6.3 Proctor/Fagerberg and Flow Table Safety Factors

When the FMP is found using the Flow Table and Penetration test procedures a safety factor is used to calculate the TML. The safety factor is incorporated into the procedures to compensate for operator error. The Proctor/Fagerberg test does not include a safety factor in the calculations, instead a slightly heavier hammer was chosen to incorporate a safety factor into the test (Fagerberg and Stavang, 1971), see Section 5.3.4.1.7.

Figure 85 and Table 18 is the combined data from Table 15 and Table 19, which are the Proctor/Fagerberg TML and Flow Table TML values from multiple tests on IOF. The difference is the Flow Table FMP has been used instead of the TML. The Flow Table FMP is the TML with the 10% safety factor removed. Figure 85 and Table 18 show that the Proctor/Fagerberg TML value is similar when compared with the Flow Table FMP. The Proctor/Fagerberg TML value is now only on average 3% greater than the Flow Table TML.

As before, another representation of the data in Table 18 can be seen in Figure 86. The correlation between the two test methods values is the same ($R^2 = 0.92$), but now they don’t vary from the equality line as significantly as Figure 82 and Figure 89 ($Y_{FT} = X_{PF} + 0.13$).

![Graph showing comparison of IOF Proctor/Fagerberg TML value and Flow Table FMP value](image-url)

*Figure 85 – Comparison of IOF Proctor/Fagerberg TML value and Flow Table FMP value. Data from Brazil is integrated with the results from this study (International Maritime Organization, 2012a)*

<table>
<thead>
<tr>
<th>Sample</th>
<th>Proctor/Fagerberg TML (GW%)</th>
<th>Flow Table FMP (35kg.f) (GW%)</th>
<th>Difference between PF TML and FT FMP (GW%)</th>
<th>Percent Difference between PF TML and FT FMP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.7</td>
<td>10.8</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>11.3</td>
<td>11.2</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>11.1</td>
<td>11.1</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>11.6</td>
<td>11.3</td>
<td>0.3</td>
<td>2.4</td>
</tr>
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<td>5</td>
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<td>2.1</td>
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<tr>
<td>6</td>
<td>11.8</td>
<td>11.6</td>
<td>0.2</td>
<td>2.1</td>
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<td>7</td>
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<td>8</td>
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<td>0.0</td>
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<tr>
<td>9</td>
<td>10.8</td>
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<td>10</td>
<td>9.3</td>
<td>9.3</td>
<td>0.0</td>
<td>0.4</td>
</tr>
</tbody>
</table>
This leads to the conclusion that when testing IOF, the Proctor/Fagerberg TML value is more closely related to the Flow Table FMP than the Flow Table TML, therefore it could be considered that the use of the Proctor/Fagerberg test on IOF excludes the safety factor. In other words, the TML values from the Proctor/Fagerberg and Flow Table test are not equivalent values.

5.3.7 Supporting Results
This study’s results can be supported by the results produced by Brazil for the International Maritime Organization (International Maritime Organization, 2012a). Figure 87 and Table 19 shows the results produced by performing tests on IOF using all three test methods stated in the 2012 IMSBC Code.

The results show that the three tests stated in the 2012 IMSBC Code produce different TML values. The Penetration test produces the lowest TML value and the Proctor/Fagerberg produces the highest. Table 20 and Table 21 show the Proctor/Fagerberg TML value can be up to 27% greater than the Penetration TML and the Proctor/Fagerberg TML value can be up to 8% greater than the Flow Table TML.
Figure 87 – Comparison by Brazil of IOF TML values using all three test methods (International Maritime Organization, 2012a)

Table 19 – Comparison by Brazil of IOF TML values using all three test methods (International Maritime Organization, 2012a)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Proctor/Fagerberg TML (GW%)</th>
<th>Flow Table TML (GW%)</th>
<th>Penetration TML (GW%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.6</td>
<td>7.8</td>
<td>6.4</td>
</tr>
<tr>
<td>2</td>
<td>8.7</td>
<td>7.5</td>
<td>6.2</td>
</tr>
<tr>
<td>3</td>
<td>8.4</td>
<td>7.7</td>
<td>6.2</td>
</tr>
<tr>
<td>4</td>
<td>12.9</td>
<td>12.2</td>
<td>11.5</td>
</tr>
<tr>
<td>5</td>
<td>12.3</td>
<td>12.3</td>
<td>10.9</td>
</tr>
<tr>
<td>6</td>
<td>8.3</td>
<td>7.5</td>
<td>6.9</td>
</tr>
<tr>
<td>7</td>
<td>8.3</td>
<td>8.1</td>
<td>6.7</td>
</tr>
<tr>
<td>8</td>
<td>10.8</td>
<td>10.6</td>
<td>9.5</td>
</tr>
<tr>
<td>9</td>
<td>10.6</td>
<td>10.5</td>
<td>9.4</td>
</tr>
<tr>
<td>10</td>
<td>8.5</td>
<td>7.7</td>
<td>6.4</td>
</tr>
<tr>
<td>11</td>
<td>8.0</td>
<td>7.4</td>
<td>5.9</td>
</tr>
<tr>
<td>12</td>
<td>8.7</td>
<td>7.4</td>
<td>6.1</td>
</tr>
<tr>
<td>13</td>
<td>8.2</td>
<td>7.7</td>
<td>6.1</td>
</tr>
</tbody>
</table>

Note: The set tamper force is unknown for the Flow Table and Penetration tests as it is not stated in the report by Brazil (International Maritime Organization, 2012a).

Another representation of the data in Table 19 can be seen in Figure 88 and Table 20 and also Figure 89 and Table 21. The correlation between the Proctor/Fagerberg and Penetration tests are acceptable ($R^2 = 0.97$), similar to the comparison between the Proctor/Fagerberg and Flow Table tests, as seen in Figure 82 (section 5.3.6.1), but the results vary from the equality line ($Y_{PT} = 1.18X_{PF} - 3.59$).
Chapter 5 - Determination of Transportable Moisture Limit of Iron Ore Fines for the Prevention of Liquefaction in Bulk Carriers

Michael Colin Munro – July 2017

Figure 88 – Comparison by Brazil of IOF TML values using the Proctor/Fagerberg and Penetration tests (International Maritime Organization, 2012a)

Table 20 – Comparison by Brazil of IOF TML values using the Proctor/Fagerberg and Penetration tests (International Maritime Organization, 2012a)

<table>
<thead>
<tr>
<th>Sample</th>
<th>TML Proctor/Fagerberg (GW%)</th>
<th>Penetration TML (GW%)</th>
<th>Difference between PF and PT TML Values (GW%)</th>
<th>Percent Difference between PF and PT TML Values (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.6</td>
<td>6.4</td>
<td>2.2</td>
<td>34.4</td>
</tr>
<tr>
<td>2</td>
<td>8.7</td>
<td>6.2</td>
<td>2.5</td>
<td>40.3</td>
</tr>
<tr>
<td>3</td>
<td>8.4</td>
<td>6.2</td>
<td>2.2</td>
<td>35.5</td>
</tr>
<tr>
<td>4</td>
<td>12.9</td>
<td>11.5</td>
<td>1.4</td>
<td>12.2</td>
</tr>
<tr>
<td>5</td>
<td>12.3</td>
<td>10.9</td>
<td>1.4</td>
<td>12.8</td>
</tr>
<tr>
<td>6</td>
<td>8.3</td>
<td>6.9</td>
<td>1.4</td>
<td>20.3</td>
</tr>
<tr>
<td>7</td>
<td>8.3</td>
<td>6.7</td>
<td>1.6</td>
<td>23.9</td>
</tr>
<tr>
<td>8</td>
<td>10.8</td>
<td>9.5</td>
<td>1.3</td>
<td>13.7</td>
</tr>
<tr>
<td>9</td>
<td>10.6</td>
<td>9.4</td>
<td>1.2</td>
<td>12.8</td>
</tr>
<tr>
<td>10</td>
<td>8.5</td>
<td>6.4</td>
<td>2.1</td>
<td>32.8</td>
</tr>
<tr>
<td>11</td>
<td>8.0</td>
<td>5.9</td>
<td>2.1</td>
<td>35.6</td>
</tr>
<tr>
<td>12</td>
<td>8.7</td>
<td>6.1</td>
<td>2.6</td>
<td>42.6</td>
</tr>
<tr>
<td>13</td>
<td>8.2</td>
<td>6.1</td>
<td>2.1</td>
<td>34.4</td>
</tr>
<tr>
<td>Average</td>
<td>9.4</td>
<td>7.6</td>
<td>1.9</td>
<td>27.0</td>
</tr>
</tbody>
</table>

Similar to the comparison between the Proctor/Fagerberg and Flow Table tests performed for this study, as seen in Figure 82, Section 5.3.6.1, the results from the Brazilian testing show the same difference in results when comparing the Proctor/Fagerberg and Flow Table tests, as seen in Figure 89 and Table 21 (International Maritime Organization, 2012a).
Based on the supporting information and data obtained, depending on which test is chosen to determine the TML of IOF, the value will vary. This was proved to be true in both this study and the study produced by Brazil for the International Maritime Organization (International Maritime Organization, 2012a). Further studies are required to determine which method gives the most reliable result when determining the TML of IOF.

5.3.8 Discussion and Recommendations

The preparation procedures, explained in Section 5.3.4, seem unsuitable for testing materials such as IOF. One concern is with the way in which water is added to the material during preparation. Throughout the three test procedures it is necessary to add water so that the samples can be tested at different moisture contents. The maximum time that the procedures set aside for curing is five minutes. From the samples of IOF tested for this study, they contained an average of 20% fine material.
(< 75µm). This amount of fine particles within a sample requires additional time to cure when compared with a uniformly graded ore concentrates, which commonly have particles 100µm to 1mm in size. When performing the Flow Table test on samples that have not been cured long enough, the sample will break apart at the joins between the compacted layers. Uneven moisture distribution reduces the accuracy and repeatability of the tests, especially the Flow Table test where operator interpretation is essential. Additionally, at low moisture contents, constant mixing of IOF may cause segregation to occur and therefore also reduce the accuracy and repeatability of the tests.

It is recommended that the preparation procedures are modified to state that when testing is performed on fine grained materials that the sample must be left to soak for a minimum of 12 hours. The preparation of samples in polythene bags and adding increments of water to each bag, will eliminate the need to change the sample’s moisture content multiple times during a test and will also eliminate the need for constant mixing. For this study, a modified preparation procedure similar to this was used.

The Penetration test states that during the preliminary test, once the FMP has been approximately determined, the material is removed from the mould, mixed back into the subsample and moisture content determined. The entire sample that was inside the mould, when the test was performed, should be used to determine the moisture content and not mixed back into the original sample prior to determining the moisture content. This is because the material in the mould and the original sample will have slightly different moisture contents by the time the test is completed.

The procedure to determine the TML, according to the Proctor/Fagerberg test, begins by drying out the material, at approximately 100°C. This step seems unnecessary as the moisture content of the sample, when received, is likely to be drier than the TML. Drying then adding moisture back into the sample will also produce an unevenly distributed moisture content, especially if there is not enough time to allow the sample to cure before compaction of the sample.

There are numerous times when the procedure uses uncommon techniques to perform common tasks that are widely used in soil mechanics and testing. A review of these procedures is needed to determine an appropriate technique for the testing of IOF and other similar materials if they are to be performed at geotechnical and soil laboratories. Additionally, the terminology used in the 2012 IMSBC Code is at times confusing and depending on the operator’s background it can determine how the code will be interpreted. Emphasis must be made regarding that the TML should be reported in gross water content not moisture content and the terminology should be standardized across all three test procedures. See Section 5.3.10 for more information on the terminology used in the 2012 IMSBC Code (International Maritime Organization, 2012b).

Currently, the TML testing being performed at laboratories around Australia seem to favour the Proctor/Fagerberg test. This can be attributed to the perception that the procedure is uncomplicated and can be easily performed. This can be misleading because the determination of the particle density is rarely taken into account. The particle density of the IOF tested during this study varied from 3.8 - 4.8t/m³ unlike the particle density of ore concentrates that can be predictable and comparatively constant, which means determining the specific gravity of IOF becomes a critical parameter.

Determining the TML by the use of the Flow Table test has its advantages and disadvantages. The main disadvantage is that the operator must be well trained to identify when the material has reached the
FMP as it can sometimes be difficult when the martial has significant amounts of coarse particles, such as in IOF. The 2012 IMSBC Code’s description of plastic deformation is vague and does not give the operator any in-depth detail of what to be monitoring to detect plastic deformation of IOF. An advantage of the Flow Table test is being able to determine if a material is unable to show plastic deformation as this could indicate that the material is non-liquefiable. Additionally, the Flow Table test does not involve having to perform any additional testing such as particle density.

To determine the pressure used for compaction of the sample in the Flow Table and Penetration tests, either the equation or table in the 2012 IMSBC Code is used, seen is Section 5.3.4.2.6. This method seems to assume a uniform density from the top to the bottom of a cargo. Also, using the bulk density in the equation for the tamping pressure does not seem to represent the actual density at the base of the vessel, where liquefaction is most likely to occur.

On the other hand, the Proctor/Fagerberg test uses a fixed energy input from the compaction hammer. This energy is based off in situ density tests of ore concentrates, to a depth of 8m, and needs to be reviewed if it is to be used for the testing of IOF. This is due to the difference in densities of the materials and the depth of the cargoes. Additionally, when reviewing the theory behind selecting the TML from 70% saturation, it seems that it was based off studies completed in 1971 using ore concentrates and not IOF.

The maximum particle size of the sample of IOF should determine which of the three tests are to be used. The particle size distribution of IOF varies significantly from place to place, which means some samples may be able to be tested using one method where another may not. Further studies need to be completed to determine the limitations of the three test methods regarding the maximum particle size and if performing the tests on samples with particles exceeding the maximum produces a different TML.

5.3.9 Conclusion
A thorough literature review, along with laboratory research, was carried out to compare the TML results from the three leading test methods to determine whether they produce reliable results when testing Iron Ore Fines (IOF).

This study has shown that the results produced by the Flow Table, Proctor/Fagerberg and Penetration test methods, stated in the 2012 International Maritime Solid Bulk Cargoes Code, vary when determining the TML of IOF. If performing the Proctor/Fagerberg test on IOF the TML can be as much as 3% greater than if the Penetration test was used. That is a 43% increase from the Penetration test to the Proctor/Fagerberg test.

It has also been found that the original materials intended for testing have significant differences in their physical properties when compared with IOF and currently no thorough study has been completed to determine which of the three test methods, if any, produce an accurate result when testing IOF.

After determining the particle size distributions of samples of IOF it was found that some samples may have more potential to liquefy than others. The physical properties that could make IOF potentially liquefiable must be studied in more detail to determine the limitations of the test procedures.
Although the three test methods produce different results, the Proctor/Fagerberg and the Flow Table tests have the potential to be modified to create a test reliable when testing IOF. Further studies are required to determine the liquefaction potential of IOF.

During this study, it was found that following the methods recommended by the 2012 International Maritime Solid Bulk Cargoes Code are not adequate for the testing IOF. An acceptable, properly instrumented physical model is needed to examine, in controlled laboratory conditions, which method is more accurate for determining the TML of IOF. Research on the physical properties of IOF, that determine the liquefaction potential, also needs to be studied and compared with the results of the physical model and the three test methods.
5.3.10 Appendix A – Terminology
The terminology used in the 2012 IMSBC Code (International Maritime Organization, 2012b), when referring to the three test methods, can be at times misleading depending on the background of the operator. Due to this, people familiar with the common terms used in soil mechanics and geotechnical engineering, and not standard testing of metallurgy or materials such as IOF, can be misled to make critical errors in calculations and reporting the results. A common guide used by metallurgists where gross water content is determined can be seen in ISO 3087 - Determination of Moisture Content of a Lot (International Standards Organization, 1998).

In soil mechanics and geotechnical engineering, the term ‘moisture content’ refers to the ratio of the mass of moisture to the mass of the solid material, as seen in Eq. 6.

\[
\text{Moisture Content (MC\%) = \frac{\text{Mass of Water}}{\text{Mass of Solids}} \times 100} \quad (\text{Eq. 6})
\]

In the Flow Table and Penetration test procedures the IMSBC Code (2012, app. 2, para. 1.1.4.1.1-2) refers to ‘moisture content’ as the percent of moisture when compared to the total sample, which is the total mass of the sample including moisture (International Maritime Organization, 2012b). In soil mechanics and geotechnical engineering this is referred to as the ‘gross water content’, as seen in Eq. 7.

\[
\text{Gross Water Content (GW\%) = \frac{\text{Mass of Water}}{\text{Total Mass}} \times 100} \quad (\text{Eq. 7})
\]

Other terms that were found to cause confusion in the 2012 IMSBC Code are terms such as ‘dry bulk density’, which should read ‘dry density’, as dry density and bulk density are different physical properties. Also, ‘density of solid material’ should read ‘particle density’ or ‘specific gravity’, in the Flow Table test, and ‘top size’ should read ‘maximum particle size’, in the Penetration test. Furthermore, some terms have different definitions when looking at the three tests independently, such as the following:

“Flow Moisture Point” (FMP):

In the Flow Table test the FMP is the gross water content at which the material is verging on plastic deformation. In the Penetration test it is the gross water content at which the depth of Penetration from the bit is 50mm. In the Proctor/Fagerberg test it is inferred as the ‘Critical Moisture Content’ or ‘TML’.

“Critical Moisture Content” (CMC):

In the Flow Table and Penetration test there is no reference to the CMC but is assumed to be equal to the ‘Flow Moisture Point’. In the Proctor/Fagerberg test it is the gross water content at which the compaction curve crosses the 70% saturation line in the graphical representation and equal also equal to the ‘TML’.

“Transportable Moisture Limit” (TML):

In the Flow Table and Penetration tests the TML is 90% of the ‘Flow Moisture Point’. In the Proctor/Fagerberg test it is also referred to as the ‘Critical Moisture Content’ and is equal to the gross water content at which the compaction curve crosses the 70% saturation line, in the graphical
representation. The TML is the maximum gross water content that bulk cargoes may contain while being transported in bulk carriers without being at risk of liquefying.

“Flow State”:

In the Flow Table test it is referred to when the material is showing plastic deformation. In the Penetration test it is referred to when the material can be penetrated by the bit to a depth greater than 50mm. This is when the material has a gross water content greater than the FMP.
5.3.11 Appendix B – Calculations

5.3.11.1 Proctor/Fagerberg Test Calculations

Using the equations given in the 2012 IMSBC Code (International Maritime Organization, 2012b) can produce improper results. The moisture content and bulk density determinations should be calculated separately unless the sample is dried inside the mould, which is impractical. This is because when the material is removed from the mould there is always going to be some material left behind meaning that the dry mass removed is not the dry mass in the mould. Furthermore, the volume of the mould is never exactly 1000cm$^3$. The volume of the mould should be measured accurately prior to testing and used in place of 1000cm$^3$. During this study Eq. 8 to Eq. 14 were used to determine the TML of IOF when performing the Proctor/Fagerberg test and to create the final graphical representations of the compaction curves:

The bulk density ($\rho$), in t/m$^3$, of each compacted specimen is:

$$\rho = \frac{m_2 - m_1}{V}$$  \hspace{1cm} (Eq. 8)

Where

$m_1$ is mass of mould and base plate (in g); and

$m_2$ is mass of mould, base plate and compacted soil (in g); and

$V$ is internal volume of the mould (in cm$^3$); and

$\rho$ is the bulk density of each compacted specimen (in t/m$^3$).

The dry density ($\rho_d$), in t/m$^3$, of each compacted specimen is:

$$\rho_d = \frac{100\rho}{100 + w}$$  \hspace{1cm} (Eq. 9)

Where

$w$ is the moisture content of the soil (in %); and

$\rho$ is the bulk density of each compacted specimen (in t/m$^3$); and

$\rho_d$ is the dry density of each compacted specimen (in t/m$^3$).

The void ratio (e) of each compacted specimen is:

$$e = \frac{\rho_{st} - \rho_d}{\rho_d}$$  \hspace{1cm} (Eq. 10)

Where

$\rho_{st}$ is the particle density of the total soil sample (in t/m$^3$); and

$\rho_d$ is the dry density of each compacted specimen (in t/m$^3$); and
The gross water content \( w_{\text{gross}} \), in %, of each compacted specimen is:

\[
w_{\text{gross}} = 100 - \frac{100}{1 + \frac{w}{100}} \cdot \frac{\text{Mass of Water}}{\text{Total Mass}} \times 100 \tag{Eq. 11}
\]

Where \( w \) is the moisture content of the soil (in %); and \( w_{\text{gross}} \) is the gross water content (in %).

The void ratio \( e \) at different gross water contents \( w_{\text{gross}} \), in %, for corresponding degrees of saturation \( S \), in %, is:

\[
e = \frac{\rho_{\text{st}} x \left( \frac{w_{\text{gross}} x 100}{100 - w_{\text{gross}}} \right)}{S} \tag{Eq. 12}
\]

Where \( \rho_{\text{st}} \) is the particle density of the total soil sample (in t/m\(^3\)); and \( S \) is the degree of saturation (in %); and \( w_{\text{gross}} \) is the gross water content (in %); and \( e \) is the void ratio of each compacted specimen.

### 5.3.11.2 Flow Table and Penetration Test Calculations

Equations given in the 2012 IMSBC Code (International Maritime Organization, 2012b) are those described in ISO 589– Hard Coal – Determination of Total Moisture (International Standards Organization, 2008). These are used when performing the Flow Table and Penetration tests.

Gross water content, in percent, of material “as received” is:

\[
w_{\text{gross}} = \frac{m_3 - m_4}{m_3} \times 100 \tag{Eq. 13}
\]

Where \( m_3 \) is mass of subsample “as received” and \( m_4 \) is mass of subsample “as received”, after drying.

The FMP, in percent, of the material is:
\[ FMP = \frac{(m_5 - m_6 + m_7 - m_8)}{m_5 - m_7} \times 100 \]  

(Eq. 14)

Where  
\( m_5 \) is mass of sample just above flow state  
\( m_6 \) is mass of sample just above flow state, after drying  
\( m_7 \) is mass of sample just below flow state,  
\( m_8 \) is mass of sample just below flow state, after drying

The TML of the material is 90% of the FMP.
5.3.12 Appendix C – Typical TML Results

Additional TML values and other final test properties of IOF obtained from further testing during this study and the results reported by Brazil (International Maritime Organization, 2012a) are shown in Table 22 to Table 24. These were obtained by using the three test methods stated in the 2012 IMSBC Code (International Maritime Organization, 2012b).

Table 22 – Typical IOF Proctor/Fagerberg TML test results from this study

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>TML (GW%)</td>
<td>8.00</td>
<td>16.80</td>
<td>11.03</td>
</tr>
<tr>
<td>Maximum Dry Density from Proctor/Fagerberg (t/m³)</td>
<td>2.05</td>
<td>2.95</td>
<td>2.55</td>
</tr>
<tr>
<td>Void Ratio at Maximum Dry Density</td>
<td>0.50</td>
<td>1.06</td>
<td>0.67</td>
</tr>
<tr>
<td>Dry Density from Proctor/Fagerberg at 70% Saturation (t/m³)</td>
<td>1.91</td>
<td>2.80</td>
<td>2.40</td>
</tr>
<tr>
<td>Void Ratio at 70% Saturation</td>
<td>0.57</td>
<td>1.24</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Table 23 – Typical IOF Flow Table TML test results from this study

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Moisture Point (GW%)</td>
<td>8.22</td>
<td>13.67</td>
<td>10.48</td>
</tr>
<tr>
<td>TML (GW%)</td>
<td>7.40</td>
<td>12.30</td>
<td>9.43</td>
</tr>
<tr>
<td>Maximum Dry Density from Flow Table using 35kg.f (t/m³)</td>
<td>2.48</td>
<td>2.84</td>
<td>2.64</td>
</tr>
</tbody>
</table>

Table 24 – Typical IOF Penetration TML test results from Brazil (International Maritime Organization, 2012a)

<table>
<thead>
<tr>
<th></th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>TML (GW%)</td>
<td>5.90</td>
<td>11.50</td>
<td>7.55</td>
</tr>
</tbody>
</table>
5.4 SUPPLEMENTARY RESULTS AND FIGURES

The supplementary results for the manuscript presented in Chapter 5 are given in Appendix B.

5.5 SUMMARY AFTER THE FACT

This manuscript provided an understanding of the range of physical properties of iron ore fines that may influence a cargo to shift and provided a valuable insight into the behaviour of the material both based on visual observations and the results produced from performing the tests. A full understanding of the current three test methods listed in the IMSBC Code for determining the TML of ores and mineral concentrates was obtained. This understanding somewhat influenced the design of the future test methods used during this research.

This manuscript also provided direction for the current attempts that were being made to obtain a sufficient sample of iron ore fines typically transported in the holds of bulk carriers. Since this manuscript was the first publication written, at this time not much was known about the soon to be introduced Modified Proctor/Fagerberg Test (MPFT) that was being developed. Research began shortly afterwards in regards to this method.
CHAPTER 6 A REVIEW OF THE NEWLY DEVELOPED METHOD USED TO PREVENT LIQUEFACTION OF IRON ORE FINES ON BULK CARRIERS

6.1 INTRODUCTION

This peer-reviewed manuscript was the second published document pertaining to this research. This manuscript introduces the newly developed Modified Proctor/Fagerberg Test (MPFT) alongside presenting a further understanding of iron ore fines, including; related history, transportation details, and production information.

More importantly are the aspects relating to the MPFT. One of which is the history, and the other, is verification. The history of the MPFT is given in relation to its origins, specifically its development from the standard Proctor/Fagerberg Test (PFT). The verification is given from a third perspective based on the information provided by the Iron Ore Technical Working Group (TWG), whom were instrumental in regards to the development of the test.

Exclusions made from this manuscript and not included in this chapter, are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made continuous throughout this document.

6.2 CITATION

Chapter 6 - A Review of the Newly Developed Method used to Prevent Liquefaction of Iron Ore Fines on Bulk Carriers

6.3 MANUSCRIPT CONTENTS

6.3.1 Abstract
Liquefaction is a commonly occurring problem affecting solid bulk cargoes on board bulk carriers. If liquefaction of a solid bulk cargo occurs on board a bulk carrier it can result in the vessel listing or capsizing resulting in the loss of human life and industry assets. Recent incidents involving bulk carriers transporting iron ore fines has initiated research into, and implementation of, a new test method used to determine a safe moisture content at which it can be transported without being at risk of liquefying. The new test method, known as the ‘Modified Proctor/Fagerberg Test for Iron Ore Fines’, has been amended in the 2015 edition of the International Maritime Solid Bulk Cargoes Code and will be entered into force in 2017. The objective of this paper is to provide a review regarding the development of the Modified Proctor/Fagerberg Test developed by the Iron Ore Technical Working Group. The review focuses on the key findings from five publicly available reports released in 2013.

6.3.2 Introduction
Liquefaction is a commonly occurring problem affecting solid bulk cargoes on board bulk carriers (Munro and Mohajerani, 2015). “Liquefaction is a phenomenon wherein a mass of soil loses a large percentage of its shear resistance, when subjected to monotonic, cyclic or shock loading, and flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance.” (Sladen et al., 1985). If liquefaction of a solid bulk cargo occurs on board a bulk carrier it can result in the vessel listing or capsizing resulting in the loss of human life and industry assets.

The International Maritime Solid Bulk Cargoes Code (IMSBC Code), published by the International Maritime Organization, is an internationally accepted code of safe practice to be referred to when transporting solid bulk cargoes which are deemed hazardous when transporting on bulk carriers (International Maritime Organization, 2013b). Recent incidents involving bulk carriers transporting iron ore fines has initiated research into, and implementation of, a new test method used to determine a safe moisture content at which iron ore fines can be transported without being at risk of liquefying.

The new test method, known as the ‘Modified Proctor/Fagerberg Test for Iron Ore Fines’ and herein referred to as the MPFT, has been amended in the 2015 edition of the IMSBC Code by the International Maritime Organization and will be entered into force in 2017 (International Maritime Organization, 2015d). The MPFT is specifically designed to determine the transportable moisture limit of iron ore fines. The IMSBC Code infers that the transportable moisture limit is the maximum gross water content that a cargo may contain without being at risk of liquefying.

The objective of this paper is to provide a review regarding the development of the MPFT developed by the TWG. The review focuses on the key findings from five publicly available reports released in 2013 (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e), which have been implemented in the 2015 edition of the IMSBC Code (International Maritime Organization, 2015d).

6.3.3 Iron Ore Fines
In order to determine the potential risk iron ore fines pose while being transported on bulk carriers, an understanding of the quantity of material being transported and vessels at risk must be determined. Iron ore is without doubt one of the most essential commodities of our time. Demand
from countries, such as China and Japan for iron ore produced in countries, such as Australia and Brazil, is only increasing (Ridsdale and Sultan, 2011). With increasing demand also comes increasing amounts being transported at sea. As iron ore fines is not a concentrate nor is it heavily refined, the geotechnical properties can vary significantly depending on where it is extracted. Various types of iron ore fines commonly transported on bulk carriers can be seen in Figure 90.

![Various types of iron ore fines commonly transported on bulk carriers](image)

Iron ore fines is a product of iron ore commonly having a particle size less than 6.3 mm (Bureau of Infrastructure Transport and Regional Economics, 2014). Seen in Figure 91 are typical particle size distribution boundaries of iron ore fines transported in bulk carriers, which were determined in a related publication (Munro and Mohajerani, 2015). The boundaries were determined by performing particle size distributions on 45 samples of iron ore fines using the sieve and hydrometer methods given in AS12893.6.1 and AS12893.6.3 respectively (Standards Australia, 2003a, 2009d).

![Particle size distribution boundaries of 45 typical samples of iron ore fines transported in bulk carriers](image)
Because iron ore fines contain a significant amount of fine particles it allows the material to retain moisture absorbed by the environment while being extracted, stored and transported. The combination of fine particles and moisture increases the liquefaction potential of the cargo (International Maritime Organization, 2013b). Iron ore fines in the hold of a bulk carrier before and after transportation can be seen in Figure 92 and Figure 93 respectively.

6.3.3.1 History
Iron ore fines were first deemed liquefiable, by the International Maritime Organization, in October 2011 in the circular DSC.1-Circ.66 where it stated “iron ore fines may liquefy and should be treated as such, in particular the Master should refer to Section 7 of the IMSBC Code, which warns about cargoes that may liquefy” (International Maritime Organization, 2011). Not until November 2013, was iron ore fines given an individual schedule (DSC.1-Circ.71), which superseded circular DSC.1-Circ.66. From November 2013 the circular DSC.1-Circ.71 could be implemented on a voluntary basis (International Maritime Organization, 2013a). The individual schedule for iron ore fines has been adopted as part of amendment 03-15 to the 2015 edition of the IMSBC Code and the mandatory entry into force date of these amendments is 1 January 2017 (International Maritime Organization, 2013a). The considerations for amendment 03-15 was released in January 2015 as MSC 95/3/Add.1 (International Maritime Organization, 2015d).

6.3.3.2 Transportation
In order to develop a new test method for determining the liquefaction potential of iron ore fines, the TWG used transportation statistics to define the conditions under which iron ore fines are most commonly transported. Iron ore fines are generally transported at sea using vessels referred to as bulk carriers, which are specifically designed to carry large volumes of loose solid cargoes and/or other commodities in bulk. Figure 94 and Figure 95 show the four major subclasses of bulk carriers used to transport iron ore fines along with the transportation statistics, which can also be seen in Table 25. As can be clearly seen in these figures, the Capesize subclass of bulk carrier transports the majority of iron ore fines around the globe.
Chapter 6 - A Review of the Newly Developed Method used to Prevent Liquefaction of Iron Ore Fines on Bulk Carriers

Michael Colin Munro – July 2017

6.3.3.3 Production

Recently, iron ore fines have been the focus of research due to the amount the material being transported around the world. Table 26 shows the worldwide production of nickel ore, bauxite and manganese ore in relation to the worldwide production of iron ore for the year 2011. These solid bulk cargoes have also shown similar liquefaction potential as iron ore fines but a considerably smaller quantity is transported by sea each year. These cargoes combined only form approximately 10% of the total worldwide production of iron ore. Due to this and recent incidents involving bulk carriers transporting iron ore fines, the MPFT was introduced specifically designed for use with iron ore fines.


<table>
<thead>
<tr>
<th>Subclass</th>
<th>Deadweight Tonnage</th>
<th>Yearly Iron Ore Fines Tonnage Transported (Figure 94)</th>
<th>Yearly Iron Ore Fines Voyages (Figure 95)</th>
<th>Vessels Worldwide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handysize</td>
<td>10,000 - 34,999</td>
<td>~ 1%</td>
<td>~ 6%</td>
<td>~ 39%</td>
</tr>
<tr>
<td>Handymax</td>
<td>35,000 - 59,999</td>
<td>~ 6%</td>
<td>~ 12%</td>
<td>~ 27%</td>
</tr>
<tr>
<td>Panamax</td>
<td>60,000 - 79,999</td>
<td>~ 92%</td>
<td>~ 82%</td>
<td>~ 34%</td>
</tr>
<tr>
<td>Capesize</td>
<td>80,000 - 199,999</td>
<td>~ 92%</td>
<td>~ 82%</td>
<td>~ 34%</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Mineral</th>
<th>Major Producers (Descending order)</th>
<th>2011 Mine Production Worldwide (Tonnes)</th>
<th>Mine Production Compared with Iron Ore (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Ore</td>
<td>China, Australia, Brazil, India and Russia.</td>
<td>2,940,000,000</td>
<td>100.00</td>
</tr>
<tr>
<td>Bauxite</td>
<td>Australia, China, Indonesia, Brazil and India.</td>
<td>259,000,000</td>
<td>8.81</td>
</tr>
<tr>
<td>Manganese Ore</td>
<td>South Africa, Australia, China, Gabon and Brazil.</td>
<td>16,000,000</td>
<td>0.54</td>
</tr>
<tr>
<td>Nickel Ore</td>
<td>Indonesia, Philippines, Russia, Canada and Australia.</td>
<td>1,940,000</td>
<td>0.07</td>
</tr>
</tbody>
</table>
6.3.4 Modified Proctor/Fagerberg Test for Iron Ore Fines

The ‘Modified Proctor/Fagerberg Test for Iron Ore Fines’ (MPFT), not to be confused with also recently developed ‘Modified Proctor/Fagerberg Test for Coal’ (Australian Coal Association Research Program (ACARP), 2014b), was first introduced in November 2013 in the circular DSC.1-Circ.71 where it could be implemented on a voluntary basis (International Maritime Organization, 2013a). Along with the individual schedule for iron ore fines, the mandatory entry into force date of this test would be 1 January 2017 (International Maritime Organization, 2013a) and, as previously mentioned, the considerations for the amendment 03-15, which has been implemented in the 2015 edition of the IMSBC Code, was released in January 2015 (International Maritime Organization, 2015d).

6.3.4.1 History

The MPFT was developed by the Iron Ore Technical Working Group (TWG) over a two year period from May 2012 (AMIRA International, 2012). The TWG was assembled by the International Maritime Organization to “consider the adequacy of current methods for determining transportable moisture limit for iron ore fines and consider new and/or amended existing methods to be included in appendix 2 of the IMSBC Code” (Iron Ore Technical Working Group, 2013e).

The TWG was managed by AMIRA International and consisted of eight sponsors and five research providers. The sponsors consisted of major industries involved in the export and transportation of iron ore fines including BHP Billiton, Cliffs Asia Pacific Iron Ore, The Chamber of Minerals and Energy Western Australia, Fortescue Metals Group, The Minerals Council of Australia, Rio Tinto, Roy Hill and Vale Australia. The five research providers from Australia and New Zealand consisted of Auckland UniServices, Creative Process Innovation, the CSIRO and the universities of Auckland and Newcastle (AMIRA International, 2012).

The MPFT is based on an existing test method given in appendix 2 of the IMSBC Code used to determine the transportable moisture limit of ‘Group A’ liquefiable solid bulk cargoes. The existing test, known as the ‘Proctor/Fagerberg Test’ and herein referred to as the PFT, was adopted by the International Maritime Organization, for use in the IMSBC Code between 1991 and 1998, to determine the transportable moisture limit of ore concentrates.

The PFT was first brought to light in a 1962 publication by Bengt Fagerberg and Kjell Eriksson (Fagerberg and Eriksson, 1962). The test was developed by a committee established by the Swedish Mining Association and several Scandinavian mining companies, which was given the task to develop a simple method for determining the transportable moisture limit of ore concentrates (Fagerberg and Stavang, 1971). The test method is based upon the use of the Proctor apparatus and procedure used in AS1289.5.1.1 and ASTM Standard D-698 (American Society for Testing and Materials, 2012; Standards Australia, 2003b), which was developed by Ralph Proctor for use in soil mechanics (Proctor, 1933).

The PFT procedure involves compaction of the material, into a standard litre compaction mould, at varying moisture contents, to produce a compaction curve with a minimum of five data points. The apparatus used along with a compacted sample can be seen in Figure 96 and a graphical compaction curve and resulting transportable moisture limit can be seen in Figure 97. Note that in Figure 97 the optimum moisture content of iron ore fines is at approximately 95% saturation, not 70% saturation as seen when performing the test on ore concentrates shown in Figure 98.
The compaction of the sample is executed in five layers by dropping a 350 g hammer, 25 times, through a guided pipe from a height of 200 mm. For each point, the gross water content and void ratio is calculated then plotted on a graph along with the corresponding degree of saturation. The resulting gross water content is then interpreted, from the graph, where the degree of saturation equals 70%. This value is referred to as the transportable moisture limit (International Maritime Organization, 2013b). The PFT requires the specific gravity of the sample to determine the void ratio and corresponding degree of saturation. It is noted that this test method is not a direct measurement of liquefaction. More information regarding the PFT and results can be seen in two related publications (Munro and Mohajerani, 2014, 2015).

![PFT apparatus and compacted sample of iron ore fines](image-url)
During the development of the PFT, Bengt Fagerberg utilized five hammers with varying drop heights and weights in order to determine which best represented the density of Scandinavian ores and concentrates in the hold of a bulk carrier (Fagerberg and Stavang, 1971). The hammer weights and drop heights along with two compaction results from a sample of magnetite, including the measured density of the magnetite in the hold a bulk carrier, can be seen in Table 27 and Figure 98 respectively.

From these results, Fagerberg decided to use compaction method C, as this compaction energy produced a lower void ratio (higher density) than the maximum density recorded on board bulk carriers, as seen in Figure 98 (Fagerberg and Stavang, 1971). The compaction method that produced a higher density was chosen because reading the transportable moisture limit from the equivalent degree of saturation equal to 70% resulted in a more conservative transportable moisture limit. Compaction method C, seen in Table 27 and Figure 98, is now referred to as the PFT in the IMSBC Code (International Maritime Organization, 2013b).

Table 27 – Hammer masses and drop heights used during the research into the PFT (Fagerberg and Stavang, 1971)

<table>
<thead>
<tr>
<th>Method</th>
<th>Hammer Mass (g)</th>
<th>Height of Drop (mm)</th>
<th>Number of Blows per Layer</th>
<th>Number of Layers</th>
<th>Compaction Energy per Blow (J)</th>
<th>Compaction Energy per Test (J)</th>
<th>Alternative Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2498</td>
<td>305</td>
<td>25</td>
<td>5</td>
<td>7.47</td>
<td>934.27</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>1000</td>
<td>200</td>
<td>25</td>
<td>5</td>
<td>1.96</td>
<td>245.25</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>350</td>
<td>200</td>
<td>25</td>
<td>5</td>
<td>0.69</td>
<td>85.84</td>
<td>PFT</td>
</tr>
<tr>
<td>D</td>
<td>150</td>
<td>150</td>
<td>25</td>
<td>5</td>
<td>0.22</td>
<td>27.59</td>
<td>MPFT</td>
</tr>
<tr>
<td>E</td>
<td>50</td>
<td>40</td>
<td>25</td>
<td>5</td>
<td>0.01</td>
<td>2.45</td>
<td>-</td>
</tr>
</tbody>
</table>
6.3.4.2 Modifications

The TWG’s decision to choose to modify the PFT over the other two methods also given in appendix 2 of the IMSBC Code was due to it being “an internationally recognised test that is suitable for determining the compaction curves of various materials, based on their degree of saturation” (Iron Ore Technical Working Group, 2013a). The modifications that were made to the PFT were based off Bengt Fagerberg’s original research accomplished from 1962 to 1971 (Fagerberg, 1965; Fagerberg and Eriksson, 1962; Fagerberg and Stavang, 1971) and additional research performed by the TWG, some of which is summarised herein.

Due to the significant amount of iron ore fines transported on Capesize bulk carriers, as seen in Figure 94 and Figure 95, the TWG focussed on the conditions under which iron ore fines are transported in this subclass of bulk carrier to develop the MPFT. They also focussed on the Handymax and Handysize subclasses of bulk carriers as these have experienced the majority of liquefaction incidents (Munro and Mohajerani, 2015).

The majority of the procedure and apparatus used during the MPFT is the same of that used during the PFT, as described in Section 6.3.4.1, except two main differences. One of the decisions made was to modify the weight and drop height of the compaction hammer. The TWG determined that the
density produced by the 350g hammer falling 200mm did not accurately represent the density of iron ore fines in the hold of a bulk carrier (Iron Ore Technical Working Group, 2013a).

During research into the MPFT, the TWG utilized similar methods as Fagerberg, as described in Section 6.3.4.1, to determine the compaction hammer (or method) that best represented the density of iron ore fines on board bulk carriers. These methods included; laser scanning, cargo observations, Cone Penetration Tests and Drop Tower Tests (Iron Ore Technical Working Group, 2013a, 2013c).

![Graph showing compaction test results](image)

Figure 99 – Compaction test results of a sample of Australian iron ore fines performed by the TWG (Iron Ore Technical Working Group, 2013c)

Figure 99 shows the TWG’s compaction results from some of the aforementioned tests for a sample of Australian iron ore fines along with the results from compaction methods C (PFT C) and D (PFT D). All the compaction results produced a higher void ratio (lower density) than compaction method D (PFT D), except from the drop tower tests (‘void ratio after drop’ and ‘void ratio after drop and 600kPa compress’). These tests were performed by dropping a sample at varying moisture contents from a height of 20m and also compressing the same sample at 600kPa after the drop. The comparable results shown in Figure 99 are the Capesize vessel after loading and before discharge. These results, produced
by laser scanning, show the average void ratio of the cargo on board a bulk carrier to have a greater
density than those produced by compaction methods D (PFT D).

A key finding by the TWG states “The dry density and void ratio values determined from the Proctor-
Fagerberg D hammer display the closest alignment to the dry density and void ratio values measured
from actual in-hold ship conditions for the iron ore fines material tested in this study.” (Iron Ore
Technical Working Group, 2013a). Therefore, along with other results presented in the reports, the
decision was made to use the 150g hammer falling from 150mm. A comparison between the hammers
used for compaction methods C (PFT) and D (MPFT) can be seen in Figure 100.

Modification to the degree of saturation at which the transportable moisture limit is determined when
interpreting from the graphical representation was also modified by using 80% instead of 70%. During
Bengt Fagerberg’s research he infers that liquefaction of the Scandinavian ores and concentrates he
was studying was most likely to occur at the Optimum Moisture Content (OMC) (Fagerberg and
Stavang, 1971). The OMC is the moisture content at which the minimum void ratio (maximum dry
density) occurs during the compaction of a material.

Fagerberg noted that at the OMC of Scandinavian ores and concentrates occurred at approximately
70% saturation and therefore the transportable moisture limit should be equal to this moisture
content (Fagerberg and Stavang, 1971). The TWG showed that the OMC of iron ore fines occurs at
approximately 90-95% saturation. On this basis, they decided that the transportable moisture limit
should be read from the graphical representation of the compaction curve where the degree of
saturation is equal to 80% to include a 10 to 15% safety factor. A comparison between the compaction
curves and transportable moisture limit results produced by the PFT and MPFT on the same sample
of iron ore fines can be seen in Figure 101.
Figure 100 – Comparison between the compaction hammers used during the PFT and the MPFT.

Figure 101 – Comparison between the compaction curves produced by the PFT and the MPFT on the same sample of iron ore fines.
In addition to the two modification made to the PFT, the TWG performed cyclic triaxial, direct shear and centrifugal tests to determine the liquefaction resistance of iron ore fines with varying amounts of goethite (Iron Ore Technical Working Group, 2013c). The results from these tests showed that the goethite content directly relates to the surface area of the particles and volume of the pores that forms iron ore fines. The TWG demonstrated that if the goethite content of iron ore fines is greater than 35% by mass then the material survived cyclic triaxial testing and became more resistant to liquefaction because of its increased water holding ability. This is also shown by the materials ability to prevent moisture migration during centrifugal testing.

The TWG also demonstrated that if the goethite content is less than 25% by mass then the material failed cyclic triaxial testing, produced more free water during centrifugal testing and therefore the potential for the material to liquify was increased (Iron Ore Technical Working Group, 2013c). It is inferred in the MPFT procedure that if a sample of iron ore fines contains more than 35% goethite that it can be considered a ‘Group C’ or non-liquefiable material and therefore the transportable moisture limit does not need to be determined (International Maritime Organization, 2015d).

6.3.4.3 Verification
In order to verify that iron ore fines do not liquefy at the transportable moisture limit produced by the newly developed MPFT, the TWG also performed hexapod testing and numerical modelling.

6.3.4.3.1 Hexapod Testing
The TWG utilized scale models where samples of iron ore fines could be tested under simulated seagoing conditions. The tests were completed using hexapods from supporting consultancies, such as the Norwegian Marine Technology Research Institute (MARINTEK), the Maritime Research Institute Netherlands (MARIN) and Deltares, which is also located in the Netherlands. These models incorporated six degrees of motion freedom to replicate bulk carriers seagoing motions while at sea (Iron Ore Technical Working Group, 2013c).

While simulating vessel motions using the hexapod the TWG did not observe liquefaction of Australian iron ore fines at any moisture content, but did observe cracking at the higher moisture contents along with compaction of the sample. Goethitic iron ore fines showed no drainage and were more stable than haematitic iron ore fines. The TWG concluded that all Australian iron ore fines were stable, even when the cargo was unconstrained, when using the hexapod (Iron Ore Technical Working Group, 2013c).

Using a scale model, owned and operated by MARINTEK, the TWG also tested Brazilian iron ore fines. Under typical seagoing motions, the samples of iron ore fines showed no sign of failure even when the moisture content was above the transportable moisture limit produced by the MPFT. Under high levels of transverse accelerations, with no vertical accelerations, it was noticed failure could occur if the moisture content is above the transportable moisture limit. They concluded that at the transportable moisture limit produced by the MPFT the samples of iron ore fines showed no signs of failure under any conditions (Iron Ore Technical Working Group, 2013c).

6.3.4.3.2 Numerical Modelling
Along with the hexapod testing, to further validate the MPFT, the TWG used numerical modelling to explain processes that occur within a cargo of iron ore fines. These models were based on the initial conditions of iron ore fines in the holds of bulk carriers and accelerations measured on multiple bulk carriers at sea.
carrier voyages (Iron Ore Technical Working Group, 2013b). The models calculated the simulated stress states within iron ore fines cargoes loaded in Capesize, Handysize and Handymax subclasses of bulk carriers under a range of typical sea conditions. The TWG concluded that, under a range of cargo configurations, iron ore fines cargoes are capable of resisting the induced levels of repeated loading from the typical motions of these subclasses of bulk carriers (Iron Ore Technical Working Group, 2013c). Additionally, the TWG concluded that due to the size of Capesize bulk carriers, they are inherently more stable than smaller bulk carriers when transporting iron ore fines (Iron Ore Technical Working Group, 2013b).

The TWG concluded that “the development of a wet base in the cargo does not necessarily lead to liquefaction and, although liquefaction of the wet base was seen in some cases, it was localised and would not compromise vessel stability”. They also concluded that “observations of free water in the holds of vessels are not necessarily an indication of liquefaction of the cargo. Additionally the presence of free water in the corners of the hold does not necessarily mean that either saturation or liquefaction has occurred” (Iron Ore Technical Working Group, 2013c). The TWG demonstrated that “liquefaction of iron ore fines can only occur when the following criteria are met:

1. The moisture of the cargo at loading exceeds the optimum moisture content; AND
2. The bulk of the material is saturated; AND
3. Moisture in the material results in excess pore water pressure; AND
4. The induced force on the vessel and cargo (including the most extreme sea conditions) exceeds the material’s resistance” (Iron Ore Technical Working Group, 2013d).

6.3.5 Discussion

The objective of this paper was to provide a review regarding the development of the ‘Modified Proctor/Fagerberg Test for Iron Ore Fines’ (MPFT) developed by the Iron Ore Technical Working Group (TWG). The review focussed on the key findings from five publicly available reports released in 2013, which have been implemented in the 2015 edition of the International Maritime Solid Bulk Cargoes Code (IMSBC Code) and to be made mandatory in January 2017.

Although the research performed by the TWG is an integral step in understanding the liquefaction potential of iron ore fines being transported in the hold of bulk carriers, based on continuing studies on the topic there are research aspects that need to be refined and fully understood. Further peer-reviewed, published and verified research is required to understand the process of liquefaction of iron ore fines. The varying properties of iron ore fines and variable stress states, depending on how the material is loaded and transported, are assumed to greatly influence moisture migration, local liquefaction and the overall liquefaction potential of the cargo.

The TWG has performed essential research that can be used as a foundation for future studies. Transportable moisture limit test methods for other minerals such as bauxite, manganese ore and nickel ore, are still absent or out-dated. Further research into the cause of liquefaction of iron ore fines and other minerals, while being transported, is essential to prevent future loss of human life and assets.
6.4 SUPPLEMENTARY RESULTS AND FIGURES

There are no supplementary results or figures relating to this manuscript.

6.5 SUMMARY AFTER THE FACT

Research related to this manuscript provided an understanding of the processes related to the transportation of iron ore fines and the scale of production compared to other solid bulk cargoes that are considered suspected of undergoing liquefaction during marine transportation.

It also demonstrates important aspects of the research performed by the Iron Ore Technical Working Group (TWG) while development of the Modified Proctor/Fagerberg test was underway. Included is the history of the MPFT and what modifications were made to the test it was based upon in order for it to produce a reliable Transportable Moisture Limit (TML) when testing of iron ore fines. Some of the main techniques used by the TWG to verify the results from the MPFT are also described.

Upon understanding the MPFT, it was decided to use the method to test the samples of the iron ore fines that were available. The TML results from the MPFT would then be compared to the three test methods currently provided in Appendix 2 of the 2012 Edition of the IMSBC Code (International Maritime Organization, 2012b) and previously analysed.
CHAPTER 7 MOISTURE CONTENT LIMITS OF IRON ORE FINES TO PREVENT LIQUEFACTION DURING TRANSPORT: REVIEW AND EXPERIMENTAL STUDY

7.1 INTRODUCTION

This peer-reviewed manuscript expands upon that previously discussed in Chapter 6. This manuscript includes information regarding some topics explained previously, such as the ‘original’ three test methods given in the 2012 Edition of the IMSBC Code and a comparison between these test methods. What is unique is an expansion upon the knowledge regarding the history of the IMSBC Code, including the TML test methods, recent developments, and additional provisions relating to the newly introduced schedule for iron ore fines and the Modified Proctor/Fagerberg Test (MPFT).

This manuscript also presents the experimental results and similar presentations to those in Chapter 5 that were gathered after performing the MPFT on varying samples of iron ore fines. The comparison between the TML produced from the MPFT and standard Proctor/Fagerberg Test (PFT) are then presented and compared to the TML results from all the methods given in the IMSBC Code.

Exclusions made from this manuscript and not included in this chapter are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made continuous throughout this document.

7.2 CITATION

7.3 MANUSCRIPT CONTENTS

7.3.1 Abstract
Iron ore is without doubt one of the most essential commodities of our time. With this, the growing demand from countries, such as China and Japan for iron ore produced in countries, such as Australia and Brazil, is only increasing. Iron Ore Fines (IOF) are a product of iron ore, commonly having a particle size less than 6.3mm, which is transported around the world in bulk carriers. Since the holds of bulk carriers are not designed to carry liquid, if liquefaction of IOF or other minerals occurs, it can cause the vessel carrying the cargo to list or even capsize. Since 2007, there have been at least seven reported bulk carrier incidents possibly caused by the iron ore cargo shifting. Currently, the only available parameter used to prevent this from occurring is the Transportable Moisture Limit (TML). The TML is the maximum gross water content that certain mineral cargoes may contain, while being loaded in bulk carriers, without being at risk of liquefying during transportation. The first half of this paper presents a review of the three test methods stated in the 2013 International Maritime Solid Bulk Cargoes Code (IMSBC Code) and the recently introduced Modified Proctor/Fagerberg test (MPFT). Along with the aforementioned tests, also reviewed are recent developments and advancements made in the field. The second half of this paper presents a comparison of the results of our experimental study with two of the three 2013 IMSBC Code tests along with the MPFT. This study shows that the three test methods which are currently used to determine the TML of minerals are not appropriate for testing of IOF and that the Modified Proctor/Fagerberg test produces a value higher than all the other test methods when used to determine the TML of IOF.

7.3.2 Introduction
The temporary reclassification of IOF, in 2011, by the International Maritime Organization (IMO), as a ‘Group A’ liquefiable material (International Maritime Organization, 2011), has initiated research into individual solid bulk cargo behaviours while being transported at sea. The focus of their research is to determine the potential risk of liquefaction that minerals, such as IOF, pose while being transported in bulk carriers (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e).

Liquefaction is the term used to describe when a soils shear stress is reduced to near zero under cyclic, static or shock loading resulting in it behaving like a liquid. The shear strength of a soil can be reduced to near zero by the momentary prevention of water drainage under cyclic loading which causes changes in the pore pressures between the particles of the soil (Eseller-Bayat et al., 2013). Sladen et al. (1985) gives a more precise definition of liquefaction; “Liquefaction is a phenomenon wherein a mass of soil loses a large percentage of its shear resistance, when subjected to monotonic, cyclic or shock loading, and flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance” (Sladen et al., 1985).

Although minerals, such as coal, fluorspar, ilmenite and mineral concentrates (e.g. nickel (United States Geological Survey, Undated-b, Undated-c)) are more susceptible to liquefaction because of their similarity to silts and sands (W. S. Wang, 1979), under certain circumstances, IOF and other similar minerals are also vulnerable primarily due to their physical properties and the varying conditions under which they are stored, loaded and transported (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e). There is no definitive test procedure in the 2013 International Maritime Solid Bulk Cargoes Code (IMSBC Code) that is applicable when determining the liquefaction potential of IOF while being transported in bulk carriers (International Maritime Organization, 2013b).
Chapter 7 - Moisture Content Limits of Iron Ore Fines to Prevent Liquefaction during Transport: Review and Experimental Study

The IMSBC Code, formally the Code of Safe Practice for Solid Bulk Cargoes (BC Code) (International Maritime Organization, 2005), which is published by the IMO, outlines the dangers associated when transporting certain types of solid bulk cargoes and provides procedures to be followed. Included in the 2013 IMSBC Code are test methods used to determine the Transportable Moisture Limit (TML) of ‘Group A’ minerals. ‘Group A’ minerals are those that have the potential to liquefy due to the proportion of fine particles and moisture they contain (International Maritime Organization, 2013b).

Prior to 2011, IOF were not specifically listed in the IMSBC Code. The circular (DSC.1/Circ66) sent out by the IMO, in 2011, temporarily reclassified IOF as a ‘Group A’, liquefiable material, until a permanent individual schedule can be agreed upon and incorporated in the 2015 IMSBC Code (International Maritime Organization, 2011).

Currently, the only parameter used to determine a minerals’ potential to liquefy, while being transported in bulk carriers, is the TML. The 2013 IMSBC Code refers to the TML as the maximum Gross Water Content (GWC) that certain mineral cargoes may contain, while being loaded in bulk carriers, without being at risk of liquefying during transportation (International Maritime Organization, 2013b). The GWC is calculated as the mass of water divided by the total wet mass. This is different from the Net Water Content (NWC), which is calculated as the mass of water divided by the total dry mass. The NWC is more commonly used in geotechnical engineering than the GWC.

On occasion, liquefaction of minerals being transported in bulk carriers can occur when repeated loading, produced by the ocean waves and vessels engine, are transmitted to the cargo in the hold of a bulk carrier (Jonas, 2010). Repeated loading can increase the pore pressures of a material which contains sufficient amounts of fine particles and moisture (Eseller-Bayat et al., 2013). The right combination of physical properties and system variables can cause the shear strength of a material to decrease. When the shear strength reduces to near zero, it can cause the material to liquefy (Bishop, 1959). Liquefaction of a material will cause it to act like a liquid until the pore pressures dissipate, therefore normalising the shear strength. IOF after being loaded into the hold of a bulk carrier can be seen in Figure 102 (Crouch and Aamlid, 2009).
Since the holds of bulk carriers are not designed to carry liquid, if liquefaction of IOF or other minerals occurs, it may cause the bulk carrier, carrying the cargo, to list or even capsize. This is mainly as a result of the weight of the unconfined cargo shifting and causing a rapid change in the bulk carriers’ buoyancy (Jonas, 2010). Since 2007, there have been at least seven reported bulk carrier incidents possibly caused by the iron ore cargo shifting, as seen in Table 28 (Bulk Carrier Guide, 2010; Devanney, Undated; Intercargo, 2007; Maritime Bulletin, 2013b; Roberts, 2012; Substandard Ship, 2013).

Table 28 – Recent bulk carrier incidents where the suspected cause was liquefaction of the cargo of IOF (Bulk Carrier Guide, 2010; Devanney, Undated; Intercargo, 2007; Maritime Bulletin, 2013b; Roberts, 2012; Substandard Ship, 2013)

<table>
<thead>
<tr>
<th>Vessel Name</th>
<th>Subclass (See Table 29)</th>
<th>Total Loss of Vessel</th>
<th>Lives Lost</th>
<th>Date</th>
<th>Origin</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chang Le Men</td>
<td>Handysize</td>
<td>No (Listed)</td>
<td>0</td>
<td>07/09/2007</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>Mezzanine</td>
<td>Handysize</td>
<td>Yes</td>
<td>26</td>
<td>27/11/2007</td>
<td>Indonesia</td>
<td>China</td>
</tr>
<tr>
<td>Asian Forest</td>
<td>Handysize</td>
<td>Yes</td>
<td>0</td>
<td>17/07/2009</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>Black Rose</td>
<td>Handymax</td>
<td>Yes</td>
<td>1</td>
<td>09/09/2009</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>Sun Spirits</td>
<td>Handysize</td>
<td>Yes</td>
<td>0</td>
<td>22/01/2012</td>
<td>Philippines</td>
<td>China</td>
</tr>
<tr>
<td>Bingo</td>
<td>General Bulker</td>
<td>Yes</td>
<td>0</td>
<td>12/08/2013</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>Anna Bo</td>
<td>Handymax</td>
<td>No (Listed)</td>
<td>0</td>
<td>04/12/2013</td>
<td>Indonesia</td>
<td>China</td>
</tr>
</tbody>
</table>

Recently, nickel ore has also shown similar liquefaction potential as IOF (Jonas, 2010), but a considerably smaller quantity is transported by sea each year. In 2011, the worldwide mine production of Nickel ore was only 0.07% of iron ore (United States Geological Survey, Undated-b, Undated-c).

7.3.2.1 Transportation of Solid Bulk Cargoes

Iron ore is extracted from beneath the surface rock then crushed and mechanically divided to produce three different qualities; fines (<6.3mm), lump (6.3-31.5mm) and pellets (6-18mm) (Bureau of Infrastructure Transport and Regional Economics, 2014). The majority of IOF produced in countries,
such as Australia and Brazil, are exported to countries, such as China, Japan and South Korea, to be refined (Ridsdale and Sultan, 2011).

Solid bulk cargoes, such as IOF, are generally transported at sea using vessels referred to as bulk carriers. Bulk carriers refer to a class of large seagoing vessels specifically designed to carry large volumes of loose minerals and/or other commodities. Table 29 shows the four major subclasses of bulk carriers used to transport IOF along with transportation statistics of IOF (Bulk Carrier Guide, 2010; Excel Maritime Carriers Ltd, 2011; Iron Ore Technical Working Group, 2013b; United Nations Conference on Trade and Development (UNCTAD), 2011). The Deadweight Tonnage (DWT) is the total maximum weight a specific vessel can safely carry, which is typically defined by the manufacturer of each vessel.

<table>
<thead>
<tr>
<th>Subclass</th>
<th>Deadweight Tonnage (DWT)</th>
<th>Yearly IOF Tonnage Transported</th>
<th>Yearly IOF Voyages</th>
<th>Vessels Worldwide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handysize and Handymax</td>
<td>10,000 - 59,999</td>
<td>~ 1%</td>
<td>~ 6%</td>
<td>~ 39%</td>
</tr>
<tr>
<td>Panamax</td>
<td>60,000 - 79,999</td>
<td>~ 6%</td>
<td>~ 12%</td>
<td>~ 27%</td>
</tr>
<tr>
<td>Capesize</td>
<td>80,000 - 199,999</td>
<td>~ 92%</td>
<td>~ 82%</td>
<td>~ 34%</td>
</tr>
</tbody>
</table>

It is assumed that the density of a cargo in the hold of a bulk carrier will depend on numerous variables, including the physical properties of the cargo and system variables under which the cargo is loaded and transported. Two important system variables, which may significantly control the density of a cargo, are the loading rate and height that the cargo is loaded into the holds. Loading rates are generally specified by the manufacturers of each individual bulk carrier (Australian Maritime Safety Authority, 2009).

Along with the loading techniques varying from one port to another, this will mean that the density of IOF, in the holds of bulk carriers, may vary significantly. The maximum depth of the cargo can also vary depending on the vessel subclass, the angle of repose and the loading sequence of the cargo. The density of a cargo being transported directly relates to its liquefaction potential (Jonas, 2010). A typical loading profile of IOF in the hold of a Capesize bulk carrier can be seen in Figure 103 (Iron Ore Technical Working Group, 2013c).
Sections 7.3.3 and 7.3.4 of this paper present a review of the three test methods stated in the 2013 International Maritime Solid Bulk Cargoes Code (IMSBC Code) and the recently introduced Modified Proctor/Fagerberg test (MPFT). Along with the aforementioned tests, also reviewed are recent developments and advancements made in the field. Section 7.3.5 of this paper presents a comparison of the results of our experimental study with two of the three 2013 IMSBC Code tests along with the MPFT.

7.3.3 Original Test Methods
In the 2013 IMSBC Code, there are three test methods used to determine the TML of ‘Group A’ cargoes, which are those that are potentially liquefiable. The three test methods are the Proctor/Fagerberg (PFT), Flow Table (FTT) and Penetration (PT) test methods (International Maritime Organization, 2013b). Section 7.3.7 shows the development of these Transportable Moisture Limit testing methods in a graphical timeline, beginning in 1962. In a related publication these three original test methods are discussed in more detail (Munro and Mohajerani, 2015).

7.3.3.1 Proctor/Fagerberg Test (PFT)
The PFT was first published in Stockholm in 1962 by Bengt Fagerberg and Kjell Eriksson as part of a committee established by the Swedish Mining Association and several Scandinavian mining companies. The committee was given the task to develop a simple method for determining the TML of ore concentrates (Fagerberg and Stavang, 1971). The test method is based upon the use of the Proctor apparatus (ASTM Standard D-698 (American Society for Testing and Materials, 2012)), which was developed by Ralph Proctor for use in soil mechanics (Proctor, 1933), and was adopted by the IMO, for use in the IMSBC Code, between 1991 and 1998.

The procedure involves compaction of the material, into a standard litre compaction mould, at varying moisture contents, to produce a compaction curve with a minimum of five data points. The compaction is executed in five layers by dropping a 350g hammer, 25 times, through a guided pipe from a height of 200mm. For each point, the GWC and void ratio is calculated then plotted on a graph along with the corresponding degree of saturation (S). The resulting GWC is then interpreted, from the graph, where S equals 70%. This value is referred to as the TML (International Maritime Organization, 2013b). The PFT uses approximately 14% of the standard Proctor compaction energy and requires the specific gravity to produce the corresponding S. A typical compaction curve of IOF, produced during this study, can be seen in Section 7.3.5.3 (Figure 109).

7.3.3.2 Flow Table Test (FTT)
The FTT has been widely used in the cement industry to test hydraulic cement (American Society for Testing and Materials, 2008). The early IMSBC Code (the BC Code) included a modified procedure, created by the Department of Mines and Technical Surveys in Canada that can be used to determine the TML of ore concentrates and coal (Fagerberg and Stavang, 1971). In 2000, this method branched out into an ISO (International Organization for Standardization) guide (ISO 12742) (International Standards Organization, 2007).

The FTT is performed by compacting a sample, in three layers, into a conical shaped mould in the centre of the Flow Table. Compaction is performed using a tamping rod, which is set to a predetermined pressure. For a typical sample of IOF, the tamping pressure used is approximately 450kPa (~33kg.f for a 30mm diameter tamper head). The tamping pressure depends on the properties of the sample being tested. The tamping pressure (P) is determined (in Pa), prior to performing the
FTT, using the formula \( P = \rho \times d \times g \), where \( \rho \) is the bulk density (in \( \text{kg/m}^3 \)) obtained by performing the standard Proctor compaction, which is described in ASTM Standard D-698 (American Society for Testing and Materials, 2012), \( d \) (in m) is the maximum depth of the cargo and \( g \) is the acceleration due to gravity (in \( \text{m/s}^2 \)).

After compaction is complete, the mould is carefully removed. Immediately after the mould is removed, the Flow Table is raised and dropped 50 times through a height of 12.5mm at a rate of 25 times per minute. This procedure is then repeated at different moisture contents. During testing at different moisture contents, the operator visually determines whether the sample is showing plastic deformation by using height and width measurements together with observing the behaviour of the sample while the Flow Table is being dropped. The point of change between the sample showing plastic deformation and not showing plastic deformation is referred to as the Flow Moisture Point (FMP). When a sample has been observed exceeding the FMP it is oven dried along with the previous sample, which should be just below the FMP, so that the GWC, of each, can be calculated. The mean of these two values is referred to as the FMP and 90% of the FMP is referred to as the TML (International Maritime Organization, 2013b).

### 7.3.3.3 Penetration Test (PT)

The PT was developed in Japan at the Research Institute of Marine Engineering (Tanaka and Ura, 1989). It was adopted by the IMO, in 1994, for determining the TML of coal and ore concentrates (Tamaki Ura, 1995).

The PT is performed by compacting a sample, in four layers, into a cylindrical mould. The sample is compacted with an adjustable tamper, using a tamping pressure similar to what would be used in the FTT, so that the surface of the sample is flat and levelled (International Maritime Organization, 2013b). The developer of the test states that "tamping does not affect the result of the PT, because the sample is quickly consolidated by vibration from the vibrating table regardless of the pressure of tamping conducted prior to the test" (Tanaka and Ura, 1989).

After compaction is complete the mould is attached to a vibrating table and a Penetration bit is placed on the surface of the material. The vibrating table is then operated at a frequency of 50-60Hz with an acceleration of 2g RMS for 6 minutes. After 6 minutes the depth of penetration, by the penetration bit, is recorded. This procedure is performed at varying moisture contents. When the depth of penetration is greater than 50mm the FMP has been exceeded and the sample is oven dried along with the previous sample, which should be just below the FMP, so that the GWC, of each, can be calculated. The mean of these two values is referred to as the FMP and 90% of the FMP is referred to as the TML (International Maritime Organization, 2013b).

### 7.3.4 Recent Developments in TML Testing

After the temporary reclassification of IOF, in 2011 (International Maritime Organization, 2011), industry and research institutions began comprehensive research in order to understand what can cause IOF to liquefy while being transported in bulk carriers and how to prevent it from occurring in the future. The outcome of their research was to implement a new test method, specifically designed for IOF, to prevent confusion caused by determining the TML using the three test methods, stated in the 2013 IMSBC Code, which were implemented for use with coal, fluorspar, ilmenite and mineral concentrates (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e).
Currently the most recognized research is being carried out by the Iron Ore Technical Working Group (TWG). The TWG was established by the IMO late 2012 to “conduct research and coordinate recommendations and conclusions about the transportation of IOF” (Iron Ore Technical Working Group, 2013c). The TWG is a collaboration between industry and research institutions managed by the Australian Mineral Industry Research Association (AMIRA). The TWG includes three of the largest iron ore producers; Rio Tinto, BHP Billiton and Vale, along with research institutions such as the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the University of Auckland and University of Newcastle (TUNRA) (AMIRA International, 2012).

The early implementation of the TWG’s research was introduced, in 2013, by the IMO in the circular DSC.1/Circ.71 (International Maritime Organization, 2013a). Included in this circular are draft schedules for iron ore and IOF; it also includes the draft for a new test method for determining the TML of IOF, the MPFT, which is discussed in Section 7.3.4.2.

The circular states that although more research is required, the draft schedules and test method will be included in amendment 03-15 of the IMSBC Code in 2015 and entered into force on January 1, 2017 (International Maritime Organization, 2013a). The Australian Maritime Safety Authority (AMSA) is one governing authority that gave the option for Australian export industries to voluntarily implement the draft schedules and draft test method for IOF (Australian Maritime Safety Authority, 2013a).

7.3.4.1 TWG Original Test Method Results

While evaluating the MPFT, the TWG tested the samples of IOF using the three methods stated in the 2013 IMSBC Code (Iron Ore Technical Working Group, 2013a). As seen in Table 30, the average variations from the FTT to the PFT, the PT to the PFT and the PT to FTT method was found to be approximately 8%, 27% and 18%, respectively. Figure 104 and Table 30 demonstrate the different TML values that can be produced depending on the chosen test method.

<table>
<thead>
<tr>
<th>Sample</th>
<th>PT TML (GWC %)</th>
<th>FTT TML (GWC %)</th>
<th>PFT TML (GWC %)</th>
<th>Increase from FTT TML to PFT TML (%)</th>
<th>Increase from PT TML to PFT TML (%)</th>
<th>Increase from PT TML to FTT TML (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>6.4</td>
<td>7.8</td>
<td>8.6</td>
<td>10.3</td>
<td>34.4</td>
<td>21.9</td>
</tr>
<tr>
<td>02</td>
<td>6.2</td>
<td>7.5</td>
<td>8.7</td>
<td>16.0</td>
<td>40.3</td>
<td>21.0</td>
</tr>
</tbody>
</table>

Figure 104 – IOF TML values using the PT, FTT and PFT produced by the TWG (Iron Ore Technical Working Group, 2013a)

Table 30 – IOF TML values using the PT, FTT and PFT and relevant increase percentages produced by the TWG (Iron Ore Technical Working Group, 2013a)
Due to the varying results, research into the establishment of a new test method was required, by the IMO, which is specifically designed for IOF, to prevent confusion caused by determining the TML using the three test methods stated in the 2013 IMSBC Code. Because of this requirement the TWG produced the MPFT, which can be used on a voluntary basis until amended in the 2015 IMSBC Code (International Maritime Organization, 2013a).

**7.3.4.2 Modified Proctor/Fagerberg Test (MPFT)**

In 2013, the MPFT was introduced, by the IMO, in the circular DSC.1/Circ.71 (International Maritime Organization, 2013a). The MPFT is the only test method specifically designed for use with IOF.

The TWG is the main driving force behind the implementation of the MPFT, which is sometimes referred to as D80. The abbreviation D80 comes from previous research carried out by Bengt Fagerberg and Arne Stavang in 1971, where compaction method D was performed using a 150g hammer falling from 150mm, instead of a 350g hammer falling 200mm, which is the PFT and method C in Fagerberg and Stavang research (Fagerberg and Stavang, 1971), as seen in Table 27. Also, instead of reading the TML from the intersection of the compaction curve and Degree of Saturation (S) equal to 70%, as stated in the PFT, it was recommended, by the TWG, to read the TML from the intersection of the compaction curve and S equal to 80%, for IOF (Iron Ore Technical Working Group, 2013a). Apart from the difference in S and compaction energy, the same procedure is used for both the PFT and MPFT (International Maritime Organization, 2013a).

<table>
<thead>
<tr>
<th>Method</th>
<th>Hammer Mass (g)</th>
<th>Height of Drop (mm)</th>
<th>Number of Blows per Layer</th>
<th>Number of Layers</th>
<th>Compaction Energy per Blow (J)</th>
<th>Compaction Energy per Test (J)</th>
<th>Alternative Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2498</td>
<td>305</td>
<td>25</td>
<td>5</td>
<td>7.47</td>
<td>934.27</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>1000</td>
<td>200</td>
<td>25</td>
<td>5</td>
<td>1.96</td>
<td>245.25</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>350</td>
<td>200</td>
<td>25</td>
<td>5</td>
<td>0.69</td>
<td>85.84</td>
<td>PFT (C70)</td>
</tr>
<tr>
<td>D</td>
<td>150</td>
<td>150</td>
<td>25</td>
<td>5</td>
<td>0.22</td>
<td>27.59</td>
<td>MPFT (D80)</td>
</tr>
<tr>
<td>E</td>
<td>50</td>
<td>40</td>
<td>25</td>
<td>5</td>
<td>0.01</td>
<td>2.45</td>
<td>-</td>
</tr>
</tbody>
</table>

In 1971, Fagerberg and Stavang performed compactions on Magnetite to compare the void ratio and the water content by volume, as seen in Figure 105 and Figure 106. These compactions were compared with multiple in situ void ratios of Magnetite, measured onboard bulk carriers. From these comparisons Fagerberg and Stavang came to the conclusion that method C was adequate for replicating the density of mineral concentrates in the holds of bulk carriers and that at S equal to 70%,
which is the approximate maximum density, mineral concentrates have the greatest potential to liquefy (Fagerberg and Stavang, 1971).

To verify this procedure the TWG measured the bulk density of IOF in the holds of multiple bulk carriers, before and after transportation, through means of height measurements, laser scanning and cone penetration testing (Iron Ore Technical Working Group, 2013a, 2013c). Using this data and additional bulk densities determined by drop tower testing the TWG concluded that the density produced by compaction during the MPFT or method D in Fagerberg and Stavang research (Fagerberg and Stavang, 1971), was more than sufficient for replicating the density of IOF in the holds of bulk carriers (Iron Ore Technical Working Group, 2013c).

The TWG states that based on the research completed by Fagerberg and Stavang (Fagerberg and Stavang, 1971), the MPFT includes a safety factor of approximately 10-15% based on the S and approximately 10% based on the TML. This depends on the compaction curve produced by the different types of IOF. The MPFT uses around 5% of the standard Proctor compaction energy and 32% of the PFT compaction energy (Iron Ore Technical Working Group, 2013a).
7.3.4.3 Particle Size Provisions
In the draft individual schedule for IOF, given in the circular DSC.1/Circ.71 (International Maritime Organization, 2013a), it is stated that when transporting iron ore cargoes containing 10% or more of fine particles less than 1mm and 50% or more of particles less than 10mm the individual schedule for IOF must be followed and therefore classified as a ‘Group A’ liquefiable material and if not then the schedule for iron ore should be followed and therefore classified as a ‘Group C’ non-liquefiable material (International Maritime Organization, 2013a). A graphical representation of this can be seen in Section 7.3.5.4 (Figure 110), where it is compared to particle size distribution results of IOF obtained during this study.

7.3.4.4 Goethite Content Provisions
Iron ore is commonly made up of three main constituents; goethite, hematite and magnetite. The TWG performed cyclic triaxial, direct shear and centrifugal tests to determine the liquefaction resistance of IOF with varying amounts of goethite (Iron Ore Technical Working Group, 2013c).

According to the research carried out by the TWG, the goethite content directly relates to the surface area of the particles and the volume of the pores that make up the structure of IOF. Furthermore, as the goethite content of IOF increases the material’s ability to hold water also increases. The TWG demonstrated that if the goethite content of IOF is greater than 35% by mass then the material survived cyclic triaxial testing and became more resistant to liquefaction because of its increased water holding ability. This is also shown by the material’s ability to prevent moisture migration during centrifugal testing. They also demonstrated that if the goethite content is less than 25% by mass then the material failed cyclic triaxial testing, produced more free water during centrifugal testing and therefore the potential for the material to liquefy increased (Iron Ore Technical Working Group, 2013c).

In the draft individual schedule for IOF it is stated that, regardless of the particle size, if the material contains more than 35% goethite by mass then the IOF can be treated as iron ore and therefore classified as a ‘Group C’ non-liquefiable material, otherwise the material is to be treated as IOF and therefore classified as a ‘Group A’ liquefiable material (International Maritime Organization, 2013a).

7.3.4.5 TWG Scale Model Testing
The TWG utilized scale models where IOF could be tested under simulated seagoing conditions. The tests were completed using hexapods along with the additional use of apparatus from supporting consultancies, such as the Norwegian Marine Technology Research Institute (MARINTEK), the Maritime Research Institute Netherlands (MARIN) and Deltares, which is also located in the Netherlands. These models incorporated six degrees of motion freedom to replicate bulk carriers seagoing motions while at sea (Iron Ore Technical Working Group, 2013c).

While simulating vessel motions using the hexapod the TWG did not observe liquefaction of Australian IOF at any moisture content, but did observe cracking at the higher moisture contents along with compaction of the sample. Goethitic IOF showed no drainage and were more stable than haematitic IOF. The TWG concluded that Australian IOF were stable, even when the cargo was unconstrained, when using the hexapod (Iron Ore Technical Working Group, 2013c).

Using a scale model, owned and operated by MARINTEK, the TWG also tested Brazilian IOF. They concluded that at the TML, determined by the MPFT, the samples of IOF showed no signs of failure.
Typical seagoing motions also caused no failures in the samples of IOF even when the moisture content was above the TML, determined by the MPFT, but under high levels of transverse accelerations with no vertical accelerations, failure can occur if the moisture content is above the TML (Iron Ore Technical Working Group, 2013c).

7.3.5 Experimental Results

The following Section of this paper presents a comparison of the results of a previous experimental study with two of the three 2013 IMSBC Code test methods along with new experimental results from the newly developed MPFT.

7.3.5.1 Materials, Methods and Equipment

The IOF that were used during this study were obtained from various locations around Australia. Table 32 to Table 34 show some of the typical physical properties of the IOF used during this study as well as in the related publication (Munro and Mohajerani, 2015).

Table 32 – Typical properties of IOF samples used during this study as well as in the related publication (Munro and Mohajerani, 2015)

<table>
<thead>
<tr>
<th>Property</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Moisture Content (NWC%)</td>
<td>3.4</td>
<td>7.9</td>
<td>10.3</td>
</tr>
<tr>
<td>Particle Density (t/m³)</td>
<td>3.78</td>
<td>4.27</td>
<td>4.91</td>
</tr>
<tr>
<td>Coefficient of Uniformity (Cu)</td>
<td>24.9</td>
<td>119.3</td>
<td>273.2</td>
</tr>
<tr>
<td>Coefficient of Curvature (Cc)</td>
<td>0.7</td>
<td>1.7</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Table 33 – Properties of a typical sample of IOF that was used during this study as well as in the related publication (Munro and Mohajerani, 2015)

<table>
<thead>
<tr>
<th>Property</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Dry Density (t/m³)</td>
<td>2.12</td>
</tr>
<tr>
<td>Maximum Dry Density (t/m³)</td>
<td>3.08</td>
</tr>
<tr>
<td>Liquid Limit (NWC%)</td>
<td>18</td>
</tr>
<tr>
<td>Plastic Limit (NWC%)</td>
<td>16</td>
</tr>
<tr>
<td>Plasticity Index (NWC%)</td>
<td>2</td>
</tr>
<tr>
<td>Standard Proctor Compaction - Optimum Moisture Content (NWC%)</td>
<td>12.0</td>
</tr>
<tr>
<td>Standard Proctor Compaction - Maximum Dry Density (t/m³)</td>
<td>2.73</td>
</tr>
</tbody>
</table>

Table 34 – Typical particle size distribution sieve data of IOF used during this study as well as in the related publication (Munro and Mohajerani, 2015)

<table>
<thead>
<tr>
<th>Sieve Aperture (mm)</th>
<th>Sieve Number</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.0</td>
<td>3/4&quot;</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>13.2</td>
<td>0.530&quot;</td>
<td>96</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>9.5</td>
<td>3/8&quot;</td>
<td>87</td>
<td>98</td>
<td>100</td>
</tr>
<tr>
<td>6.7</td>
<td>0.265&quot;</td>
<td>74</td>
<td>93</td>
<td>100</td>
</tr>
<tr>
<td>4.75</td>
<td>No. 4</td>
<td>64</td>
<td>85</td>
<td>98</td>
</tr>
<tr>
<td>2.36</td>
<td>No. 8</td>
<td>49</td>
<td>69</td>
<td>85</td>
</tr>
<tr>
<td>1.18</td>
<td>No. 16</td>
<td>36</td>
<td>55</td>
<td>71</td>
</tr>
<tr>
<td>0.6</td>
<td>No. 30</td>
<td>25</td>
<td>45</td>
<td>63</td>
</tr>
<tr>
<td>0.425</td>
<td>No. 40</td>
<td>21</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>0.3</td>
<td>No. 50</td>
<td>18</td>
<td>36</td>
<td>58</td>
</tr>
<tr>
<td>0.15</td>
<td>No. 100</td>
<td>11</td>
<td>28</td>
<td>51</td>
</tr>
<tr>
<td>0.075</td>
<td>No. 200</td>
<td>7</td>
<td>20</td>
<td>39</td>
</tr>
<tr>
<td>0.038</td>
<td>No. 400</td>
<td>5</td>
<td>13</td>
<td>25</td>
</tr>
</tbody>
</table>
A graphical representation of the particle size boundaries of 45 samples of IOF can be seen in Section 7.3.5.4 (Figure 110), where they are compared to the maximum particle size of IOF classified in the draft individual schedule for IOF (International Maritime Organization, 2013a).

All the physical properties in Table 32 to Table 34 were obtained using the methods and equipment stated in AS1289 (Standards Australia, 2000). The following experimental results, which were produced during this study and the previous study, were obtained using the methods and equipment which is explained in sections 7.3.3.1, 7.3.3.2 and 7.3.4.2 for the PFT, FTT and MPFT respectively.

### 7.3.5.2 Flow Table and Proctor/Fagerberg Test Results Produced during Previous Study

During previous research, samples of IOF were tested using the FTT and the PFT as stated in the 2013 IMSBC Code (International Maritime Organization, 2013b). These results have been presented in a related publication (Munro and Mohajerani, 2015). According to this research, when comparing the TML values produced using these two methods it can be clearly seen that there is a significant difference in the results. Seen Table 35, the results of the PFT can vary up to 16% more than the results from the FTT, with the average being 12%. This is mainly due to the difference in compacted densities that each test produces.

A graphical representation of the data from Table 35 can be seen in Figure 107. The coefficient of determination is 0.97, but the data significantly varies from the equality line.

**Table 35 – Comparison of IOF TML values using the PFT and FTT produced during previous research and presented in a related publication (Munro and Mohajerani, 2015)**

<table>
<thead>
<tr>
<th>Sample</th>
<th>PFT TML (GWC %)</th>
<th>FTT TML (35kg.f) (GWC %)</th>
<th>Difference between PFT and FTT TML Values (GWC %)</th>
<th>Increase from PFT to FTT TML Values (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>10.7</td>
<td>9.7</td>
<td>1.0</td>
<td>10.31</td>
</tr>
<tr>
<td>B</td>
<td>11.3</td>
<td>10.1</td>
<td>1.2</td>
<td>11.88</td>
</tr>
<tr>
<td>C</td>
<td>11.1</td>
<td>10.0</td>
<td>1.1</td>
<td>11.00</td>
</tr>
<tr>
<td>D</td>
<td>11.6</td>
<td>10.2</td>
<td>1.4</td>
<td>13.73</td>
</tr>
<tr>
<td>E</td>
<td>11.8</td>
<td>10.4</td>
<td>1.4</td>
<td>13.46</td>
</tr>
<tr>
<td>F</td>
<td>11.8</td>
<td>10.4</td>
<td>1.4</td>
<td>13.46</td>
</tr>
<tr>
<td>G</td>
<td>12.3</td>
<td>10.6</td>
<td>1.7</td>
<td>16.04</td>
</tr>
<tr>
<td>H</td>
<td>11.0</td>
<td>9.9</td>
<td>1.1</td>
<td>11.11</td>
</tr>
<tr>
<td>I</td>
<td>10.8</td>
<td>9.9</td>
<td>0.9</td>
<td>9.09</td>
</tr>
<tr>
<td>J</td>
<td>9.3</td>
<td>8.4</td>
<td>0.9</td>
<td>10.71</td>
</tr>
<tr>
<td>K</td>
<td>13.1</td>
<td>11.3</td>
<td>1.8</td>
<td>15.93</td>
</tr>
<tr>
<td>Average</td>
<td>11.4</td>
<td>10.1</td>
<td>1.3</td>
<td>12.43</td>
</tr>
</tbody>
</table>
Figure 107 – Comparison of IOF TML values using the PFT and FTT produced during previous research and presented in a related publication (Munro and Mohajerani, 2015)

Based on the data obtained during this previous research and presented in the related publication (Munro and Mohajerani, 2015), the PFT will produce a consistently higher TML value than the FTT when testing samples of IOF.

7.3.5.3 Modified Proctor/Fagerberg Test Results Produced during this Study

The MPFT, created in 2013 by the TWG, is the only test method designed specifically for use with IOF (International Maritime Organization, 2013a). For this study, compactions on samples of typical IOF were performed using the PFT and MPFT, as seen in Figure 108 and Table 36. The average variation from the PFT to the MPFT was found to be approximately 14%, which is the same variation that was seen by the TWG (Iron Ore Technical Working Group, 2013c).

Figure 108 – IOF TML values from the PFT and MPFT produced during this study
Chapter 7 - Moisture Content Limits of Iron Ore Fines to Prevent Liquefaction during Transport: Review and Experimental Study

Table 36 – IOF TML values from the PFT and MPFT produced during this study

<table>
<thead>
<tr>
<th>Sample</th>
<th>Standard PFT TML (GWC %)</th>
<th>Modified PFT TML (GWC %)</th>
<th>Difference between Standard and Modified PFT TML Values (GWC %)</th>
<th>Increase from Standard to Modified PFT TML Values (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>10.7</td>
<td>12.2</td>
<td>1.5</td>
<td>14.0</td>
</tr>
<tr>
<td>002</td>
<td>10.9</td>
<td>12.7</td>
<td>1.8</td>
<td>16.5</td>
</tr>
<tr>
<td>003</td>
<td>11.0</td>
<td>12.5</td>
<td>1.5</td>
<td>13.6</td>
</tr>
<tr>
<td>004</td>
<td>11.1</td>
<td>12.4</td>
<td>1.3</td>
<td>11.7</td>
</tr>
<tr>
<td>005</td>
<td>11.2</td>
<td>12.5</td>
<td>1.3</td>
<td>11.6</td>
</tr>
<tr>
<td>006</td>
<td>11.2</td>
<td>13.2</td>
<td>2.0</td>
<td>17.9</td>
</tr>
<tr>
<td>007</td>
<td>11.3</td>
<td>13.1</td>
<td>1.8</td>
<td>15.9</td>
</tr>
<tr>
<td>008</td>
<td>11.3</td>
<td>12.9</td>
<td>1.6</td>
<td>14.2</td>
</tr>
<tr>
<td>009</td>
<td>11.3</td>
<td>13.1</td>
<td>1.8</td>
<td>15.9</td>
</tr>
<tr>
<td>010</td>
<td>11.4</td>
<td>12.9</td>
<td>1.5</td>
<td>13.2</td>
</tr>
<tr>
<td>011</td>
<td>11.4</td>
<td>13.0</td>
<td>1.6</td>
<td>14.0</td>
</tr>
<tr>
<td>012</td>
<td>11.4</td>
<td>12.8</td>
<td>1.4</td>
<td>12.3</td>
</tr>
<tr>
<td>013</td>
<td>11.6</td>
<td>13.1</td>
<td>1.5</td>
<td>12.9</td>
</tr>
<tr>
<td>014</td>
<td>11.9</td>
<td>13.4</td>
<td>1.5</td>
<td>12.6</td>
</tr>
<tr>
<td>Average</td>
<td>11.3</td>
<td>12.8</td>
<td>1.6</td>
<td>14.0</td>
</tr>
</tbody>
</table>

A graphical representation of compactions performed on sample 011 of IOF, using the PFT and MPFT test, can be seen in Figure 109. The result of using a lighter compaction hammer and a lower hammer drop height, than the PFT, and interpreting the TML from \( S \) equal to 80% instead of \( S \) equal to 70%, is a TML value greater than that produced by the three test methods stated in the 2013 IMSBC Code. The increased TML, produced by the MPFT, will allow IOF cargoes to be transported in bulk carriers with higher moisture contents than if one of the three test methods, stated in the 2013 IMSBC Code, was used.

![Figure 109 – Graphical representation of the compaction curves of IOF (sample 011) using the PFT and MPFT produced during this study](image-url)
7.3.5.4 Particle Size Distributions Produced during this Study

During this study the particle size boundaries of 45 samples of IOF were produced using AS 1289.3.6.1 and AS 1289.3.6.3 (Standards Australia, 2003a, 2009d). These boundaries along with the maximum particle size of IOF, as classified in the 2013 draft schedule (International Maritime Organization, 2013a), are shown in Figure 110.

![Particle size boundaries of IOF](image)

Figure 110 – Particle size boundaries of IOF, which were produced during this study, along with the maximum particle size as classified in the 2013 draft schedule (International Maritime Organization, 2013a)

If the 2013 draft schedule for IOF was used and the particle size provisions followed, as described in Section 7.3.4.3, all the samples used to produce the boundaries seen in Figure 110 would be required to be transported in accordance with the draft individual schedule for IOF and therefore be classified as ‘Group A’ liquefiable materials (International Maritime Organization, 2013a). This is excluding the goethite content provisions, which are described in Section 7.3.4.4.

7.3.6 Conclusion

The first half of this paper presents a review of the three test methods stated in the 2013 International Maritime Solid Bulk Cargoes Code (IMSBC Code) and the recently introduced Modified Proctor/Fagerberg test (MPFT). Along with the aforementioned tests, also reviewed are recent developments and advancements made in the field. The second half of this paper presents a comparison of the results of our experimental study with two of the three 2013 IMSBC Code tests along with the MPFT.

Research by the TWG has produced draft schedules, in relating to TML testing of IOF, with the implementation of the MPFT, limitations on particle size and also goethite content, which are to be amended in the 2015 IMSBC Code.

The experimental results from this study, along with the results produced by the TWG, show that the original test methods, stated in the 2013 IMSBC Code, give significantly different TML values when used on IOF.
Experimental results from this study also show that typical cargoes of IOF can be transported with significantly higher moisture contents when using the MPFT to determine the TML when compared to using the three original test methods, stated in the 2013 IMSBC Code.

The introduction of the MPFT and goethite content provisions, given in the circular DSC.1/Circ.71, increases the allowable moisture content that IOF can contain when being loaded into bulk carriers and reduces the required amount of TML testing to be performed on IOF. The research that was performed is important to understand the behaviour IOF exhibit while being transported in bulk carriers.

The TWG has performed essential research that can be used as a foundation for future studies. TML test methods for other minerals such as bauxite, manganese ore and nickel ore, are still absent or outdated. Further investigations on the mechanism of liquefaction of IOF and other similar materials need to be explored and further research on the causes of bulk carrier incidents involving these materials is essential to prevent future loss of human life and assets.

7.3.7 Timeline References
The following are the references included in the timeline in Section 7.3.8:

- [1] (Iron Ore Technical Working Group, 2013a),
- [2] (International Maritime Organization, 2013a),
- [3] (Fagerberg and Eriksson, 1962),
- [4] (Fagerberg, 1965),
- [5] (Fagerberg and Stavang, 1971),
- [6] (Tanaka and Ura, 1989),
- [7] (Tamaki Ura, 1995),
- [10] (International Standards Organization, 2007),
- [11] (Gossett, 2012),
- [12] (International Maritime Organization, 2005),
- [13] (International Maritime Organization, 2011) and
7.3.8 Appendix A – TML Testing Timeline

Note 1: Since November 2013, IOF with more than 35% goethite can be classified as a ‘Group C’ non-liquefiable material and does not need to be TML tested if voluntarily implemented by the relevant authority. This will be mandatory after the introduction of the 2017 IMSBC Code [2].

Note 2: This timeline was last updated June 2015.
7.4 SUPPLEMENTARY RESULTS AND FIGURES

The supplementary results for the manuscript presented in Chapter 7 are given in Appendix C.

7.5 SUMMARY AFTER THE FACT

The research related to this manuscript provided an understanding of the problems associated with performing the Modified Proctor/Fagerberg Test (MPFT), how these problems are handled in the amendment, using provisions and limitations, and how the results from the MPFT compared to the standard Proctor/Fagerberg Test (PFT).

The comparison of the MPFT showed that by implementing this test method, cargoes of iron ore fines would be able to be transported at higher moisture contents than if any of the other three methods were used, which, at the time, was acceptable. Additionally, provisions allowed the testing of certain iron ore fines cargoes to cease altogether.

Resulting from the data presented in the supplementary results was design choices implemented later in this research concerning the development of the unique test methods to confirm the phenomenon occurring, and a comparison with the MPFT of the results influencing this phenomenon.

It is noted that not long after this publication was written, the bulk carrier Mezzanine, that is listed in Table 28, was removed from the list of vessels where liquefaction of the cargo was suspected. This was due to new details emerging relating to the incident.

Upon completion of this stage of research, it was decided to present a review of this information at a conference to receive feedback from researchers that are familiar with the liquefaction of soils. By discussing the test methods and the relationship of the methods to liquefaction, it was anticipated that confirmation of the current direction of the research being undertaken would be made.
CHAPTER 8 MOISTURE CONTENT LIMITS OF IRON ORE FINES FOR THE PREVENTION OF LIQUEFACTION IN BULK CARRIERS

8.1 INTRODUCTION

This conference paper is based upon the manuscript presented in Chapter 7. There is no additional information presented in this publication that has not already been presented previously. The paper was presented at the 11th International Conference on Hydrodynamics in Singapore during the period 19th to the 24th October 2014. This presentation was made in order to receive feedback concerning the direction of research currently adopted.

Exclusions made from this manuscript and not included in this chapter are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made continuous throughout this document.

8.2 CITATION

8.3 MANUSCRIPT CONTENTS

8.3.1 Abstract
In 2013, over 500 million tonnes of Iron Ore Fines (IOF) were transported around the world using bulk carriers, more than any other unrefined mineral. Since the holds of bulk carriers have not been designed to carry liquid, if liquefaction of IOF or other minerals occur it can cause the vessel carrying the cargo to list or even capsize. Since 2007, there have been at least seven reported bulk carrier incidents possibly caused by the iron ore cargo shifting. Currently, the only available parameter used to prevent this from occurring is the Transportation Moisture Limit (TML). The TML is the maximum gross water content that certain mineral cargoes may contain, while being loaded in bulk carriers, without being at risk of liquefying during transportation. The objective of this study is to compare the three test methods stated in the 2013 International Maritime Solid Bulk Cargoes Code (IMSBC Code), which are used to determine the TML of IOF. They are the Proctor/Fagerberg, Flow Table and Penetration test methods. The study also covers recent developments and advancements made in the field, which includes the Modified Proctor/Fagerberg test along with goethite content provisions, which are included in the 2013 draft individual schedule for IOF, and to be amended in the 2015 IMSBC Code. This study shows that the three test methods, stated in the 2013 IMSBC Code, which are used to determine the TML of minerals, are not appropriate for testing of IOF and that recent developments, such as the Modified Proctor/Fagerberg test along with goethite content provisions, permits IOF to be transported at higher moisture contents than if one of the previous three test methods were used.

8.3.2 Introduction
After extraction, iron ore is mechanically divided to produce three different qualities; pellets (9.5-16mm), lump (6.3-31.5mm) and fines (<6.3mm). Iron Ore Fines (IOF) make up approximately 48% of the iron ore trade, which in 2011, was approximately 1,300 million tonnes. In 2013, the majority of the 500 million tonnes of IOF that were transported around the world, using bulk carriers, were transported from Australia and Brazil.

The temporary reclassification of IOF, in 2011, by the International Maritime Organization (IMO), as a ‘Group A’ liquefiable material, has initiated research into individual bulk cargo behaviours while being transported at sea (International Maritime Organization, 2011). The focus of their research is to determine the potential risk of liquefaction that minerals, such as IOF, pose while being transported in bulk carriers. Although minerals, such as coal, fluorspar, ilmenite and mineral concentrates are more susceptible to liquefaction, under certain circumstances, IOF and other similar minerals are also vulnerable primarily due to their physical properties and the varying conditions under which they are stored, loaded and transported. There is no definitive test procedure in the 2013 International Maritime Solid Bulk Cargoes Code (IMSBC Code) that is applicable when determining the liquefaction potential IOF while being transported in bulk carriers.

On occasion, liquefaction of minerals being transported in bulk carriers can occur when repeated loading, produced by the ocean waves and vessels engine, are transmitted to the cargo in the hold of a bulk carrier. Repeated loading can increase the pore pressures of a material which contains sufficient amounts of fine particles and moisture. The right combination of physical properties and system variables can cause the shear strength of a material to decrease. When the shear strength reduces to
near zero, it can cause the material to liquefy. Liquefaction of a material will cause it to act like a liquid until the pore pressures dissipate, therefore normalising the shear strength.

Since the holds of bulk carriers are not designed to carry liquid, if liquefaction of IOF or other minerals occur it can cause the bulk carrier, carrying the cargo, to list or even capsize. This is mainly as a result of the weight of the unconfined cargo shifting and causing a rapid change in the bulk carriers’ buoyancy, which cannot be promptly corrected with ballast. Since 2007, there have been at least seven reported bulk carrier incidents possibly caused by the iron ore cargo shifting, as seen in Table 37.

Table 37 – Recent bulk carrier incidents possibly caused by the iron ore cargo shifting [2-7]

<table>
<thead>
<tr>
<th>Vessel Name</th>
<th>Subclass</th>
<th>Total Loss</th>
<th>Lives Lost</th>
<th>Date</th>
<th>Origin</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chang Le Men</td>
<td>Handysize</td>
<td>No (Listed)</td>
<td>0</td>
<td>07/09/2007</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>Mezzanine</td>
<td>Handysize</td>
<td>Yes</td>
<td>26</td>
<td>27/11/2007</td>
<td>Indonesia</td>
<td>China</td>
</tr>
<tr>
<td>Asian Forest</td>
<td>Handysize</td>
<td>Yes</td>
<td>0</td>
<td>17/07/2009</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>Black Rose</td>
<td>Handymax</td>
<td>Yes</td>
<td>1</td>
<td>09/09/2009</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>Sun Spirits</td>
<td>Handysize</td>
<td>Yes</td>
<td>0</td>
<td>22/01/2012</td>
<td>Philippines</td>
<td>China</td>
</tr>
<tr>
<td>Bingo</td>
<td>General Bulker</td>
<td>Yes</td>
<td>0</td>
<td>12/08/2013</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>Anna Bo</td>
<td>Handymax</td>
<td>No (Listed)</td>
<td>0</td>
<td>04/12/2013</td>
<td>Indonesia</td>
<td>China</td>
</tr>
</tbody>
</table>

The IMSBC Code, published by the IMO, outlines the dangers associated with certain types of solid bulk cargoes and provides procedures to be followed when transporting these materials (International Maritime Organization, 2013b). Included in the 2013 IMSBC Code are test methods used to determine the Transportable Moisture Limit (TML) of ‘Group A’ minerals. ‘Group A’ minerals are those that have the potential to liquefy due to the proportion of fine particles and moisture they contain (International Maritime Organization, 2013b). Prior to 2011, IOF were not specifically listed in the IMSBC Code. The circular (DSC.1/Circ66) sent out by the IMO, in 2011, temporarily reclassified IOF as a ‘Group A’, liquefiable material, until a permanent individual schedule can be agreed upon and incorporated in the IMSBC Code (International Maritime Organization, 2011).

Currently, the only parameter used to determine a minerals potential to liquefy, while being transported in bulk carriers, is the TML. The 2013 IMSBC Code refers to the TML as the maximum Gross Water Content (GWC) that certain mineral cargoes may contain, while being loaded in bulk carriers, without being at risk of liquefying during transportation (International Maritime Organization, 2013b). The GWC is calculated as the mass of water divided by the total wet mass. This is different from the moisture content or net water content, which is calculated as the mass of water divided by the total dry mass. Moisture content is more commonly used in geotechnical engineering than the GWC.

The objective of this study is to review the three test methods stated in the 2013 IMSBC Code, which are used to determine the TML of IOF. They are the Proctor/Fagerberg (PFT), Flow Table (FTT) and Penetration (PT) test methods. The study also covers recent developments and advancements made in the field, which includes details regarding goethite content provisions and results from the Modified Proctor/Fagerberg Test (MPFT), which are included in the 2013 draft individual schedule for IOF, and to be amended in the 2015 IMSBC Code (International Maritime Organization, 2013a).
8.3.3 Original Test Methods

In the 2013 IMSBC Code, there are three test methods used to determine the TML of ‘Group A’ cargoes, which are those that are potentially liquefiable. The three test methods are the Proctor/Fagerberg (PFT), Flow Table (FTT) and Penetration (PT) test methods (International Maritime Organization, 2013b). More details in regards to the three test methods stated in the 2013 IMSBC Code can be found in the associated comprehensive comparison study (Munro and Mohajerani, 2015).

8.3.3.1 Proctor/Fagerberg Test (PFT)

The PFT was first published in Stockholm in 1962 by Bengt Fagerberg and Kjell Eriksson as part of a committee established by the Swedish Mining Association and several Scandinavian mining companies. The committee was given the task to develop a simple method for determining the TML of ore concentrates (Fagerberg and Stavang, 1971). The test method is based upon the use of the Proctor apparatus (ASTM Standard D-698), which was developed by Ralph Proctor for use in soil mechanics (Proctor, 1933), and was adopted by the IMO, for use in the IMSBC Code, between 1991 and 1998.

The procedure involves compaction of the material, into a standard litre compaction mould, at varying moisture contents, to produce a compaction curve with a minimum of five data points. The compaction is executed in five layers by dropping a 350g hammer, 25 times, through a guided pipe from a height of 200mm. For each point, the GWC and void ratio is calculated then plotted on a graph along with the corresponding degree of saturation ($S_w$). The resulting GWC is then interpreted, from the graph, where $S_w$ equals 70%. This value is referred to as the TML (International Maritime Organization, 2013b). The PFT uses approximately 14% of the standard Proctor compaction energy and requires the specific gravity to produce the corresponding $S_w$. A typical compaction curve of IOF, produced during this study, can be seen in Figure 111.

![Figure 111 – Graphical representation of a typical PFT compaction curve of IOF produced during this study](image-url)
8.3.3.2 Flow Table Test (FTT)

The FTT has been widely used in the cement industry to test hydraulic cement. The early IMSBC Code included a modified procedure, created by the Department of Mines and Technical Surveys in Canada that can be used to determine the TML of ore concentrates and coal (Fagerberg and Stavang, 1971). In 2000, this method branched out into an ISO (International Organization for Standardization) guide (ISO 12742).

The FTT is performed by compacting a sample, in three layers, into a conical shaped mould in the centre of the Flow Table. Compaction is performed using a tamping rod, which is set to a predetermined pressure. For a typical sample of IOF, the tamping pressure used is approximately 450kPa (~33kg.f for a 30mm diameter tamper head). The tamping pressure depends on the properties of the sample being tested. The tamping pressure ($P$) is determined (in Pa), prior to performing the FTT, using the formula $P = \rho \times d \times g$, where $\rho$ is the bulk density (in kg/m$^3$) obtained by performing the standard Proctor compaction, which is described in ASTM Standard D-698, $d$ (in m) is the maximum depth of the cargo and $g$ is the acceleration due to gravity (in m/s$^2$).

After compaction is complete, the mould is carefully removed. Immediately after the mould is removed, the Flow Table is raised and dropped 50 times through a height of 12.5mm at a rate of 25 times per minute. This procedure is then repeated at different moisture contents. During testing at different moisture contents, the operator visually determines whether the sample is showing plastic deformation by using height and width measurements together with observing the behaviour of the sample while the Flow Table is being dropped. The point of change between the sample showing plastic deformation and not showing plastic deformation is referred to as the Flow Moisture Point (FMP). When a sample has been observed exceeding the FMP it is oven dried along with the previous sample, which should be just below the FMP, so that the GWC, of each, can be calculated. The mean of these two values is referred to as the FMP and 90% of the FMP is referred to as the TML (International Maritime Organization, 2013b).

8.3.3.3 Penetration Test (PT)

The PT was developed in Japan at the Research Institute of Marine Engineering (Tanaka and Ura, 1989). It was adopted by the IMO, between 1991 and 1998, for determining the TML of coal and ore concentrates.

The PT is performed by compacting a sample, in four layers, into a cylindrical mould. The sample is compacted with an adjustable tamper, using a tamping pressure similar to what would be used in the FTT, so that the surface of the sample is flat and level. The developer of the test states that “tamping does not affect the result of the PT, because the sample is quickly consolidated by vibration from the vibrating table regardless of the pressure of tamping conducted prior to the test” (Tanaka and Ura, 1989).

After compaction is complete the mould is attached to a vibrating table and a Penetration bit is placed on the surface of the material. The vibrating table is then operated at a frequency of 50-60Hz with an acceleration of 2g RMS for 6 minutes. After 6 minutes the depth of penetration, by the penetration bit, is recorded. This procedure is performed at varying moisture contents. When the depth of penetration is greater than 50mm the FMP has been exceeded and the sample is oven dried along with the previous sample, which should be just below the FMP, so that the GWC, of each, can be
calculated. The mean of these two values is referred to as the FMP and 90% of the FMP is referred to as the TML (International Maritime Organization, 2013b).

8.3.4 Recent Developments in Transportable Moisture Limit Testing
After the temporary reclassification of IOF, in 2011 (International Maritime Organization, 2011), industry and research institutions began comprehensive research in order to understand the causes of liquefaction of IOF, while being transported. The outcome of their research was to implement a new test method, specifically designed for IOF, to prevent confusion caused by determining the TML using the three test methods, stated in the 2013 IMSBC Code, which were implemented for use with coal, fluorspar, ilmenite and mineral concentrates.

Currently the most recognized research is being carried out by the Iron Ore Technical Working Group (TWG). The TWG was established by the IMO late 2012 to “conduct research and coordinate recommendations and conclusions about the transportation of IOF” (Iron Ore Technical Working Group, 2013c). The TWG is a collaboration of industry and research institutions managed by the Australian Mineral Industry Research Association (AMIRA). The TWG includes three of the largest iron ore producers; Rio Tinto, BHP Billiton and Vale, along with research institutions such as the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the University of Auckland and University of Newcastle (TUNRA) (AMIRA International, 2012).

The early implementation of the TWG’s research was introduced, in 2013, by the IMO in the circular DSC.1/Circ.71 (International Maritime Organization, 2013a). Included in this circular are draft schedules for iron ore and IOF, it also includes the draft for a new test method for determining the TML of IOF, the Modified Proctor/Fagerberg Test (MPFT), which is discussed in Section 8.3.4.2.

The circular states that although more research is required, the draft schedules and test method will be included in amendment 03-15 of the IMSBC Code in 2015 and entered into force on January 1, 2017. The Australian Maritime Safety Authority (AMSA) is one governing authority which has given the option for Australian export industries to voluntarily implement the draft schedules and draft test method for IOF (Australian Maritime Safety Authority, 2013a).

8.3.4.1 Goethite Content Provisions
Iron ore is commonly made up of three main constituents; goethite, hematite and magnetite. The TWG performed cyclic triaxial, direct shear and centrifugal tests to determine the liquefaction resistance of IOF with varying amounts of goethite (Iron Ore Technical Working Group, 2013c).

According to the research carried out by the TWG, the goethite content directly relates to the surface area of the particles and the volume of the pores that forms IOF. Furthermore, as the goethite content of IOF increases the material’s ability to hold water also increases. The TWG demonstrated that if the goethite content of IOF is greater than 35% by mass then the material survived cyclic triaxial testing and became more resistant to liquefaction because of its increased water holding ability. This is also shown by the material’s ability to prevent moisture migration during centrifugal testing. They also demonstrated that if the goethite content is less than 25% by mass then the material failed cyclic triaxial testing, produced more free water during centrifugal testing and therefore the potential for the material to liquefy was increased (Iron Ore Technical Working Group, 2013c).
In the draft individual schedule for IOF, it is stated that if the material contains more than 35% goethite by mass then the IOF can be treated as iron ore and therefore classified as a ‘Group C’ non-liquefiable material, otherwise the material is to be treated as IOF and therefore classified as a ‘Group A’ liquefiable material (International Maritime Organization, 2013a).

8.3.4.2 Modified Proctor/Fagerberg Test (MPFT)

In 2013, the MPFT was introduced, on a voluntary basis, by the IMO, in the circular DSC.1/Circ.71 (International Maritime Organization, 2013a). The MPFT is the only test method specifically designed for use with IOF.

The TWG is the main driving force behind the implementation of the MPFT, which is sometimes referred to as D80. The abbreviation D80 comes from previous research carried out by Bengt Fagerberg and Arne Stavang in 1971, where compaction method D was performed using a 150g hammer falling from 150mm, instead of a 350g hammer falling 200mm, which is the PFT and method C in Fagerberg and Stavang research (Fagerberg and Stavang, 1971). Also, instead of reading the TML from the intersection of the compaction curve and Sw equal to 70%, as stated in the PFT, it was recommended, by the TWG, to read the TML from the intersection of the compaction curve and Sw equal to 80%, for IOF (Iron Ore Technical Working Group, 2013a). Apart from the difference in Sw and compaction energy, the same procedure is used for both the PFT and MPFT, which can be seen Section 7.3.3.1.

To verify this procedure the TWG measured the bulk density of IOF in the holds of multiple bulk carriers, before and after transportation, through the means of height measurements, laser scanning and cone penetration testing. Using this data and additional bulk densities determined by drop tower testing the TWG concluded that the density produced by compaction during the MPFT was more than sufficient for replicating the density of IOF in the holds of bulk carriers. The MPFT is said to include a safety margin of approximately 10-15%, depending on the type of IOF being tested and uses around 5% of the standard Proctor compaction energy and 32% of the PFT compaction energy (Iron Ore Technical Working Group, 2013a).

8.3.4.3 Original Test Method Results

While evaluating the MPFT, the TWG tested the same samples of IOF using the three methods stated in the 2013 IMSBC Code (Iron Ore Technical Working Group, 2013a). The average variation from the PT to the FTT, the FTT to the PFT and the PT to PFT method was found to be approximately 18%, 8% and 27%, respectively. Figure 104, Table 30 and Table 39 demonstrates the different TML values that can be produced depending on the test method that is chosen.
Due to the varying results, research into the establishment of a new test method was required, by the IMO, which is specifically designed for IOF, to prevent confusion caused by determining the TML using the three test methods stated in the 2013 IMSBC Code. Because of this requirement the TWG produced the MPFT, which can be used on a voluntary basis until amended in the 2015 IMSBC Code (International Maritime Organization, 2013a). More comparisons, in regards to the three test methods
stated in the 2013 IMSBC Code, can be found in the associated comprehensive comparison study (Munro and Mohajerani, 2015).

8.3.5 This Studies Experimental Work

8.3.5.1 Physical Properties of IOF

Seen in Table 40 and Table 41 are typical properties of IOF that were tested during this study and the associated comprehensive comparison study (Munro and Mohajerani, 2015). The samples of IOF were obtained from various locations around Australia.

Table 40 – Properties of a typical sample of IOF that was used in this study

<table>
<thead>
<tr>
<th>Property</th>
<th>Result</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Dry Density (t/m³)</td>
<td>2.12</td>
<td>AS1289.5.5.1</td>
</tr>
<tr>
<td>Maximum Dry Density (t/m³)</td>
<td>3.08</td>
<td>AS1289.5.5.1</td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>18</td>
<td>AS1289.3.1.2</td>
</tr>
<tr>
<td>Plastic Limit (%)</td>
<td>16</td>
<td>AS1289.3.2.1</td>
</tr>
<tr>
<td>Plasticity Index (%)</td>
<td>2</td>
<td>AS1289.3.3.1</td>
</tr>
<tr>
<td>Standard Proctor Compaction - Optimum Moisture Content (%)</td>
<td>12.0</td>
<td>AS1289.5.1.1</td>
</tr>
<tr>
<td>Standard Proctor Compaction - Maximum Dry Density (t/m³)</td>
<td>2.73</td>
<td>AS1289.5.1.1</td>
</tr>
</tbody>
</table>

Table 41 – Typical ranges of properties of IOF used in this study

<table>
<thead>
<tr>
<th>Property</th>
<th>Minimum</th>
<th>Average</th>
<th>Maximum</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Moisture Content (%)</td>
<td>3.4</td>
<td>7.9</td>
<td>10.3</td>
<td>AS1289.2.1.1</td>
</tr>
<tr>
<td>Particle Density (t/m³)</td>
<td>3.78</td>
<td>4.27</td>
<td>4.91</td>
<td>AS1289.3.5.1</td>
</tr>
<tr>
<td>Coefficient of Uniformity (C_u)</td>
<td>24.9</td>
<td>119.3</td>
<td>273.2</td>
<td>AS1289.3.6.1</td>
</tr>
<tr>
<td>Coefficient of Curvature (C_c)</td>
<td>0.7</td>
<td>1.7</td>
<td>7.4</td>
<td>AS1289.3.6.1</td>
</tr>
</tbody>
</table>

8.3.5.2 Modified Proctor/Fagerberg Test Results

The MPFT, discussed in Section 8.3.4.2, is the only test method designed specifically for use with IOF (International Maritime Organization, 2013a). For this study, compactions on the same samples of typical IOF were performed using the PFT and MPFT, as seen in Figure 108 and Table 36. The average variation from the PFT to the MPFT was found to be approximately 14%. The same variation was seen by the TWG during their research into the MPFT (Iron Ore Technical Working Group, 2013c).

![Figure 113 – IOF TML values from the PFT and MPFT produced during this study](image-url)
Table 42 – IOF TML values from the PFT and MPFT produced during this study

<table>
<thead>
<tr>
<th>Sample</th>
<th>PFT TML (GWC %)</th>
<th>MPFT TML (GWC %)</th>
<th>Difference between the PFT and MPFT TML (GWC %)</th>
<th>Increase from PFT to MPFT TML (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>001</td>
<td>10.7</td>
<td>12.2</td>
<td>1.5</td>
<td>14.0</td>
</tr>
<tr>
<td>002</td>
<td>10.9</td>
<td>12.7</td>
<td>1.8</td>
<td>16.5</td>
</tr>
<tr>
<td>003</td>
<td>11.0</td>
<td>12.5</td>
<td>1.5</td>
<td>13.6</td>
</tr>
<tr>
<td>004</td>
<td>11.1</td>
<td>12.4</td>
<td>1.3</td>
<td>11.7</td>
</tr>
<tr>
<td>005</td>
<td>11.2</td>
<td>12.5</td>
<td>1.3</td>
<td>11.6</td>
</tr>
<tr>
<td>006</td>
<td>11.2</td>
<td>13.2</td>
<td>2.0</td>
<td>17.9</td>
</tr>
<tr>
<td>007</td>
<td>11.3</td>
<td>13.1</td>
<td>1.8</td>
<td>15.9</td>
</tr>
<tr>
<td>008</td>
<td>11.3</td>
<td>12.9</td>
<td>1.6</td>
<td>14.2</td>
</tr>
<tr>
<td>009</td>
<td>11.3</td>
<td>13.1</td>
<td>1.8</td>
<td>15.9</td>
</tr>
<tr>
<td>010</td>
<td>11.4</td>
<td>12.9</td>
<td>1.5</td>
<td>13.2</td>
</tr>
<tr>
<td>011</td>
<td>11.4</td>
<td>13.0</td>
<td>1.6</td>
<td>14.0</td>
</tr>
<tr>
<td>012</td>
<td>11.4</td>
<td>12.8</td>
<td>1.4</td>
<td>12.3</td>
</tr>
<tr>
<td>013</td>
<td>11.6</td>
<td>13.1</td>
<td>1.5</td>
<td>12.9</td>
</tr>
<tr>
<td>014</td>
<td>11.9</td>
<td>13.4</td>
<td>1.5</td>
<td>12.6</td>
</tr>
<tr>
<td>Average</td>
<td>11.3</td>
<td>12.8</td>
<td>1.6</td>
<td>14.0</td>
</tr>
</tbody>
</table>

The outcome of using a lighter compaction hammer and a lower hammer drop height, than the PFT, and interpreting the TML from the Degree of Saturation ($S_w$) equal to 80% instead of $S_w$ equal to 70%, all combine to produce a TML value greater than that produced by the three test methods stated in the 2013 IMSBC Code. The increased TML, produced by the MPFT, will allow IOF cargoes to be transported in bulk carriers with higher moisture contents than if one of the three test methods, stated in the 2013 IMSBC Code, were used.

8.3.6 Discussion

Since the temporary reclassification of IOF as a ‘Group A’ liqueifiable material, by the IMO in 2011, industry and research institutions have begun widespread research into individual bulk cargo behaviours while being transported at sea. The focus of their research is to determine the potential risk of liquefaction that minerals, such as IOF, pose while being transported in bulk carriers and to re-examine whether the test methods, stated in the 2013 IMSBC Code, are acceptable when determining the liquefaction potential of IOF.

Research by the TWG has produced draft schedules, in relating to TML testing of IOF, with the implementation of the MPFT and goethite content provisions, which are to be amended in the 2015 IMSBC Code. These recent developments could potentially solve the problem of liquefaction of IOF.

This study demonstrates that the test methods, stated in the 2013 IMSBC Code, are not appropriate for testing of IOF due to the TML values varying between test methods. Limited experimental results from this study shows that typical IOF can be transported with significantly higher moisture contents based on determining the TML using the MPFT when compared to the original test methods.

The TWG has performed essential research that can be used as a foundation for future studies. TML test methods for other minerals such as bauxite, manganese ore and nickel ore, are still absent or outdated. Further research into the cause of liquefaction of IOF and these other minerals, while being transported, is essential to prevent future loss of human life and assets.
8.4 SUPPLEMENTARY RESULTS AND FIGURES

There are no additional supplementary results and figures for this conference paper other than those included in the manuscript presented in Chapter 7, which are given in Appendix C. The supplementary results are the same, as this conference paper was based upon the manuscript presented in Chapter 7.

8.5 SUMMARY AFTER THE FACT

The summary after the fact, for this conference paper, includes the summary given in section 7.5 as this conference paper was based on the publication presented in Chapter 7. Additional to this information, by discussing the test methods in regards to liquefaction with others, it was confirmation of the direction of the research that we were undertaking. After the conference, preliminary testing began in order to design and develop the scale model presented in Chapter 14 and Chapter 16.
CHAPTER 9 VARIATION OF THE GEOTECHNICAL PROPERTIES OF IRON ORE FINES UNDER CYCLIC LOADING

9.1 INTRODUCTION

In order to design and develop the scale model presented in Chapter 14 and Chapter 16, preliminary testing had to be performed to understand the parameters that could and should be monitored. This peer-reviewed manuscript first introduces the four test methods used to determine the Transportable Moisture Limit (TML) of iron ore fines at the time. It then goes on to describe three different methods of experimental testing that were undertaken at this stage.

The methods undertaken during this stage of research were preliminary vibratory testing, hydraulic conductivity testing, and testing using the Iron Ore Fines Plunger (IOFP), which was designed and developed for this research. This plunger was developed alongside the scale model in order to give a quantifiable value to the loss of shear strength observed during the vibration of iron ore fines.

Exclusions made from this manuscript and not included in this chapter are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made continuous throughout this document.

9.2 CITATION

9.3 MANUSCRIPT CONTENTS

9.3.1 Abstract
Liquefaction, which can result in a vessel capsizing, is one of many hazards involved when transporting bulk cargoes. The objective of this study is to determine the variability of the geotechnical properties of Iron Ore Fines (IOF) under cyclic loading at different moisture contents to determine the liquefaction potential. The geotechnical properties include the void ratio, dry density, degree of saturation and angle of repose. Previous studies have proven that in a partially saturated material, under cyclic loading, these properties directly affect the shear strength and may cause a material to liquefy. Also, by measuring the penetration of a free-floating IOF Plunger (IOFP), developed during this study, the loss of shear strength was monitored. The results from this study show that significant variations occur in the geotechnical properties of IOF under cyclic loading at the varying moisture contents tested. Penetration from the IOFP was also observed, which indicated a reduction of effective stress and therefore shear strength within the samples IOF. The samples tested showed signs of liquefaction between the Proctor/Fagerberg and Modified Proctor/Fagerberg transportable moisture limits. It was concluded that the liquefaction potential of IOF is a function of the time of cyclic loading and initial moisture content.

9.3.2 Introduction
9.3.2.1 General
Iron Ore Fines (IOF) is a product produced from refining iron ore and commonly has a maximum particle size of 6.3 mm and a natural iron content of approximately 40 - 60%. Producing pig iron, which is used to make steel, from iron ore has been around since the Iron Age. Over the previous century improvements in the smelting process, used to create pig iron, has allowed companies to process ores with higher impurities, including IOF. Due to the improved processing abilities and therefore value of IOF, transporting this material around the world using bulk carriers has also increased. There are many hazards involved in the transportation of bulk granular mineral cargoes, one of which is liquefaction. Although not well understood at the time, liquefaction of bulk cargoes has been known to occur since 1910 with the loss of the Bengal (Sandvik and Rein, 1992). When a cargo such as IOF shifts in the hold of a bulk carrier, it is possible the weight of the unconstrained cargo can't be corrected with the available ballast. This, or a rapid change in the centre of gravity, can result in the transport vessel listing or even capsizing. Over the past seven years, liquefaction of IOF has been suspected of being the cause of at least nine cargo shifts, seven of which have resulted in the total loss of the vessel, as seen in Table 43 (Munro and Mohajerani, 2016b).

Table 43 – Recent incidents involving bulk carriers transporting IOF (Munro and Mohajerani, 2016b; TML Testing Wiki, 2015)

<table>
<thead>
<tr>
<th>Vessel Name</th>
<th>Subclass</th>
<th>Total Loss</th>
<th>Lives Lost</th>
<th>Date</th>
<th>Origin</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chang Le Men</td>
<td>Handysize</td>
<td>No (Listed)</td>
<td>0</td>
<td>07/09/2007</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>Mezzanine</td>
<td>Handysize</td>
<td>Yes</td>
<td>26</td>
<td>27/11/2007</td>
<td>Indonesia</td>
<td>China</td>
</tr>
<tr>
<td>Asian Forest</td>
<td>Handysize</td>
<td>Yes</td>
<td>0</td>
<td>17/07/2009</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>(see Figure 114)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hodasco 15</td>
<td>General Bulker</td>
<td>Yes</td>
<td>0</td>
<td>30/08/2009</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>Black Rose</td>
<td>Handymax</td>
<td>Yes</td>
<td>1</td>
<td>09/09/2009</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>(see Figure 115)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bright Ruby</td>
<td>Handymax</td>
<td>Yes</td>
<td>7</td>
<td>21/11/2011</td>
<td>Malaysia</td>
<td>China</td>
</tr>
<tr>
<td>Sun Spirits</td>
<td>Handysize</td>
<td>Yes</td>
<td>0</td>
<td>22/01/2012</td>
<td>Philippines</td>
<td>China</td>
</tr>
<tr>
<td>Bingo</td>
<td>General Bulker</td>
<td>Yes</td>
<td>0</td>
<td>12/08/2013</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>Anna Bo</td>
<td>Handymax</td>
<td>No (Listed)</td>
<td>0</td>
<td>04/12/2013</td>
<td>Indonesia</td>
<td>China</td>
</tr>
</tbody>
</table>
The International Maritime Solid Bulk Cargoes Code (IMSBC Code) has procedures to be followed when transporting solid bulk cargoes, which are considered to be potentially liquefiable (International Maritime Organization, 2013b). According to the IMSBC Code, these potentially liquefiable solid bulk cargoes, or ‘Group A’ cargoes, are to undergo Transportable Moisture Limit (TML) testing. The IMSBC Code infers the TML is the maximum Gross Water Content (GWC) that a cargo may contain without being at risk of liquefying. The GWC of a material is not as commonly used in geotechnical engineering as the Net Water Content (NWC). The GWC is calculated as a percentage using the moisture divided by the wet mass instead of the moisture divided by the dry mass.

9.3.2.2 Transportable Moisture Limit Test Methods

Currently, in the 2013 IMSBC Code, there are three test methods used to determine the TML of ‘Group A’ cargoes, which are those that are potentially liquefiable, including IOF (International Maritime Organization, 2013b). The three test methods are the Proctor/Fagerberg (PFT), Flow Table (FTT) and Penetration (PT) test methods and are discussed in Section 7.3.3.1 to 7.3.3.3. Typical results produced when testing IOF can be found in a related publication (Munro and Mohajerani, 2015).

Also, discussed in Section 8.3.4.2., is the new Modified Proctor/Fagerberg Test (MPFT). After the temporary reclassification of IOF, in 2011, as a potentially liquefiable material (International Maritime Organization, 2011), industry and research institutions began comprehensive research in order to understand the causes of liquefaction of IOF while being transported. The early implementation of this research was introduced, in 2013, by the IMO in the circular DSC.1/Circ.71 (International Maritime Organization, 2013a). Included in this circular is a draft schedule for iron ore, a draft schedule for IOF and a draft for a new test method for determining the TML of IOF, the MPFT. The circular states that although more research is required, the draft schedules and test method will be included in amendment 03-15 of the IMSBC Code in 2015 and entered into force on January 1, 2017 (International Maritime Organization, 2013a). Some flag administrations, including Brazil, Australia and the Marshall Islands, have voluntarily adopted the aforementioned schedules and test method as recommended by the IMO (International Maritime Organization, 2013a; UK P&I Club, 2014). Further information on the recent developments of TML testing of IOF can be found in a related publication (Munro and Mohajerani, 2016b).
9.3.2.2.1 Proctor/Fagerberg Test (PFT)

The PFT was first published in Stockholm in 1962 by Bengt Fagerberg and Kjell Eriksson as part of a committee established by the Swedish Mining Association and several Scandinavian mining companies. The committee was given the task to develop a simple method for determining the TML of ore concentrates (Fagerberg and Stavang, 1971). The test method is based upon the use of the Proctor apparatus (ASTM Standard D-698 (American Society for Testing and Materials, 2012)), which was developed by Ralph Proctor for use in soil mechanics (Proctor, 1933), and was adopted by the IMO, for use in the IMSBC Code, between 1991 and 1998.

The procedure involves compaction of a material, into a standard litre compaction mould, at varying moisture contents, to produce a compaction curve with a minimum of five data points. The compaction is executed in five layers by dropping a 350 g hammer, 25 times, through a guided pipe from a height of 200 mm. For each point, the GWC and void ratio is calculated then plotted on a graph along with the corresponding Degree of Saturation (S). The resulting GWC is then interpreted, from the graph, where S equals 70%. This value is referred to as the TML (International Maritime Organization, 2013b). The PFT uses approximately 14% of the standard Proctor compaction energy (e.g. AS1289 5.1.1 (Standards Australia, 2003b)) and requires the particle density (e.g. AS1289 3.5.1 (Standards Australia, 2006)) to produce the corresponding S. A typical compaction curve of IOF, produced during this study, can be seen in Figure 116 and the PFT apparatus can be seen in Figure 117.

![Graphical representation of a typical PFT compaction curve of IOF produced during a previous study](image-url)
9.3.2.2.2  Flow Table Test (FTT)
The FTT has been widely used in the cement industry to test hydraulic cement (American Society for Testing and Materials, 2008). The early IMSBC Code included a modified procedure, created by the Department of Mines and Technical Surveys in Canada that can be used to determine the TML of ore concentrates and coal (Fagerberg and Stavang, 1971). In 2000, this method branched out into an ISO (International Organization for Standardization) guide (International Standards Organization, 2007).

The FTT is performed by compacting a sample, in three layers, into a conical shaped mould in the centre of the Flow Table. Compaction is performed using a tamping rod, which is set to a predetermined pressure. The FTT, mould, table and tamper can be seen in Figure 118 and Figure 119 respectively. For a typical sample of IOF, the tamping pressure used is approximately 450 kPa (32.4 kg.f for a 30 mm diameter tamper head). The tamping pressure depends on the properties of the sample being tested. The tamping pressure \( P \) is determined (in Pa), prior to performing the FTT, using the formula \( P = \rho \times d \times g \), where \( \rho \) is the bulk density (in kg/m\(^3\)), \( d \) (in m) is the maximum depth of the cargo and \( g \) is the acceleration due to gravity (in m/s\(^2\)). The bulk density \( \rho \) is obtained by performing a single Proctor compaction, described in ASTM Standard D-698 (American Society for Testing and Materials, 2012), on a sample of the cargo at the moisture content at the time of loading.
After compaction is complete, the mould is carefully removed. Immediately after the mould is removed, the Flow Table is raised and dropped 50 times through a height of 12.5 mm at a rate of 25 times per minute. This procedure is then repeated at different moisture contents. During testing at different moisture contents, the operator visually determines whether the sample shows plastic deformation by using height and width measurements together with observing the behaviour of the sample while the Flow Table is being dropped. The point of change between the sample not showing plastic deformation and showing plastic deformation is referred to as the Flow Moisture Point (FMP). When a sample has been observed exceeding the FMP it is oven dried along with the previous sample, which should be just below the FMP, so that the GWC, of each, can be calculated. The mean of these two values is referred to as the FMP and 90% of the FMP is referred to as the TML (International Maritime Organization, 2013b).

9.3.2.2.3 Penetration Test (PT)

The PT was developed in Japan at the Research Institute of Marine Engineering (Tanaka and Ura, 1989). It was adopted by the IMO, between 1991 and 1998, for determining the TML of coal and ore concentrates.

The PT is performed by compacting a sample, in four layers, into a cylindrical mould. Although the developer of the test states that “tamping does not affect the result of the Penetration Test, because the sample is quickly consolidated by vibration from the vibrating table regardless of the pressure of tamping conducted prior to the test” (Tanaka and Ura, 1989), the IMSBC Code states the sample is to be compacted with an adjustable tamper using the same pressure that would be used during the FTT so that the surface of the sample is flat and level (International Maritime Organization, 2013b).
After compaction is complete the mould is attached to a vibrating table and a Penetration bit is placed on the surface of the material. The penetration bit used depends on the material being tested, 5 kPa for coals or 10 kPa for ore concentrates. The PT apparatus and penetration bits can be seen in Figure 120 and Figure 121 respectively. After the penetration bit is placed on the sample the vibrating table is then operated at a frequency of 50-60 Hz with an acceleration of 2 g RMS for 6 minutes. After 6 minutes the depth of penetration, by the penetration bit, is recorded. This procedure is performed at varying moisture contents. When the depth of penetration is greater than 50 mm the FMP has been exceeded and the sample is oven dried along with the previous sample, which should be just below the FMP, so that the GWC, of each, can be calculated. The mean of these two values is referred to as the FMP and 90% of the FMP is referred to as the TML (International Maritime Organization, 2013b).

9.3.2.2.4 Modified Proctor/Fagerberg Test (MPFT)

In 2013, the Modified Proctor/Fagerberg Test (MPFT) was introduced, on a voluntary basis by the International Maritime Organization (IMO) in the circular DSC.1/Circ.71 (International Maritime Organization, 2013a). The MPFT, which is sometimes referred to as D80, is the only test method specifically designed for use with IOF. The abbreviation D80 comes from previous research carried out by Bengt Fagerberg and Arne Stavang in 1971, where compaction method D was performed using a 150 g hammer falling from 150 mm, instead of the 350 g hammer falling 200 mm, which is used for the PFT described in Section 7.3.3.1 and method C in Fagerberg and Stavang research (Fagerberg and Stavang, 1971). Also, instead of reading the TML from the intersection of the compaction curve and Degree of Saturation (S) equal to 70%, as stated in the PFT, it was recommended, by the Iron Ore Technical Working Group (TWG), to read the TML from the intersection of the compaction curve and
S equal to 80%, for IOF (Iron Ore Technical Working Group, 2013a). A comparison between the PFT and MPFT compaction hammers and typical compaction curves can be seen in Figure 122 and Figure 123 respectively. Apart from the difference in $S$, and compaction energy, the same procedure is used for both the PFT and MPFT.

*Figure 122 – Comparison between the compaction hammers used during the PFT and the MPFT*
During development of the MPFT the bulk density of IOF in the holds of multiple bulk carriers were measured, before and after transportation, through the means of height measurements, laser scanning and cone penetration testing. By using this data it was concluded that the density produced by compaction during the MPFT was more than sufficient for replicating the density of IOF in the holds of a bulk carrier after transportation (Iron Ore Technical Working Group, 2013a, 2013c). The MPFT is said to include a safety margin of approximately 10-15%, depending on the type of IOF being tested and uses around 5% of the standard Proctor compaction energy (e.g. AS1289 5.1.1 (Standards Australia, 2003b)) and 32% of the PFT compaction energy (Iron Ore Technical Working Group, 2013a).

9.3.2.2.5  Summary of Current Test Methods
The four Transportable Moisture Limit (TML) test methods mentioned each have their pros and cons relating to when they should be implemented and for which cargoes. Table 44 has been provided to clearly identify the main differences between the test methods.
## Table 44 – Differences between the test methods currently used to determine the TML of ‘Group A’ or liquefiable solid bulk cargoes

<table>
<thead>
<tr>
<th></th>
<th>Proctor/Fagerberg Test (PFT)</th>
<th>Flow Table Test (FTT)</th>
<th>Penetration Test (PT)</th>
<th>Modified Proctor/Fagerberg Test (MPFT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters Needed</td>
<td>Specific Gravity</td>
<td>FMP, TML</td>
<td>FMP, TML</td>
<td>Specific Gravity</td>
</tr>
<tr>
<td>Safety Factor</td>
<td>None a</td>
<td>10% of FMP</td>
<td>Coal and Ore Concentrates</td>
<td>TML</td>
</tr>
<tr>
<td>Cargo Type</td>
<td>Ore Concentrates</td>
<td>1-7 mm (depending on percentage of particles)</td>
<td>Coal and Ore Concentrates</td>
<td>Iron Ore Fines</td>
</tr>
<tr>
<td>Maximum Particle Size</td>
<td>5mm</td>
<td>10 mm (1.7 L mould) or 25 mm (4.7 L mould)</td>
<td>Objective</td>
<td>50% or more of particles less than 10 mm</td>
</tr>
<tr>
<td>Objective/Subjective</td>
<td>Objective</td>
<td>Subjective</td>
<td>Objective</td>
<td>Objective</td>
</tr>
<tr>
<td>Sample Needed</td>
<td>~20 kg</td>
<td>~5 to 10 kg</td>
<td>~25 kg (10 mm Particle Size) or ~70 kg (25 mm Particle Size)</td>
<td>20 kg</td>
</tr>
<tr>
<td><strong>Advantages</strong></td>
<td>- Incorporates common equipment and procedures known by competent geotechnical laboratories.</td>
<td>- Incorporates common equipment and procedures.</td>
<td>- Calculations are very simple.</td>
<td>- Incorporates common equipment and procedures known by competent geotechnical laboratories.</td>
</tr>
<tr>
<td></td>
<td>- Equipment portable.</td>
<td>- Widely used test not only in the geotechnical engineering field but also in the cement industry.</td>
<td>- Can be used on cargoes with large particle sizes up to 25 mm.</td>
<td>- Equipment portable.</td>
</tr>
<tr>
<td></td>
<td>- Proven to be repeatable and reproducible between laboratories due to the objective nature of the test.</td>
<td>- The technical background and concept behind the methodology is based on common geotechnical science and engineering practice (i.e. operator can visually see deformation caused by pore pressures within the material building).</td>
<td>- Proven to be repeatable and reproducible between laboratories due to the objective nature of the test (i.e. penetration greater or less than 50 mm).</td>
<td>- Proven to be repeatable and reproducible between laboratories due to the objective nature of the test.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Needs the least amount of material to perform the test.</td>
<td>- Although the cyclic loading has no relation to real word conditions on a vessel, the technical background and concept behind the methodology is based on common geotechnical science and engineering practice.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Takes the least amount of time to perform (same as PT).</td>
<td>- Takes the least amount of time to perform (same as FTT).</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Includes a significant safety factor.</td>
<td>- Includes a significant safety factor.</td>
<td></td>
</tr>
<tr>
<td><strong>Disadvantages</strong></td>
<td>- Needs the specific gravity of the cargo which can be determined a number of ways, varying the results.</td>
<td>- FMP heavily dependent on the operator’s ability to determine plastic deformation.</td>
<td>- Expensive and sensitive and equipment used that is not typically found in geotechnical laboratories.</td>
<td>- Needs the specific gravity of the cargo which can be determined a number of ways, varying the results.</td>
</tr>
</tbody>
</table>
- The technical background and concept behind the methodology is not based on common geotechnical science and engineering practice (i.e. Proctor tests in soil mechanics never used to determine liquefaction potential of soils).
- Calculations are complicated and can result in erroneous results.
- Takes the longest time to perform due to the specific gravity being needed.
- Can only be used on cargoes with small particle sizes.
- The technical background and concept behind the methodology is not based on common geotechnical science and engineering practice (i.e. Proctor tests in soil mechanics never used to determine liquefaction potential of soils).
- Calculations are complicated and can result in erroneous results.
- Takes the longest time to perform due to the specific gravity being needed.

*a* There is no safety factor applied or built into the PFT as inferred by Bengt Fagerberg; liquefaction is likely to occur at the Optimum Moisture Content (OMC) and the OMC of the ore concentrates researched by Fagerberg occurred at 70% saturation and this is where Fagerberg decided to obtain the TML (Fagerberg and Stavang, 1971).

*b* Approximately 10% based on the same theory given above whereby the research group considered IOF liquefiable at the OMC for IOF (between 90 and 95% saturation) and then taking the TML at the degree of saturation equal to 80% (Iron Ore Technical Working Group, 2013a).

*c* Inferred from the individual schedule for IOF (International Maritime Organization, 2015e).

Although only subjective observations have been made, a disadvantage that all the tests have is that non-uniformity of the physical properties can occur throughout a solid bulk cargo. All the tests mentioned in Table 44 use the average properties of the material to determine the FMP and TML. This is simply due to the complex nature of a non-uniform unsaturated cargo and the sheer amount of possibly combinations that would need testing. It is noted that the average properties used to determine the FMP and TML may not be the “worst case scenario” conditions that may occur in the hold of a bulk carrier. This also means that even if a cargo is loaded under the TML a portion of the cargo may become wetter due to moisture migration and exceed the TML. Future research hopes to determine the chance that this may occur.

A previous study has shown the differences between the TML produced by the four test methods, which can be seen in Figure 124 and Figure 125. It is clearly seen that each test has a general trend. The PT test produces the most conservative results, with the lowest TML values. The FTT, PFT and MPFT follow giving increasing TML values, respectively.

Figure 124 – IOF TML values determined using the PT, FTT and PFT produced by the TWG (Iron Ore Technical Working Group, 2013a)

Figure 125 – IOF TML values determined using the PFT and MPFT (Munro and Mohajerani, 2016b)
9.3.2.3 Objective

Issue 197 of Gard News published in 2010 is an article in on liquefaction of unprocessed mineral ores (Jonas, 2010). Discussed within are regulatory requirements, details regarding the test methods stated in the IMSBC Code and the principals of liquefaction of bulk cargoes. Conversed within is that “Although [solid bulk cargoes] often look dry in appearance at the time of loading, these cargoes contain moisture within the particles” and that due to cyclic loading, compaction of the cargo occurs, which “leads to a reduction of the spaces within the particles”.

The objective of this study is to determine the variation in the geotechnical properties of IOF under cyclic loading at varying moisture contents to determine the risk of liquefaction during transportation. These geotechnical properties include the maximum deviation of void ratio, dry density, degree of saturation and angle of repose. Previous studies have proven that in a partially saturated material under cyclic loading, these properties directly affect the pore pressures and therefore govern the resulting effective stress. If the effective stress is reduced to near zero, the undrained shear strength will also be reduced and may cause the material to liquefy. Also investigated is whether it can be determined if samples of IOF have reduced shear strength under cyclic loading at high moisture contents by directly measuring the penetration of an IOF Plunger (IOFP), developed during this study.

This is a preliminary study that will be used in the future to determine the feasibility of producing a scale model to determine, more accurately, the liquefaction potential of IOF.

9.3.3 Materials

The two samples of IOF that were tested during this study, seen in Figure 126 and Figure 127, were obtained from locations around Australia. The geotechnical properties of the two samples and the standards to which they were obtained can be seen in Table 45 and Figure 128.
### Table 45 – Geotechnical properties of the two samples of IOF used during this study

<table>
<thead>
<tr>
<th>Test</th>
<th>Standard</th>
<th>IOF Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atterberg Limits:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Liquid Limit                  | AS1289 3.1.2 (Standards Australia, 2009a)                                | NP (Non-Plastic) | 18% NWC  
| Plastic Limit                 | AS1289 3.2.1 (Standards Australia, 2009b)                                | NP (Non-Plastic) | 17% NWC  
| Plasticity Index             | AS1289 3.3.1 (Standards Australia, 2009c)                                | NP (Non-Plastic) | 1% NWC  
| Classification               | AS1769 Appendix A (Standards Australia, 1993)                            | NP (Non-Plastic) | ML (Low Plasticity Silt)  
| Particle Density              | AS1289 3.5.1 (Standards Australia, 2006)                                 | 3.90 t/m³    | 4.36 t/m³  
| Standard Proctor Compaction   | AS1289 5.1.1 (Standards Australia, 2003b)                                | 2.55 t/m³ at 12.5% | 2.76 t/m³ at 12.5%  
| Modified Proctor Compaction   | AS1289 5.2.1 (Standards Australia, 2003c)                                | 2.67 t/m³ at 11.0% | 2.89 t/m³ at 10.5%  
| Minimum Density               | AS1289 5.5.1 (Standards Australia, 1998)                                 | 2.00 t/m³    | 2.27 t/m³  
| Modified Proctor/Fagerberg TML| IMO Circular DSC.1/Circ.71 (International Maritime Organization, 2013a)  | 12.6% GWC with OMC at 93% Saturation | 12.7% GWC with OMC at 92% Saturation  
| Proctor/Fagerberg TML         | 2013 IMSBC Code Appendix 2 (1.3) (International Maritime Organization, 2013b) | 11.1% GWC | 11.4% GWC  
| Flow Table TML (35kg.f)       | 2013 IMSBC Code Appendix 2 (1.1) (International Maritime Organization, 2013b) | 10.2% GWC | 10.3% GWC  
| Quantitative X-Ray Diffraction: | X’Pert Pro PW3040 (N/A) X’Pert Pro PW3040 (N/A) | 54% Total Weight | 41% Total Weight *  

* According to IMO Circular DSC.1/Circ.71 and MSC 95/22/Add.2, if a cargo of iron ore fines has more than 35% goethite total weight then the schedule for iron ore (not iron ore fines) should be followed and the cargo does not need to undergo TML testing using the Modified Proctor/Fagerberg method (MPFT) as it is not considered liquefiable (International Maritime Organization, 2013a, 2015e). Research regarding the implementation of this classification of iron ore is shown in reports released relating to the development of the MPFT (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e).
The samples geotechnical properties were determined using the standard AS 1289 – Method of testing soils for engineering purposes (Standards Australia, 2000) and the TML values using the appropriate method stated in either the 2013 IMSBC Code (International Maritime Organization, 2013b) or in the circular DSC.1/Circ.71 (International Maritime Organization, 2013a). Note that it is considered to be a coincidence that the Transportable Moisture Limit (TML) results for both samples are similar as the geotechnical properties of both samples are significantly different.

As seen in Figure 128, sample MA003 has significantly finer particles than sample MA002. Sample MA003’s particle density is also significantly higher than sample MA002. These two samples were chosen for this study because they are considered to be typical samples commonly transported on bulk carriers from Australia. In a related publication the range of typical properties of IOF were determined (Munro and Mohajerani, 2015). The geotechnical properties of the two samples tested during this study are within the range of the typical properties of IOF determined in the related publication (Munro and Mohajerani, 2015).

9.3.4 Methods

9.3.4.1 Background

Liquefaction can occur in both saturated and unsaturated granular materials (e.g. (D. G. Fredlund and Rahardjo, 1993), (Ishihara, 1985) and (Lambe and Whitman, 1969)). Eq. 15 show the relationship between the effective stress (σ’), normal stress (σ) and pore water pressure (u_w) of a saturated material (e.g. (Terzaghi and Peck, 1967) and (Bishop and Eldin, 1950)). Referring to basic soil mechanics, the effective stress directly affects the resulting shear stress, and Eq. 15 show that
increasing only the pore water pressure, which can occur during cyclic loading, reduces the effective stress in a saturated material. If the effective stress of a cohesionless material is reduced to zero, the shear stress is also reduced to zero and the material can potentially liquefy.

\[ \sigma' = \sigma - u_w \]  \hspace{1cm} (Eq. 15)

Likewise, in a partially saturated cohesionless material, such as a cargo of IOF, when the effective stress is reduced to zero, the shear stress is also reduced to zero. The difference between the resulting effective stress of a saturated versus partially saturated material is the presence of pore air pressure \( u_a \) and a factor of the degree of saturation \( \chi \), as seen in Eq. 16 (e.g. (Bishop, 1959), (D.G. Fredlund et al., 1978), (J.K.M. Gan and Fredlund, 1988) and (Vanapalli et al., 1996)). If the degree of saturation is increased by densification to a point at which further cyclic loading can trigger pore pressures of sufficient magnitude and duration the shear strength maybe reduced to zero and the material may potentially liquefy.

\[ \sigma' = (\sigma - u_a) + \chi(u_a - u_w) \]  \hspace{1cm} (Eq. 16)

Since the effective stress \( \sigma' \) of a saturated material is related to the void ratio (Terzaghi, 1948), the same can therefore be said for a partially saturated material. Due to this the void ratio and degree of saturation of a material can both be considered function of a material’s ability to liquefy and determining the variations in these variables under cyclic loading is deemed critical to understand the potential a material has to liquefy.

When loading IOF into the holds of bulk carriers, the initial loading technique, drop height and varying geotechnical properties, from location to location, of different IOF will contribute to the initial density of the cargo. The initial density also highly depends on the moisture content at which the cargo is loaded. Since the density and moisture content are directly related to the void ratio and degree of saturation, these initial geotechnical properties of a loaded cargo of IOF may vary significantly. These variables along with the particle size distributions are considered to contribute significantly to the liquefaction potential of IOF (Lambe and Whitman, 1969).

Under some circumstances the initial density may not be the maximum density experienced by IOF during a voyage. A typical voyage from Australia to China can take a bulk carrier loaded with IOF 17 days and can take as much as 40 days from Brazil to China (Iron Ore Technical Working Group, 2013b). Assuming during a voyage a cargo of IOF was to undergo densification to what degree the cargo densifies depends on the initial density, moisture content and the cyclic energy transmitted to cargo. During a voyage, cyclic energy is produced by the ocean waves and transferred through the superstructure of a bulk carrier to the cargo being transported. A cargo of IOF before and after transportation can be seen in Figure 129 and Figure 130 and images of the hypothetical process can be seen in Figure 131 and Figure 132.
During a typical voyage of a bulk carrier transporting IOF, the sea state is inconsistent and varies from location to location depending on variables such as the wind, waves, currents, aquatic terrain and the vessels proximity to land mass. Due to the varying sea state throughout a voyage the authors have assumed the density change over time of a cargo, if it was to occur, would have a profile similar to what is seen in Figure 133 (Assumed). Also seen in Figure 133 is the profile that was used during Vibration Testing (Simplified). In soil mechanics, the simplified profile seen in Figure 133 is also known as strain hardening as the density is a function of a material’s shear strength. By increasing the density, the shear strength is also increased. If the combination of pore pressures and increase in the degree of saturation overcome the increase in shear strength by strain hardening the material can potentially liquefy.
Fig. 133 – Density versus time graph of assumed and simplified cargo densification during transport

9.3.4.2 Hydraulic Conductivity
In order to determine the effect periods of rest would have on the samples ability to dissipate pore pressures, a sample of IOF from the same region was placed in a Rowe Cell, saturated and consolidated under varying pressures (σ) (Head, 1998). From this, the coefficient of compressibility (\(m_v\)) and coefficient of consolidation (\(C_v\)) were determined and the hydraulic conductivity (k) was both calculated using the coefficient of consolidation and directly measured using a burette.

Stated by Lambe and Whitman (1969), the following five characteristics influence the hydraulic conductivity of a material; Particle Size, Void Ratio, Composition, Fabric and Degree of Saturation (Lambe and Whitman, 1969). Also, as discussed in Section 9.3.4.1, the void ratio and degree of saturation also relates to the effective stress of a material and therefore the internal pore pressures. It is then safe to assume that the hydraulic conductivity of IOF directly relates to the dissipation of pore air and pore water pressures at any given time.

Due to the relationship between the hydraulic conductivity and the dissipation of pore air and pore water pressures, by determining the hydraulic conductivity the authors can determine the likelihood dissipation of pore pressures would occur during calm sea states. If change in pore pressures are unlikely to occur during calm sea states, the simplified profile can be assumed to accurately represent the density change of the cargo during transportation. Analysis of the results from the Rowe Cell can be seen in Section 9.3.5.3.

9.3.4.3 Vibration Testing
In order to investigate the variation of void ratio, dry density, degree of saturation and angle of repose of IOF under cyclic loading, the authors subjected two samples to what has been termed Vibration Testing for this study. To perform these tests, the authors gently scooped samples of IOF, at varying moisture contents, into a 3 L mould, as seen in Figure 134. The mould was then placed on a vibrating table, seen in Figure 135, and while monitoring the change in height the vibrating table was turned on for 25 minutes. After 25 minutes of operation a 12 kg (6.7 kPa) surcharge, which has a diameter the same as the inner diameter of the mould, was placed on the sample and the vibration continued for...
an additional 10 minutes. This particular surcharge and mould is used in AS 1289.5.5.1 to determine the maximum dry density of a cohesionless material (Standards Australia, 1998). For this reason, it is assumed this surcharge will produce the maximum density for this sample size.

![Figure 134 – Vibration Test mould and sample](image)

![Figure 135 – Mould on vibrating table](image)

The vibrating table was set at a nominal frequency of 50 Hz and a vertical double amplitude setting of 0.5 ±0.05 mm. This frequency and amplitude is also used in AS 1289.5.5.1-1998 to determine the maximum dry density of a cohesionless material (Standards Australia, 1998), and similar to the IMSBC Code’s Penetration test frequency, which is discussed in Section 7.3.3.3. Although the frequency and amplitude at which the vibrating table was operated does not replicate the frequency and amplitude of the cyclic energy that would be applied to a bulk carrier during a voyage it will indicate to what extent the geotechnical properties of IOF will vary. It will also allow us to monitor the possible variation of the geotechnical properties, including the shear strength of the sample, over a more feasible period of time.

The compaction profile produced by a compaction hammer would be significantly different to that of a vibrating table. Vibrating IOF at low moisture contents will increase the density due to particle rearrangement. At the higher moisture contents, pore pressures within the material will change possibly causing moisture and air to migrate to the surface resulting in an increase in density. If a compaction hammer was used to perform compactions, at low moisture contents a thin film of water tends to keep particles within the material apart producing a low density. When the moisture content is increased the additional lubrication allows the particles to be more closely packed together and therefore the density increases. Once the majority of air voids are filled with water, further compactions by a hammer increase the pore water pressure within the sample expelling material and therefore reducing the density (Head, 1992).

During recent studies, it has been concluded that there is no more than a 1% reduction in the moisture content from loading to the discharge of a cargo of IOF. This is based on bilge pump data from bulk carriers carrying IOF (Iron Ore Technical Working Group, 2013b). Due to this finding, the authors have completed the Vibration Tests under undrained conditions where the moisture content of each sample of IOF remained constant.
9.3.4.4 Penetration by Iron Ore Fines Plunger (IOFP)

To verify that loss of shear strength of IOF occurs under cyclic loading the authors also utilized a free-floating IOF Plunger (IOFP), as seen in Figure 136 and Figure 137, with a contact pressure of 845 g (16.36 kPa). The IOFP was used to determine the change in penetration over a range of moisture contents. The IOFP was based off the apparatus used during the Penetration Test described in 7.3.3.3. Because IOF contains larger particles compared with the original materials that the Penetration Test was designed for, specifically coal and ore concentrates, the dimensions of the IOFP were increased along with the contact pressure. Originally 15 mm diameter indicator bits were used during the Penetration Test with contact pressures of 5 kPa and 10 kPa. During this study, we manufactured the IOFP with an increased diameter of 25.4 mm and contact pressure of 16.36 kPa. We assumed by that increasing these variables the IOFP would not be obstructed by the larger particles within the sample and will produce a more repeatable test.

The sample was placed into a 30 L rectangular mould with a maximum depth of 250 mm. After the sample had been vibrated for 3600 seconds (1 hour) and reached its maximum density, the IOFP was placed on the sample and vibrated for an additional 900 seconds (15 minutes). During the penetration of the IOFP the time and depth of penetration by the IOFP was recorded.

Based on the theory discussed in Section 9.3.4.1, if the IOFP penetrates into the material then it can be assumed the effective stress surrounding the IOFP has reduced to zero along with the shear strength and therefore the material may have undergone liquefaction. It is hoped that by using this method the authors can determine a critical moisture content for the material at which liquefaction may occur under the applied magnitude and time of cyclic loading.
9.3.5 Analysis of Results

9.3.5.1 Vibration Testing

To investigate the variation of the physical of IOF under cyclic loading, the authors subjected two samples of IOF to Vibration Testing, as described in Section 9.3.4.3. For each sample, the authors performed three Vibration Tests at different moisture contents corresponding to the Proctor/Fagerberg Test TML (Point A), the Modified Proctor/Fagerberg TML (Point B) and approximately one percent wetter than the Modified Proctor/Fagerberg TML (Point C). These values, which can be seen in Table 46, varied slightly from the TML’s seen in Section 9.3.3 due to minor discrepancies while adding moisture to the samples. The PFT and MPFT are discussed in more detail in Section 8.3.3.

Table 46 – Vibration Test moisture contents for sample MA002 and sample MA003

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sample MA002</th>
<th></th>
<th></th>
<th>Sample MA003</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point A</td>
<td>Point B</td>
<td>Point C</td>
<td>Point A</td>
<td>Point B</td>
<td>Point C</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>(PFT TML)</td>
<td>(MPFT TML)</td>
<td>(MPFT TML + 1%)</td>
<td>(PFT TML)</td>
<td>(MPFT TML)</td>
<td>(MPFT TML + 1%)</td>
</tr>
<tr>
<td>(% NWC)</td>
<td>12.29</td>
<td>13.99</td>
<td>14.80</td>
<td>12.81</td>
<td>14.54</td>
<td>15.27</td>
</tr>
<tr>
<td>Gross Water Content (% GWC)</td>
<td>10.94</td>
<td>12.27</td>
<td>12.89</td>
<td>11.36</td>
<td>12.70</td>
<td>13.25</td>
</tr>
</tbody>
</table>

In order to present the change in volume of the samples over the duration of the Vibration Tests, Figure 138 to Figure 143 illustrate the change in height against time using a selection of measurements that were taken during testing. This produces a visual surface profile of each sample. As expected, the samples tested at Point C, which are seen in Figure 142 and Figure 143, show the fastest decrease in height. Further increasing the time or magnitude of cyclic loading may produce no significant change in the final surface profile of these samples. The time and magnitude of cyclic loading was used as it is considered to represent the worst-case scenario, when compared to the conditions experienced by a cargo in the hold of a bulk carrier. These height measurements directly relate to the volume and therefore the geotechnical properties of the material could be calculated.
One of the geotechnical properties that could be calculated from the height measurements taken during the Vibration Tests is the angle of repose of the material against the time of vibration. The initial average angle of repose along with the average changes of the angle of repose during the vibration test from Point A to Point B are shown in Table 47 and Figure 144.

Table 47 – sample MA002 and MA003 average variation of the angle of repose during the Vibration Test

<table>
<thead>
<tr>
<th>Time (Secs)</th>
<th>Angle of Repose (°)</th>
<th>Average of sample MA002 and MA003</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Point A (PFT TML)</td>
<td>Point B (MPFT TML)</td>
</tr>
<tr>
<td>0</td>
<td>35</td>
<td>32</td>
</tr>
<tr>
<td>1</td>
<td>35</td>
<td>31</td>
</tr>
<tr>
<td>5</td>
<td>31</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>31</td>
<td>29</td>
</tr>
</tbody>
</table>
Figure 144 – sample MA002 and MA003 average variation of the angle of repose during the Vibration Test (Point A = PFT TML, Point B = MPFT TML and Point C = 1% + MPFT TML)

The data shown in Table 47 and Figure 144 show that as the moisture content of the samples of IOF increases so does the time and extent of change of the angle of repose. The sample tested at the highest moisture content (Point C = 1% + MPFT TML) indicates a trend that will end with the sample having no angle of repose (level surface), which is expected if the material has liquefied.

Additional to the angle of repose, by measuring the sample height to determine the volume and using the measured moisture content, the void ratio, dry density and degree of saturation could be calculated. The tabulated data produced while performing the Vibration Tests from Point A to Point C can be seen in Table 48 to Table 50 respectively, and a summary of the final properties can be seen in Table 51 and Table 52.

Table 48 – sample MA002 and MA003 variation in dry density, void ratio and degree of saturation during the Vibration Test (point A)

<table>
<thead>
<tr>
<th>Time (Seconds)</th>
<th>Sample MA002 (GWC = 10.94%)</th>
<th>Sample MA003 (GWC = 11.36%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Density (t/m³)</td>
<td>Change in Dry Density (t/m³)</td>
</tr>
<tr>
<td>0</td>
<td>1.54</td>
<td>N/A</td>
</tr>
<tr>
<td>1</td>
<td>1.63</td>
<td>0.09</td>
</tr>
<tr>
<td>5</td>
<td>1.74</td>
<td>0.20</td>
</tr>
<tr>
<td>10</td>
<td>1.77</td>
<td>0.23</td>
</tr>
<tr>
<td>20</td>
<td>1.81</td>
<td>0.27</td>
</tr>
<tr>
<td>40</td>
<td>1.85</td>
<td>0.31</td>
</tr>
<tr>
<td>60</td>
<td>1.87</td>
<td>0.34</td>
</tr>
<tr>
<td>120</td>
<td>1.92</td>
<td>0.38</td>
</tr>
</tbody>
</table>
Table 49 – sample MA002 and MA003 variation in dry density, void ratio and degree of saturation during the Vibration Test (point B)

<table>
<thead>
<tr>
<th>Time (Seconds)</th>
<th>Sample MA002 (GWC = 12.27%)</th>
<th>Sample MA003 (GWC = 12.70%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Density (t/m³)</td>
<td>Change in Dry Density (t/m³)</td>
</tr>
<tr>
<td>0</td>
<td>1.64</td>
<td>N/A</td>
</tr>
<tr>
<td>1</td>
<td>1.72</td>
<td>0.08</td>
</tr>
<tr>
<td>5</td>
<td>1.83</td>
<td>0.19</td>
</tr>
<tr>
<td>10</td>
<td>1.88</td>
<td>0.24</td>
</tr>
<tr>
<td>20</td>
<td>1.92</td>
<td>0.28</td>
</tr>
<tr>
<td>40</td>
<td>1.96</td>
<td>0.32</td>
</tr>
<tr>
<td>60</td>
<td>1.98</td>
<td>0.35</td>
</tr>
<tr>
<td>120</td>
<td>2.03</td>
<td>0.39</td>
</tr>
<tr>
<td>240</td>
<td>2.06</td>
<td>0.43</td>
</tr>
<tr>
<td>480</td>
<td>2.10</td>
<td>0.46</td>
</tr>
<tr>
<td>900</td>
<td>2.13</td>
<td>0.49</td>
</tr>
<tr>
<td>1500</td>
<td>2.17</td>
<td>0.53</td>
</tr>
<tr>
<td>2100 (with</td>
<td>2.27</td>
<td>0.63</td>
</tr>
<tr>
<td>Surcharge)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 50 – sample MA002 and MA003 variation in dry density, void ratio and degree of saturation during the Vibration Test (point C)

<table>
<thead>
<tr>
<th>Time (Seconds)</th>
<th>Sample MA002 (GWC = 12.89%)</th>
<th>Sample MA003 (GWC = 13.25%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry Density (t/m³)</td>
<td>Change in Dry Density (t/m³)</td>
</tr>
<tr>
<td>0</td>
<td>1.78</td>
<td>N/A</td>
</tr>
<tr>
<td>1</td>
<td>1.86</td>
<td>0.09</td>
</tr>
<tr>
<td>5</td>
<td>1.97</td>
<td>0.19</td>
</tr>
<tr>
<td>10</td>
<td>2.02</td>
<td>0.25</td>
</tr>
<tr>
<td>20</td>
<td>2.08</td>
<td>0.30</td>
</tr>
<tr>
<td>40</td>
<td>2.13</td>
<td>0.35</td>
</tr>
<tr>
<td>60</td>
<td>2.18</td>
<td>0.40</td>
</tr>
<tr>
<td>120</td>
<td>2.25</td>
<td>0.47</td>
</tr>
<tr>
<td>240</td>
<td>2.28</td>
<td>0.50</td>
</tr>
<tr>
<td>480</td>
<td>2.28</td>
<td>0.50</td>
</tr>
<tr>
<td>900</td>
<td>2.27</td>
<td>0.50</td>
</tr>
<tr>
<td>1500</td>
<td>2.29</td>
<td>0.51</td>
</tr>
<tr>
<td>2100 (with</td>
<td>2.43</td>
<td>0.66</td>
</tr>
<tr>
<td>Surcharge)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 51 – Summary of final sample geotechnical properties after 1500 seconds with vibration only and no surcharge

<table>
<thead>
<tr>
<th>Point</th>
<th>Sample MA002</th>
<th>Sample MA003</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gross Water Content (%)</td>
<td>Dry Density (t/m$^3$)</td>
</tr>
<tr>
<td>A</td>
<td>10.94</td>
<td>2.00</td>
</tr>
<tr>
<td>B</td>
<td>12.27</td>
<td>2.17</td>
</tr>
<tr>
<td>C</td>
<td>12.89</td>
<td>2.29</td>
</tr>
</tbody>
</table>

Table 52 – Summary of final sample geotechnical properties after 2100 seconds with the addition of the surcharge

<table>
<thead>
<tr>
<th>Point</th>
<th>Sample MA002</th>
<th>Sample MA003</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gross Water Content (%)</td>
<td>Dry Density (t/m$^3$)</td>
</tr>
<tr>
<td>A</td>
<td>10.94</td>
<td>2.08</td>
</tr>
<tr>
<td>B</td>
<td>12.27</td>
<td>2.27</td>
</tr>
<tr>
<td>C</td>
<td>12.89</td>
<td>2.43</td>
</tr>
</tbody>
</table>

In order to visually analyse the results the tabulated data seen in Table 48 to Table 52 is graphically presented in Figure 145 to Figure 149. Included in these figures are the changes in dry density, void ratio and degree of saturation against time for both samples for Point A to Point C.
Figure 146 – sample MA002 and MA003 variation in void ratio and dry density versus time during the Vibration Test (Point B = MPFT TML)

Figure 147 – sample MA002 and MA003 variation in void ratio and dry density versus time during the Vibration Test (Point C = 1% + MPFT TML)
Chapter 9 - Variation of the Geotechnical Properties of Iron Ore Fines under Cyclic Loading

Figure 148 – sample MA002 and MA003 variation in degree of saturation versus time during the Vibration Test (Point A = PFT, Point B = MPFT and Point C = 1% + MPFT TML)

Figure 149 – sample MA002 and MA003 degree of saturation versus gross water content after 1500 seconds (without surcharge) and 2100 seconds (with surcharge)

Figure 150 – sample MA002 and MA003 variation in dry density versus time during the Vibration Test (Point A = PFT, Point B = MPFT and Point C = 1% + MPFT TML). This figure is the same dry density data seen in Figure 145 to Figure 147 but with a linear scale
As expected, the data reveals under cyclic loading the samples of IOF show an increase in the final dry density and degree of saturation as the moisture content increases. As sample MA003 has a finer particle size distribution than sample MA002, the change in the dry density and degree of saturation of sample MA003 is greater at all points than sample MA002. Additionally, the initial and final void ratio of sample MA003 is lower than MA002 during all three tests as the void ratio is inversely related to the dry density.

The data produced while testing the samples of IOF at the moisture content similar to the TML produced by the PFT (Point A), seen in Table 48, Figure 145 and Figure 148 show the lowest produced final dry density and degree of saturation of the three moisture contents tested. As the final degree of saturation for sample MA002 and MA003 are 55% and 64%, respectively, and there was no sign of moisture migration within the sample, the authors assume that the densification of the samples are related to the rearrangement of particles within the sample and the densification is not due to the excess air and water being expelled by the change in pore pressures, as described in Section 9.3.4.3.

The data produced while testing the samples of IOF at the moisture content approximately 1% higher than the TML produced by the MPFT (Point C), seen in Table 50, Figure 147 and Figure 148, show a rapid change in properties to a point where both samples stabilize with no real changes in density until the 12 kg (6.7 kPa) surcharge was applied. After applying the surcharge both samples show an increase in the degree of saturation to above 95%, which can also be seen in Figure 149. As Section 9.3.4.1, the degree of saturation is a major contributing factor regarding the liquefaction potential of a material (Bishop, 1959). This significant increase in the degree of saturation, during densification, can be assumed to directly affect the materials stress state variables. Additionally, during testing at Point C it was noticed that there was significant moisture migration to the surface of the sample. The migration of moisture was seen to transport finer particles to the surface of the sample further increasing the liquefaction potential of the material.

Figure 150 shows both samples variation in dry density versus time during the Vibration Tests with a linear scale, which are also seen in Figure 145 to Figure 147 in logarithmic scale. This figure is to demonstrate that the assumed simplified cargo densification curve for IOF, seen in Figure 133 (section 9.3.4.1), has a similar trend to the densification curves produced during the Vibration Tests.

Figure 151 and Figure 152 show the density increase during the three main stages throughout the Vibration Test alongside the compaction curves and TML produced by the PFT and MPFT. Additionally, shown in Figure 153 and Figure 154 are the changes in void ratio over the full duration of the Vibration Tests for the two samples at the three different moisture contents. Note that it is considered to be a coincidence that both TML results for sample MA002 and MA003 are similar as the geotechnical properties of both samples are significantly different.
Figure 151 – sample MA002 dry density versus gross water content produced by the Vibration Test and results from the Proctor/Fagerberg test and Modified Proctor/Fagerberg test

Figure 152 – sample MA003 dry density versus gross water content produced by the Vibration Test and results from the Proctor/Fagerberg test and Modified Proctor/Fagerberg test
The data in Figure 151 and Figure 152 show that the increase in dry density during the Vibration Tests, at a nominal frequency of 50 Hz and a vertical double amplitude setting of 0.5 ±0.05 mm, produces densities similar to that of the MPFT. With the addition of the 12 kg (6.7 kPa) surcharge the density of the sample at Point C reaches a density greater than both the MPFT and the PFT.

It is noted that the density curves produced by the Vibration Tests are steeper than the density curves produced by both the PFT and MPFT. This is due to different forms of kinetic energy being applied to the samples to perform the compactions, as described in Section 9.3.4.3.
Figure 153 and Figure 154 show that during the Vibration Tests significant change occurs in regards to both the void ratio and degree of saturation. For both samples, Point C stabilises over a shorter period of time than Points A and B. Sample MA003 show that the sample stabilises within 60 seconds of vibration. This can be attributed to the higher moisture content of Point C and sample MA003 having a finer particle size distribution than sample MA002. Furthermore, after significant cyclic loading and addition of the surcharge, both samples degree of saturation at point C increase to above 95% and as discussed previously the potential for a saturated sample to liquefy is much higher than an unsaturated sample.

9.3.5.2 Penetration by Iron Ore Fines Plunger (IOFP)
As discussed in Section 9.3.4.4, in order to determine if the shear strength of IOF decreases under cyclic loading the authors utilised a free-floating IOF Plunger (IOFP) with a contact pressure of 845 g (16.36 kPa). The IOFP was placed on sample MA003 for 15 minutes after 3600 seconds (1 hour) of initial vibration. The sample was allowed to vibrate initially for 3600 seconds (1 hour) to allow the sample to reach its maximum density and degree of saturation under the applied magnitude of cyclic loading. It has been proven that after approximately 1 hour of vibration these conditions will be met.

Although not the same samples used during the Vibration Test, the IOFP was placed on samples with moisture contents covering the same range as in the Vibration Test. The moisture contents used during this test can be seen in Table 53.

Table 53 – Moisture contents of sample MA003 where the IOFP was applied

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Sample MA003</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PFT TML</td>
</tr>
<tr>
<td>Moisture Content (% NWC)</td>
<td>12.68</td>
</tr>
<tr>
<td>Gross Water Content (% GWC)</td>
<td>11.25</td>
</tr>
</tbody>
</table>

During the tests, the depth of penetration of the IOFP along with the time was recorded. These results can be seen in Figure 155 and Figure 156. The shear strength index shown in Figure 155 and Figure 156 is an indication value used in this study which is a direct inverse relationship to the maximum penetration of the IOFP.
Chapter 9 - Variation of the Geotechnical Properties of Iron Ore Fines under Cyclic Loading

Figure 155 – Penetration of 845 g (16.36 kPa) IOFP on sample MA003

Figure 156 – Penetration of 845 g (16.36 kPa) IOFP on sample MA003 after 1, 20, 120 and 900 seconds of penetration

Seen in Figure 155 and Figure 156, as the moisture content of the samples are increased the depth and speed of penetration of the IOFP is also increased. The sample tested at 11.25% GWC (PFT TML) is initially penetrated by the bit 15% of the sample’s depth and then gradually increases to 20%. This is attributed to the IOFP only penetrating the surface layer of the sample, which is loosely compacted. The next sample performed at 12.82% GWC (MPFT TML) is penetrated by the bit near linearly. It is safe to assume that at this moisture content the IOFP will eventually reach the maximum penetration possible after a further 100 seconds of vibration. As the moisture content is further increased to 13.37% GWC (1% more than MPFT) and 14.09% GWC (2% more than MPFT) the speed of penetration is increased respectively and both reach the maximum penetration possible using this apparatus.

It can be seen in Figure 155 and Figure 156 at 12.82% GWC (MPFT TML), after 900 seconds (15 minutes) of vibration, the sample can be seen to behave similar to the sample at 13.37% GWC (1% more than MPFT) after 300 seconds (5 minutes) of testing. This demonstrates that by increasing the time and magnitude of cyclic loading the critical conditions can be met on a sample with a relatively low moisture content and that by increasing the moisture content the critical conditions are met...
sooner. Based on the tests performed at the MPFT TML and 1% more than the MPFT TML the liquefaction potential of IOF can be seen to be a function of the time of cyclic loading and initial moisture content.

It has been determined from these tests that the sample at 11.25% GWC (PFT TML) is unlikely to reach any critical conditions that may cause liquefaction under this magnitude and time of cyclic loading, which is in excess of what would be experienced in the hold of a bulk carrier. After only 480 seconds (8 minutes) of vibration at 13.37% GWC (1% more than MPFT) and 14.09% GWC (2% more than MPFT) the IOFP reached the maximum depth of penetration. It is therefore safe to assume that these two samples have liquefied. If extrapolated, the data for the sample tested at 12.82% GWC (MPFT TML) shows the possibility of reaching these conditions after 1000 seconds (~16.5 minutes) of vibration when the IOFP will reach the maximum depth of penetration. Based on the results from this test, on a typical sample of IOF, under the applied magnitude and time of cyclic loading, the sample showed liquefaction characteristics between the standard PFT TML and the recently recommended MPFT TML.

Further testing is required to determine the state of pore pressures within the samples of IOF to confirm whether the conditions for the material to liquefy have been met.

9.3.5.3 Hydraulic Conductivity
As discussed in Section 9.3.4.2, in order to determine the effect periods of rest would have on the samples ability to dissipate pore pressures the coefficient of compressibility \(m_v\) and coefficient of consolidation \(C_v\) were determined and the hydraulic conductivity \(k\) was both calculated using the coefficient of consolidation and directly measured using a burette under the same conditions. The test was performed on a saturated sample of IOF using a Rowe Cell at varying consolidation pressures \(\sigma\) (Head, 1998). The values produced from the Rowe Cell can be seen in Table 54 and Figure 157.

Table 54 – Coefficients of compressibility \(m_v\), coefficient of consolidation \(C_v\), void ratio \(e\) and hydraulic conductivity \(k\) of a typical sample of IOF under varying consolidation pressures \(\sigma\)

<table>
<thead>
<tr>
<th>Consolidation Pressure (\sigma) (kPa)</th>
<th>Void Ratio (e)</th>
<th>Coefficient of Compressibility (m_v) (m³/MN)</th>
<th>Coefficient of Consolidation (C_v) (m³/yr)</th>
<th>Hydraulic Conductivity (Calculated) (k) (m/s)</th>
<th>Hydraulic Conductivity (Direct Measurement) (k) (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.14</td>
<td>43.22</td>
<td>20</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>10</td>
<td>0.99</td>
<td>12.41</td>
<td>139</td>
<td>5E-07</td>
<td>5E-05</td>
</tr>
<tr>
<td>50</td>
<td>0.85</td>
<td>2.13</td>
<td>2481</td>
<td>2E-06</td>
<td>2E-04</td>
</tr>
<tr>
<td>100</td>
<td>0.80</td>
<td>0.24</td>
<td>3789</td>
<td>3E-07</td>
<td>3E-05</td>
</tr>
<tr>
<td>200</td>
<td>0.75</td>
<td>0.15</td>
<td>4092</td>
<td>2E-07</td>
<td>2E-05</td>
</tr>
<tr>
<td>400</td>
<td>0.71</td>
<td>0.04</td>
<td>4222</td>
<td>5E-08</td>
<td>5E-06</td>
</tr>
<tr>
<td>600</td>
<td>0.67</td>
<td>0.02</td>
<td>4055</td>
<td>2E-08</td>
<td>2E-06</td>
</tr>
</tbody>
</table>
As discussed in 9.3.4.2, the hydraulic conductivity of a material relates to the ability it has to dissipate pore pressures. As seen in Figure 157 the hydraulic conductivity of IOF varies from $1 \times 10^{-5}$ m/s to $2 \times 10^{-8}$ m/s at 10 kPa to 600 kPa, respectively. Understanding that this is the static hydraulic conductivity of IOF, where the rate of change differs from the cyclic hydraulic conductivity, and that the permeability of saturated materials are greater than partially saturated materials, the values for hydraulic conductivity are considered to be low with poor drainage (Holtz and Kovacs, 1981; Lambe and Whitman, 1969; Terzaghi and Peck, 1967). The authors expect a similar trend when the hydraulic conductivity of IOF is plotted against the time during the Vibration Tests. This means that dissipation of pore air and water pressures within the sample of IOF are likely to take a significant amount of time to occur. Although, this determination does not definitively conclude if changes in pore pressures or moisture migration may occur in this sample during periods of rest, it does show that under these conditions the samples ability to dissipate pore pressures during periods of rest will be hindered.

Since changes in pore pressures are unlikely to occur during calm sea states, the simplified profile seen in Section 9.3.4.2 can be assumed to accurately represent the density change of the cargo during transportation. More accurate loading combinations, with periods of rest, and techniques such as the implementation of pressure transducers may be used in the future to determine the changes in pore pressures within the material.

9.3.6 Conclusion

The objective of this study was to determine if the geotechnical properties of IOF will vary under cyclic loading at varying moisture contents to determine the risk of liquefaction during transportation. These geotechnical properties included the maximum deviation of void ratio, dry density, degree of saturation and angle of repose. Previous studies have proven that in a partially saturated material under cyclic loading, these properties directly affect the pore pressures and therefore govern the resulting effective stress. If the effective stress reduces to near zero, the undrained shear strength will also be reduced and may cause the material to liquefy. Also investigated was whether it can be determined if samples of IOF have reduced shear strength under cyclic loading at high moisture contents by directly measuring the penetration of the IOF Plunger (IOFP), developed during this study.
The results from the Vibration Test show that significant changes occur in regards to the void ratio, dry density, degree of saturation and angle of repose. The density and degree of saturation were shown to increase more rapidly and more significantly as the moisture content increases. The samples tested at the higher moisture contents stabilised over a shorter period of time than the lower moisture contents and with the addition of a 12 kg (6.7 kPa) surcharge, both samples tested at the higher moisture content increased to over 95% saturation. This significant increase in the degree of saturation during densification can be assumed to directly reduce the effective stress, which has been shown in previous studies to contribute to the potential the material has of liquefying.

During testing at the lower moisture contents, the authors assumed that the densification of the samples is related to the rearrangement of particles and is not due to a change in pore pressures. During testing at the higher moisture contents, it was noticed that there was significant moisture migration to the surface of the samples, which infers that matric suction, or pore pressures, within the material had changed significantly. The migration of moisture also transported finer particles to the surface of the sample. It is noted that further investigation is needed to determine the significance of moisture migration and how this relates to the material’s potential to liquefy.

The penetration of a plunger (the IOFP) was also applied to one of the samples of IOF to study the loss of shear strength within the sample under cyclic loading at the Proctor/Fagerberg Test (PFT) Transportable Moisture Limit (TML), the Modified Proctor/Fagerberg Test (MPFT) TML and approximately 1% and 2% wetter than the MPFT TML. It has been concluded from the results that by increasing the time and magnitude of cyclic loading the critical conditions can occur on a sample having a moisture content equal to the TML from the MPFT and that by increasing the moisture content the critical conditions are met sooner. It can therefore be said that the liquefaction potential of IOF can be seen to be a function of the time of cyclic loading and initial moisture content. Based on the results from this study on two typical samples of IOF, under the applied magnitude and time of cyclic loading, the samples showed liquefaction characteristics between the standard PFT TML and the recently recommended MPFT TML.

It is noted that further investigation is needed to determine how the variation of void ratio and degree of saturation along with the hydraulic conductivity relates to the pore air and pore water pressures and suction within the samples of IOF and therefore the overall liquefaction potential. To confirm the results from this study a scale model, which more accurately represents the conditions IOF experience in the hold of a bulk carrier, is to be developed and utilized in order to determine the effect cyclic loading and moisture content has on the liquefaction potential of IOF. Additionally, using the scale model it is hoped to quantitatively analyse the non-uniformity of the physical properties that may possibly arise throughout a cargo being transported.
9.4 SUPPLEMENTARY RESULTS AND FIGURES

There are no supplementary results or figures relating to this manuscript.

9.5 SUMMARY AFTER THE FACT

Research related to this manuscript provided an understanding of the problems that may be faced when designing and developing the scale model. It was realized that the parameters that we were able to monitor were not as precise as we wanted in the small 1 Litre mould. It was also noticed that there needed to be additional monitoring of other parameters that could relate to a loss of shear strength within the sample and, therefore, possibly lead to a cargo shift.

It is noted again, that not long after this publication was written, the bulk carrier Mezzanine, that is listed in Table 43, was removed from the list of vessels where liquefaction of the cargo was suspected. This was due to new details emerging relating to the incident.

The preliminary results from the Iron Ore Fines Plunger (IOFP) presented in this manuscript, gave the first indications that under significant dynamic loading iron ore fines exhibit a significant loss of shear strength less than the Transportable Moisture Limit (TML) obtained by using the Modified Proctor/Fagerberg Test. During the time that this manuscript was being published, preliminary testing using the scale model was being performed. It is noted that the conditions of dynamic loading applied during this stage of research, do not represent that expected in the hold of a bulk carrier.

Subsequent to this study, an investigation was made into the all the incidents where liquefaction was suspected to have caused a bulk carrier to list or founder. This aspect of the research would allow comparisons to be made concerning the expected behaviour of a cargo undergoing liquefaction and the actual behaviour the cargo exhibited during these incidents.
CHAPTER 10 BULK CARGO LIQUEFACTION INCIDENTS DURING MARINE TRANSPORTATION AND POSSIBLE CAUSES

10.1 INTRODUCTION

This peer-reviewed manuscript includes both an analysis of suspected liquefaction incidents and an experimental study. Foremost, the basics of liquefaction and the stability of ships are discussed in the introduction followed by an analysis of all the suspected liquefaction incidents. The analysis includes a summary of the incident and casualty statistics for the type of cargo involved, the type of vessel involved, the location the vessel originated, and more.

This manuscript also presents similar experimental results to those presented in Chapter 9. That is in regards to the new apparatus designed and developed for this study, referred to as the Iron Ore Fines Plunger (IOFP). This plunger was developed alongside the scale model, discussed further on in Chapter 14, in order to give a quantifiable value to the loss of shear strength observed during the vibration of iron ore fines.

Exclusions made from this manuscript and not included in this chapter are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made continuous throughout this document.

10.2 CITATION

10.3 MANUSCRIPT CONTENTS

10.3.1 Abstract
During marine transportation, a combination of cyclic loading, fine particles and moisture within a bulk cargo can result in liquefaction causing the bulk carrier to list or capsize. The objective of this study is to investigate incidents where bulk cargoes liquefied during transportation and what resulted from these incidents, including the loss of human life and industry assets. In addition, the effectiveness of determining the Transportable Moisture Limit (TML) using the Modified Proctor/Fagerberg Test (MPFT) for Iron Ore Fines (IOF) is questioned by developing an apparatus used to observe the apparent shear strength of a sample of IOF. Between 1988 and 2016, 23 incidents were reported where liquefaction of a bulk cargo was suspected. These incidents resulted in 138 casualties and the loss of 17 vessels. It was found that incidents are continuing to occur even after the implementation of mandatory testing. Using an apparatus developed for this study, samples of IOF showed a sudden loss of shear strength at moisture contents lower than the TML with indications liquefaction had occurred. Although further testing is required to confirm some assumptions made, the study concluded that the IOF tested was assumed to be liquefiable at the TML determined using the MPFT.

10.3.2 Introduction
Liquefaction of solid bulk cargoes on board bulk carriers is a frequent problem whereby a combination of fine particles, moisture and changing pore pressures within a cargo result in the mass acting like a liquid. Liquefaction of a solid bulk cargo on board a bulk carrier can cause the vessel to list and possibly capsize resulting in the loss of human life and industry assets. Sladen et al., and the National Research Council Committee (1985) provide a more definite description of liquefaction: “Liquefaction is a phenomenon wherein a mass of soil loses a large percentage of its shear resistance, when subjected to transient or periodic loading, and flows in a manner resembling a liquid” (National Research Council, 1985; Sladen et al., 1985).

For a bulk carrier to list, the vessels overturning moment, $M_O$, must exceed the vessels restoring moment, $M_R$. This unstable condition is depicted in Figure 158 (right) where it is shown that the centre of buoyancy of the hull, $B$, stays inwards of the centre of gravity of the vessel, $G$. The resulting metacentre, $M$, under these conditions is below the centre of gravity, and causes the overturning moment, $M_O$, which exceeds the restoring moment, $M_R$. This causes the vessel to develop a permanent list and may possibly capsize if measures are not taken to right the vessel, which is commonly achieved using water as ballast.

There are two occurrences resulting from the liquefaction of cargo that can cause a bulk carrier to list. As being examined herein, if the cargo mass as whole begins to behave as a liquid the resulting free surface effect will reduce the metacentric height, distance from $G$ to $M$. The other occurrence is if partial liquefaction takes place at a point within the cargo mass resulting in the cargo shifting to one side. In that case the centre of gravity will move and the vessel will have a permanent heel angle.
Where: $B =$ Centre of buoyancy of hull; $F_b =$ Buoyancy force; $G =$ Centre of gravity of vessel; $M =$ Metacentre; $M_R =$ Overturning moment; $M_R =$ Restoring moment; $W =$ Vessel weight; $\alpha =$ Angle of heel.

**Figure 158 – Illustrations depicting stable vessels (left and middle) and an unstable vessel (right)**

To minimise the risk of liquefaction, the International Maritime Organization (IMO) outlines test methods that are used to determine the Transportable Moisture Limit (TML) of liquefiable cargoes. The TML is the maximum Gross Water Content (GWC) that a liquefiable cargo may contain without being at risk of liquefying (International Maritime Organization, 2016). Currently, four methods are used to determine the TML of ‘Group A’ or liquefiable solid bulk cargoes: i. Flow Table Test, ii. Penetration Test, iii. Proctor/Fagerberg Test, and iv. Modified Proctor/Fagerberg Test for Iron Ore Fines.

The International Maritime Solid Bulk Cargoes Code (IMSBC Code), which came into force on a mandatory basis on 1 January 2011 (International Maritime Organization MSC85/26/Add.2, 2008) and is published by the IMO, is an internationally recognized code of safe practice to be followed when transporting hazardous solid bulk cargoes. Appendix 2 of the 2013 IMSBC Code outlines three of the four test methods: Flow Table, Penetration and Proctor/Fagerberg. These three test methods are currently used to determine the TML of solid bulk cargoes listed as ‘Group A’ or liquefiable in Appendix 4 of the IMSBC Code (International Maritime Organization, 2013b). These tests are described in detail in a related publication (Munro and Mohajerani, 2015).

Industry and research associations have recently introduced the fourth test method specifically designed for determining the TML of Iron Ore Fines (IOF) (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e). The Modified Proctor/Fagerberg Test for IOF (MPFT) was first introduced in November 2013 in the circular DSC.1-Circ.71 for implementation on a voluntary basis (International Maritime Organization, 2013a). The use of this test became mandatory on 1 January 2017 (International Maritime Organization, 2013a, 2015d) and is now included in Appendix 2 of the 2016 IMSBC Code (International Maritime Organization, 2016).

The MPFT procedure involves compaction of the material into a standard litre compaction mould at varying moisture contents, to produce a compaction curve with a minimum of five data points. The compaction is executed in five layers by dropping a 150 g hammer 25 times through a guided pipe from a height of 150 mm. For each point, the GWC and void ratio is calculated and plotted on a graph along with the corresponding degree of saturation (S). The resulting GWC is then interpreted from the
graph where the degree of saturation equals 80%, which is considered to produce the TML (International Maritime Organization, 2016). A typical compaction curve for the IOF produced during this study can be seen in Section 10.3.4.1.1 (Figure 167).

There are questions regarding the validity of using the MPFT to determine the TML of IOF. A similar method, the Proctor compaction method, is used extensively in soil mechanics to determine the compaction characteristics of soils at varying moisture contents (American Society for Testing and Materials, 2012; Standards Australia, 2003b, 2003c). However, in soil mechanics, the Proctor compaction method is not used to determine the liquefaction potential of soils, which is what is inferred in the IMSBC Code as the TML. It is therefore to be noted that this study questions the MPFT method described in the 2016 IMSBC Code (International Maritime Organization, 2016). Further information about the MPFT can be seen in two related publications (Munro and Mohajerani, 2014, 2016b).

The objective of this study is to investigate recent incidents during the transportation on bulk carriers where liquefaction of the solid bulk cargo was suspected, and the impact these incidents had on the loss of human life and industry assets. In addition, the effectiveness of determining the TML using the MPFT for IOF is questioned and tested by developing an apparatus that will be used to determine the shear strength boundaries of a sample of IOF. The apparatus developed during this study is to be developed further in the future to include additional sensors to further confirm the liquefaction potential of IOF.

10.3.2.1 Theory
In order to understand the observations made using the new apparatus developed during this study, the basic theory relating to the shear strength of unsaturated soils and the relationship this theory has to solid bulk cargoes being transported on bulk carriers needs to be reviewed. Eq. 17 shows the widely accepted equation used to determine the shear strength of a soil. This equation was derived by Karl Terzaghi, and is commonly referred to as the Mohr-Coulomb failure criterion (Terzaghi, 1942). It expresses that the shear strength, \( \tau \), of a granular material is a function of its friction angle, \( \phi' \), and cohesion, \( c' \), along with the applied effective stress, \( \sigma' \):

\[
\tau = c' + \sigma' \tan \phi'
\]  

(Eq. 17)

Eq. 18 shows Bishop’s equation for effective stress of an unsaturated soil, which is used as a variable in Eq. 17 (Bishop, 1959). Eq. 18 introduces the variables pore air pressure, \( u_a \), pore water pressure, \( u_w \), and the normal stress, \( \sigma \), along with parameter, \( \chi \), which is a value between 0 and 1 relating to the degree of saturation, where 1 is fully-saturated:

\[
\sigma' = (\sigma - u_a) + \chi(u_a - u_w)
\]  

(Eq. 18)

According to Eq. 18, in fully saturated soils (when \( \chi = 1 \)), the reduction in effective stress is directly related to the pore water pressure (i.e. \( \sigma' = \sigma - u_w \)). In unsaturated soils, when the degree of saturation is low, soil suction or negative pore water pressure occurs within the pores. As the saturation is increased, suction is reduced and allows moisture migration to occur. Significant moisture migration may result in densification and a reduction in the void ratio of the soil. By considering the theory of effective stress it can be shown that the shear strength of a soil is directly related to the ability the material has to dissipate changes in the pore air and water pressure. If the effective stress
is reduced to near zero by changing pore pressures, the shear strength will also reduce and the soil may liquefy. Pore pressures within a cargo being transported in a bulk carrier can be increased or decreased based on the applied dynamic loading, which can be influenced by the surrounding sea state or harmonic vibrations caused by the vessel’s engines (Iron Ore Technical Working Group, 2013b).

The cargo holds of bulk carriers have the facility to allow drainage to occur through strainer plates at the base of each hold. The strainers are used to stop the cargo entering the bilge pipes and pumps (Transportation Safety Board of Canada, 2005). With the strainer plates and bilge systems working correctly, a cargo in these conditions is assumed to have two-way drainage – from the base and to the surface. These conditions allow for pore pressures within the material to dissipate.

Cargoes that contain significant amounts of fine-particles commonly block the strainer plates, pipes and pumps on bulk carriers that are not correctly fitted to facilitate drainage, and to prevent entry of the cargo into the bilge system. To prevent these blockages from occurring there have been recorded instances of crew members using cardboard, plastic sheeting, and duct tape to seal the strainer plates, as seen in Figure 159 (Transportation Safety Board of Canada, 2005). Whether it is the crew members or the cargo blocking the strainer plates, the occurrence would prevent drainage from the base and reduce the ability for the dissipation of pore pressures within these areas.

Additionally, to further prevent the dissipation of pore pressures, densification may occur during loading or transportation, thereby reducing the hydraulic conductivity (permeability) of the cargo (Munro and Mohajerani, 2017c). As shown in Eq. 18, if this occurs, the pore pressure changes within the cargo along with the increased degree of saturation due to the densification, which can lead to a decrease in the effective stress resulting in a reduction in the shear strength, and, possibly, liquefaction of the cargo.
10.3.3 Analysis of Recent Suspected Liquefaction Incidents

A summarized list of recent suspected liquefaction incidents was established to understand the impact they have on the loss of human life and industry assets. It is noted that some of the incidents summarized herein were only suspected of being caused by liquefaction of the solid bulk cargo due to the cargoes being fine-grained and possibly containing significant amounts of moisture. Some incidents are entirely speculative in regards to liquefaction being the cause, but, rightly so, due to the similarities between them and certain liquefaction incidents that have been extensively documented (Munro and Mohajerani, 2016a). The summary provided herein is based upon reports and articles referenced in Section 10.3.6. The possibility of the cargo shifting due to slope instability and failure has also been analysed, and the results and conclusions are given in a related publication (Munro and Mohajerani, 2017f).

Section 10.3.6 and Section 10.3.7 show that 23 incidents were reported between 1988 and 2016 where liquefaction was the suspected cause. These incidents resulted in the loss of 138 lives and 17 vessels. The list and summaries provided do not include incidents where liquefaction of a cargo might have been caused by the ingress of water due to structural failure of a bulk carrier. Two of these incidents are shown in Figure 160 and Figure 161.

Figure 160 – Bulk Carrier ‘Chang Le Men’ after suspected liquefaction incident off Mangalore India (2007) (Mangalorean, 2007) - see Section 10.3.6
Table 55 – Incidents and resulting casualties for individual solid bulk cargo, 1988-2016, including group classification as of 2016 (see Section 10.3.6)

<table>
<thead>
<tr>
<th>Solid Bulk Cargo</th>
<th>Classification as of 2016</th>
<th>Incidents</th>
<th>Casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>#</td>
<td>%</td>
</tr>
<tr>
<td>Bauxite</td>
<td>Group C</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Fluorspar</td>
<td>Group A and B</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Iron Ore (Fines)</td>
<td>Group C &amp; Group A (Fines)</td>
<td>7</td>
<td>30</td>
</tr>
<tr>
<td>Nickel Ore</td>
<td>Group A</td>
<td>13</td>
<td>57</td>
</tr>
<tr>
<td>Undetermined Ore</td>
<td>N/A</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

* Cargoes classified ‘Group A’ in the 2013 IMSBC Code are considered to be potentially liquefiable and must undergo TML testing (International Maritime Organization, 2013b, 2015d)
### Table 56 – Incidents and resulting casualties for bulk carrier subclasses, 1988-2016 (see Section 10.3.6)

<table>
<thead>
<tr>
<th>Bulk Carrier Subclass</th>
<th>DWT $^{ab}$ (tonnes)</th>
<th>Incidents</th>
<th>Casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>#</td>
<td>%</td>
</tr>
<tr>
<td>General Bulker</td>
<td>&lt; 9,999</td>
<td>2</td>
<td>9%</td>
</tr>
<tr>
<td>Handysize</td>
<td>10,000 – 39,999</td>
<td>11</td>
<td>48%</td>
</tr>
<tr>
<td>Handymax</td>
<td>40,000 – 59,999</td>
<td>10</td>
<td>43%</td>
</tr>
<tr>
<td>Panamax</td>
<td>60,000 – 99,999</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Capesize</td>
<td>&gt; 100,000</td>
<td>0</td>
<td>0%</td>
</tr>
</tbody>
</table>

$^a$ DWT, Dead Weight Tonnage is a measure of how much mass a vessel can safely carry. It does not include the weight of the vessel, but includes things such as the cargo, crew, passengers, ballast and fuel.

$^b$ The DWT for each subclass is based on UNCTAD’s Review of Maritime Transport (2014) (United Nations Conference on Trade and Development (UNCTAD), 2014)

### Figure 163 – Incidents (left) and resulting casualties (right) for bulk carrier subclasses, 1988-2016 (see Section 10.3.6)

### Table 57 – Incidents and resulting casualties for export countries, 1988-2016 (see Section 10.3.6)

<table>
<thead>
<tr>
<th>Export Country</th>
<th>Incidents</th>
<th>Casualties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#</td>
<td>%</td>
</tr>
<tr>
<td>Brazil</td>
<td>1</td>
<td>4%</td>
</tr>
<tr>
<td>Hong Kong</td>
<td>1</td>
<td>4%</td>
</tr>
<tr>
<td>India</td>
<td>5</td>
<td>21%</td>
</tr>
<tr>
<td>Indonesia</td>
<td>10</td>
<td>42%</td>
</tr>
<tr>
<td>Malaysia</td>
<td>2</td>
<td>8%</td>
</tr>
<tr>
<td>New Caledonia</td>
<td>2</td>
<td>8%</td>
</tr>
<tr>
<td>Philippines</td>
<td>3</td>
<td>13%</td>
</tr>
</tbody>
</table>
Table 55 to Table 57 and Figure 162 to Figure 164 show a summary of the suspected liquefaction incidents on board bulk carriers along with the resulting casualties and the accompanying tabulated data is detailed in Section 10.3.6. It can be seen that incidents involving nickel ore and iron ore (including iron ore fines) being transported on the Handy subclass of bulk carriers (Handysize and Handymax) originating from Southeast Asia were involved in the majority of the recent suspected liquefaction incidents. This was assumed to be attributed to the increasing demand for minerals originating from Southeast Asia from China and South Korea where the smaller Handy subclass bulk carrier are frequently used (Glencore, 2013).

Additional factors that may contribute to the high number of incidents include the political status and tropical climate of the regions where the respective bulk carriers disembarked. An inability to comply with the most recent IMSBC Code requirements can result in an increase in the possibility for liquefaction to occur. The locations of the ports where cargoes were loaded are often remote and ill-equipped to perform the necessary tests required to prevent cargo liquefaction. Additionally, incidents occurred in regions where the weather can introduce additional moisture to the cargo (Munro and Mohajerani, 2016a). Moisture in the environment can be absorbed by the stockpiles of fine-grained minerals prior to and during loading if the proper procedures are not implemented to protect the cargo.

For perspective we have included data showing the percentage that specific subclasses of bulk carrier were used to transport iron ore fines (IOF) in 2012 (Iron Ore Technical Working Group, 2013b). Figure 165 and Table 58 shows that although the most common subclass of bulk carrier is the Capesize bulk carrier, all incidents where IOF was suspected of undergoing liquefaction involved a Handy subclass of bulk carrier or smaller.
Table 58 – Percentage of iron ore fines (IOF) tonnage transported and voyages for specific subclasses of bulk carrier, 2012 (Iron Ore Technical Working Group, 2013b)

<table>
<thead>
<tr>
<th>Bulk Carrier Subclass</th>
<th>DWT ab (tonnes)</th>
<th>% Tonnage in 2012</th>
<th>% Voyages in 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handysize</td>
<td>10,000 – 39,999</td>
<td>0.3</td>
<td>3.1</td>
</tr>
<tr>
<td>Handymax</td>
<td>40,000 – 59,999</td>
<td>1.1</td>
<td>3.1</td>
</tr>
<tr>
<td>Panamax</td>
<td>60,000 – 99,999</td>
<td>5.7</td>
<td>11.9</td>
</tr>
<tr>
<td>Capesize</td>
<td>&gt; 100,000</td>
<td>93.0</td>
<td>81.9</td>
</tr>
</tbody>
</table>

a DWT, Dead Weight Tonnage is a measure of how much mass a vessel can safely carry. It does not include the weight of the vessel, but includes things such as the cargo, crew, passengers, ballast and fuel

b The DWT for each subclass is based on UNCTAD’s Review of Maritime Transport (2014) (United Nations Conference on Trade and Development (UNCTAD), 2014)

Figure 165 – Percentage of tonnage transported and voyages for specific subclasses of bulk carrier, 2012 (Iron Ore Technical Working Group, 2013b)

Figure 166 shows the cumulative liquefaction incidents over time and the date, 2011, when the IMSBC Code was adopted on a mandatory basis (International Maritime Organization MSC85/26/Add.2, 2008). It can be seen that the suspected liquefaction incidents on board bulk carriers are continuing to occur at a rate of nearly two per year even after the mandatory implementation of the IMSBC Code.
Due to the continuing incidents where liquefaction is suspected, the effectiveness of the test methods used to determine the TML of solid bulk cargoes have come under question, and, ultimately, led to the development of the Iron Ore Fines Plunger (IOFP) used during this study. The IOFP was developed in order to observe the apparent shear strength of iron ore fines to the TML determined using the Modified Proctor/Fagerberg Test (MPFT).

10.3.4 Experimental Study

10.3.4.1 Material and Method

10.3.4.1.1 Material

The sample of Iron Ore Fines (IOF) tested in this study, identified as MA003, was obtained from Western Australia. The physical properties of the sample and the standards to which these properties were obtained are seen in Table 59, Figure 167 and Figure 168.

The moisture contents given in Table 59 are reported according to the relevant standard. In AS 1289, the moisture content is reported in Net Water Content (NWC), which is the percentage of the mass of moisture to the mass of dry material (Standards Australia, 2000). In the IMSBC Code, the moisture content (including TML) is reported in Gross Water Content (GWC), which is the percentage of the mass of moisture to the total mass of wet material (International Maritime Organization, 2013b). In geotechnical engineering and soil mechanics, the NWC is commonly used whereas in most other cases, including metallurgy and transportation of solid bulk cargoes, the GWC is preferred. In Table 59, both the GWC and NWC are shown for convenience.
Table 59 – Physical properties of the sample of IOF used during this study

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard / Apparatus</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Identification</td>
<td>N/A</td>
<td>MA003</td>
</tr>
<tr>
<td>IMSBC Code Schedule Applied</td>
<td>MSC 95/22/Add.2 (International Maritime Organization, 2015e)</td>
<td>Iron ore (as cargo contains more than 35% goethite d)</td>
</tr>
<tr>
<td>Atterberg Limits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Limit</td>
<td>AS1289.3.1.2 (Standards Australia, 2009a)</td>
<td>18% NWC or 15.3% GWC a</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>AS1289.3.2.1 (Standards Australia, 2009b)</td>
<td>17% NWC or 14.5% GWC a</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>AS1289.3.3.1 (Standards Australia, 2009c)</td>
<td>1% NWC/GWC a (Non-Plastic)</td>
</tr>
<tr>
<td>Particle Size Distribution c</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel (&gt;2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>27%</td>
</tr>
<tr>
<td>Sand (75 μm – 2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>50%</td>
</tr>
<tr>
<td>Silt (2 μm – 75 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>19%</td>
</tr>
<tr>
<td>Clay (&lt;2 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>3%</td>
</tr>
<tr>
<td>Classification</td>
<td>AS1726 (Standards Australia, 1993)</td>
<td>Silty sand (SM)</td>
</tr>
<tr>
<td>Particle Density</td>
<td>AS1289.3.5.1 (Standards Australia, 2006)</td>
<td>4.36 t/m³</td>
</tr>
<tr>
<td>Standard Proctor Compaction MDD and OMC</td>
<td>AS1289.5.1.1 (Standards Australia, 2003b)</td>
<td>2.76 t/m³ at 12.5% NWC or 11.1% GWC a</td>
</tr>
<tr>
<td>Modified Proctor/Fagerberg for IOF (D Hammer) TML</td>
<td>MSC 95/3/Add.1 (International Maritime Organization, 2015d)</td>
<td>12.8% GWC or 14.7% NWC at 80% Saturation with the maximum density occurring at 92% Saturation ab</td>
</tr>
<tr>
<td>Quantitative X-Ray Diffraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hematite (Fe₂O₃)</td>
<td>X'Pert Pro PW3040</td>
<td>54% Total Weight</td>
</tr>
<tr>
<td>Goethite (FeOOH)</td>
<td>X'Pert Pro PW3040</td>
<td>41% Total Weight d</td>
</tr>
</tbody>
</table>

a Reported moisture content unit, according to the relevant standard, is presented first (i.e. GWC or NWC).

b The compaction curve produced during the MPFT and resulting TML can be seen in Figure 167.

c The particle size distribution curve produced can be seen in Figure 168.

d According to MSC 95/22/Add.2, if a cargo of iron ore fines has more than 35% goethite total weight then the schedule for iron ore (not iron ore fines) should be followed and the cargo does not need to undergo testing using the Modified Proctor/Fagerberg method (MPFT) as it is not considered liquefiable (International Maritime Organization, 2015e). Research regarding the implementation of this classification of iron ore is shown in reports released relating to the development of the MPFT (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e).
This sample was chosen for this study because it was considered a typical sample of IOF commonly transported on bulk carriers from Australia. The physical properties of the sample tested during this study were within the range of the typical properties of IOF determined in a related publication (Munro and Mohajerani, 2015).
10.3.4.1.2 Method
10.3.4.1.2.1 Apparatus
A free-floating IOF Plunger (IOFP) with a contact pressure of 16.36 kPa and diameter of 25.4 mm, as seen in Figure 169, was developed and used to observe the apparent shear strength of the sample of IOF under cyclic loading. After testing, the results were compared with the TML produced by the MPFT (Figure 167). Future modifications to this apparatus will allow the measurement of pore pressures, within the sample, to objectively determine the liquefaction potential.

The design of the IOFP was based on the penetration bits used during the Penetration test described in Appendix 2 of the IMSBC Code, which was designed to determine the TML of coal and ore concentrates (International Maritime Organization, 2016). The Penetration test utilizes a penetration bit with a diameter of 15 mm and a contact pressure of either 5 kPa for coal or 10 kPa for ore concentrates (International Maritime Organization, 2016). Because of the properties of IOF, primarily the particle size, the IOFP was designed with a contact pressure and diameter greater than the penetration bits used during the Penetration test. This increased the repeatability of the test by allowing the plunger to penetrate the sample without being obstructed or deflected by the larger particles within the IOF.

The procedure that was developed for this study involved placing samples of IOF, with varying moisture contents, into an acrylic mould with dimensions scaled from the hold of a Capesize bulk carrier. The mould was then placed on a vibrating table and vibrated at a frequency of 50 - 60 Hz with an acceleration of 6 ± 0.3 g Root Mean Square (RMS) for 3600 seconds (1 hour). This total test time
was used because this was the maximum density produced by the applied frequency and amplitude. Additionally, the dry density that was produced was similar to that produced by the compaction during the MPFT, as seen in Figure 172. When densification of the sample was complete, as seen in Figure 170 (3600 seconds), the free-floating IOFP was placed on the sample, as seen in Figure 171, and the vibrating table was operated for an additional 900 seconds (15 minutes). During the application of the IOFP, the depth of penetration was recorded at specific time intervals to obtain a graphical representation of the depth of penetration at varying moisture contents.

The frequency, amplitude and time of vibration, previously mentioned, was used to simulate the ‘worst case scenario’ conditions expected during transportation. Recent investigations have shown that the maximum acceleration expected during a typical voyage of a bulk carrier was 1 g at a frequency of 0.1 Hz (Iron Ore Technical Working Group, 2013b).

During the application of the plunger, if penetration of the sample occurs, it was assumed that the effective stress and therefore shear strength surrounding the IOFP was close to zero and therefore
liquefaction was said to have occurred. As described in Section 10.3.2.1, this was assumed to be due to the change in pore pressures within the sample. By using this method, both the Failure Threshold (FT) and the Critical Failure Curve (CFC) could be determined. These were terms used in this study to refer to the boundaries at which the sample of IOF was suspected to be potentially and highly liquefiable under the applied magnitude and time of cyclic loading. These boundaries are to be verified once modifications have been made to the apparatus which will include the addition of transducers to measure the pore pressures during vibration.

10.3.4.2 Experimental Results
The moisture contents of the samples of IOF that were used during this study and the identification used to describe the samples during the analysis of the results can be seen in Table 60. The physical properties of the IOF used is described in Section 10.3.4.1.1.

Table 60 – Identification and moisture contents of the samples of IOF tested during this study

<table>
<thead>
<tr>
<th>Sample Identification</th>
<th>Gross Water Content by Weight, GWC (%)</th>
<th>Net Water Content by Weight, NWC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point A</td>
<td>10.88</td>
<td>12.20</td>
</tr>
<tr>
<td>Point B</td>
<td>11.25</td>
<td>12.68</td>
</tr>
<tr>
<td>Point C (MPFT TML)</td>
<td>12.82</td>
<td>14.71</td>
</tr>
<tr>
<td>Point D</td>
<td>13.37</td>
<td>15.44</td>
</tr>
<tr>
<td>Point E</td>
<td>14.09</td>
<td>16.40</td>
</tr>
</tbody>
</table>

Figure 172 – MPFT compaction curve (including TML) and the sample densities produced by the initial 3600 seconds (1 hour) of vibration prior to the application of the IOFP

Figure 172 shows a comparison of two compaction curves. The first compaction curve was produced while performing the MPFT, which is also seen in Figure 167. The second compaction curve was
produced by the initial vibration prior to the application of the IOFP (1 hour of vibration at a frequency of 50 – 60 Hz with an acceleration of 6 ± 0.3 g RMS). The different types of energy applied to the samples to produce the curves, as seen in Figure 172, caused a greater difference in the void ratio at the lower moisture contents and are therefore considered to be conservative. This study mainly focused on the void ratio (density) at which the MPFT TML occurred. The difference is assumed to be more or less negligible around this area of the curve (near Points C, D and E). Additionally, the void ratio produced by the MPFT compaction procedure at the lower moisture contents, was lower (increased density). Therefore, at these points, it was safe to assume that less penetration by the IOFP would occur, hence the conservative nature of the results.

Although partially saturated, the liquefaction of a solid bulk cargo is similar to what occurs in saturated sand during an earthquake. The phenomenon, which has been extensively studied, occurs more commonly in materials with specific particle sizes. Shown in Figure 173 are the particle size distribution boundaries of most liquefiable soils (Ishihara, 1985) and the particle size distribution of the sample used during this study. It can be seen that approximately 75% of the material is considered potentially liquefiable.

The results from the data recorded during the application of the IOFP can be seen in Table 61 to Table 65 and graphical representations of this data are seen in Figure 174 and Figure 175. It is noted that an average initial bearing capacity of the samples of IOF at the time the IOFP was applied was calculated to be greater than 20kPa. This indicated that the reduction in shear strength being observed is not due to volumetric compression of the sample around the IOFP. Also, after the initial 3600 seconds (1 hour) of vibration the samples as a whole were measured and did not undergo any further significant volumetric densification.
### Table 61 – The variation in penetration by the IOFP for Point A after the initial 3600 seconds (1 hour) of vibration

<table>
<thead>
<tr>
<th>Time IOFP Applied (Seconds)</th>
<th>Total Vibration Time (Seconds)</th>
<th>IOFP Penetration Depth (mm)</th>
<th>IOFP Penetration of sample Height (172 mm) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Initial)</td>
<td>3600 (Initial)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>3601</td>
<td>4.3</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>3605</td>
<td>7.5</td>
<td>4.4</td>
</tr>
<tr>
<td>10</td>
<td>3610</td>
<td>9.5</td>
<td>5.5</td>
</tr>
<tr>
<td>20</td>
<td>3620</td>
<td>12.0</td>
<td>7.0</td>
</tr>
<tr>
<td>40</td>
<td>3640</td>
<td>14.5</td>
<td>8.4</td>
</tr>
<tr>
<td>60</td>
<td>3660</td>
<td>16.0</td>
<td>9.3</td>
</tr>
<tr>
<td>120</td>
<td>3720</td>
<td>18.5</td>
<td>10.8</td>
</tr>
<tr>
<td>240</td>
<td>3840</td>
<td>21.0</td>
<td>12.2</td>
</tr>
<tr>
<td>480</td>
<td>4080</td>
<td>25.0</td>
<td>14.5</td>
</tr>
<tr>
<td>900 (Final)</td>
<td>4500 (Final)</td>
<td>29.5</td>
<td>17.2</td>
</tr>
</tbody>
</table>

### Table 62 – The variation in penetration by the IOFP for Point B after the initial 3600 seconds (1 hour) of vibration

<table>
<thead>
<tr>
<th>Time IOFP Applied (Seconds)</th>
<th>Total Vibration Time (Seconds)</th>
<th>IOFP Penetration Depth (mm)</th>
<th>IOFP Penetration of sample Height (162 mm) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Initial)</td>
<td>3600 (Initial)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>3601</td>
<td>3.5</td>
<td>2.2</td>
</tr>
<tr>
<td>5</td>
<td>3605</td>
<td>8.0</td>
<td>4.9</td>
</tr>
<tr>
<td>10</td>
<td>3610</td>
<td>11.5</td>
<td>7.1</td>
</tr>
<tr>
<td>20</td>
<td>3620</td>
<td>13.5</td>
<td>8.3</td>
</tr>
<tr>
<td>40</td>
<td>3640</td>
<td>16.5</td>
<td>10.2</td>
</tr>
<tr>
<td>60</td>
<td>3660</td>
<td>17.5</td>
<td>10.8</td>
</tr>
<tr>
<td>120</td>
<td>3720</td>
<td>20.5</td>
<td>12.7</td>
</tr>
<tr>
<td>240</td>
<td>3840</td>
<td>23.5</td>
<td>14.5</td>
</tr>
<tr>
<td>480</td>
<td>4080</td>
<td>26.5</td>
<td>16.4</td>
</tr>
<tr>
<td>900 (Final)</td>
<td>4500 (Final)</td>
<td>30.0</td>
<td>18.5</td>
</tr>
</tbody>
</table>

### Table 63 – The variation in penetration by the IOFP for Point C (MPFT TML) after the initial 3600 seconds (1 hour) of vibration

<table>
<thead>
<tr>
<th>Time IOFP Applied (Seconds)</th>
<th>Total Vibration Time (Seconds)</th>
<th>IOFP Penetration Depth (mm)</th>
<th>IOFP Penetration of sample Height (138 mm) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Initial)</td>
<td>3600 (Initial)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>3601</td>
<td>2.5</td>
<td>1.8</td>
</tr>
<tr>
<td>5</td>
<td>3605</td>
<td>6.5</td>
<td>4.7</td>
</tr>
<tr>
<td>10</td>
<td>3610</td>
<td>8.0</td>
<td>5.8</td>
</tr>
<tr>
<td>20</td>
<td>3620</td>
<td>10.5</td>
<td>7.6</td>
</tr>
<tr>
<td>40</td>
<td>3640</td>
<td>14.0</td>
<td>10.1</td>
</tr>
<tr>
<td>60</td>
<td>3660</td>
<td>17.0</td>
<td>12.3</td>
</tr>
<tr>
<td>120</td>
<td>3720</td>
<td>24.0</td>
<td>17.4</td>
</tr>
<tr>
<td>240</td>
<td>3840</td>
<td>34.0</td>
<td>24.6</td>
</tr>
<tr>
<td>480</td>
<td>4080</td>
<td>62.0</td>
<td>44.9</td>
</tr>
<tr>
<td>900 (Final)</td>
<td>4500 (Final)</td>
<td>117.0</td>
<td>84.8</td>
</tr>
</tbody>
</table>
### Table 64 – The variation in penetration by the IOFP for Point D after the initial 3600 seconds (1 hour) of vibration

<table>
<thead>
<tr>
<th>Time IOFP Applied (Seconds)</th>
<th>Total Vibration Time (Seconds)</th>
<th>IOFP Penetration Depth (mm)</th>
<th>IOFP Penetration of sample Height (135 mm) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Initial)</td>
<td>3600 (Initial)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>3601</td>
<td>2.5</td>
<td>1.9</td>
</tr>
<tr>
<td>5</td>
<td>3605</td>
<td>7.0</td>
<td>5.2</td>
</tr>
<tr>
<td>10</td>
<td>3610</td>
<td>10.0</td>
<td>7.4</td>
</tr>
<tr>
<td>20</td>
<td>3620</td>
<td>16.0</td>
<td>11.9</td>
</tr>
<tr>
<td>40</td>
<td>3640</td>
<td>25.5</td>
<td>18.9</td>
</tr>
<tr>
<td>60</td>
<td>3660</td>
<td>33.5</td>
<td>24.8</td>
</tr>
<tr>
<td>120</td>
<td>3720</td>
<td>59.5</td>
<td>44.1</td>
</tr>
<tr>
<td>240</td>
<td>3840</td>
<td>96.5</td>
<td>71.5</td>
</tr>
<tr>
<td>480</td>
<td>4080</td>
<td>122.0</td>
<td>90.4</td>
</tr>
<tr>
<td>900 (Final)</td>
<td>4500 (Final)</td>
<td>126.0</td>
<td>93.3</td>
</tr>
</tbody>
</table>

### Table 65 – The variation in penetration by the IOFP for Point E after the initial 3600 seconds (1 hour) of vibration

<table>
<thead>
<tr>
<th>Time IOFP Applied (Seconds)</th>
<th>Total Vibration Time (Seconds)</th>
<th>IOFP Penetration Depth (mm)</th>
<th>IOFP Penetration of sample Height (105 mm) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (Initial)</td>
<td>3600 (Initial)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>3601</td>
<td>5.0</td>
<td>4.8</td>
</tr>
<tr>
<td>5</td>
<td>3605</td>
<td>19.5</td>
<td>18.6</td>
</tr>
<tr>
<td>10</td>
<td>3610</td>
<td>31.2</td>
<td>29.7</td>
</tr>
<tr>
<td>20</td>
<td>3620</td>
<td>47.0</td>
<td>44.8</td>
</tr>
<tr>
<td>40</td>
<td>3640</td>
<td>69.5</td>
<td>66.2</td>
</tr>
<tr>
<td>60</td>
<td>3660</td>
<td>85.2</td>
<td>81.1</td>
</tr>
<tr>
<td>120</td>
<td>3720</td>
<td>95.5</td>
<td>91.0</td>
</tr>
<tr>
<td>240</td>
<td>3840</td>
<td>97.0</td>
<td>92.4</td>
</tr>
<tr>
<td>480</td>
<td>4080</td>
<td>97.0</td>
<td>92.4</td>
</tr>
<tr>
<td>900 (Final)</td>
<td>4500 (Final)</td>
<td>98.0</td>
<td>93.3</td>
</tr>
</tbody>
</table>

### Figure 174 – The variation in penetration of the IOFP against time for Points A to E

*Note: IOFP applied to samples after 1 hour of initial vibration.*
The curves produced in Figure 174 and Figure 175 indicate that the rate of penetration increased as the moisture content increased. The curves are not typical of those produced when determining the shear strength of soils using a traditional shear vane (Standards Australia, 2001a), which typically increase exponentially as the moisture content reduces. This indicates that the shear strength of the sample is not reducing in a typical manner and that liquefaction may be occurring.

The initial penetration of the samples tested at Points A and B was attributed to the IOFP only penetrating the surface layer of the sample, which was loosely compacted. At Point C (MPFT TML) the speed of penetration increased and it was assumed it would reach the maximum penetration possible after an additional 100 seconds of vibration. As the moisture content further increased to Points D and E, the speed of penetration also increased, and, therefore, both reached the maximum penetration possible using the apparatus.

Figure 174 shows that after 900 seconds (15 minutes) of vibration, the sample tested at Point C could be seen to reach a similar penetration by the plunger as the sample at Point D after 300 seconds (5 minutes) of vibration. As expected, this demonstrated that the penetration of the samples could be seen to be a function of both the time of cyclic loading and the initial moisture content. Increasing the moisture content only meant that the observed critical conditions occurred sooner.

Although further validation is required, it was assumed that the samples at Points A and B were unlikely to reach the critical conditions to cause liquefaction. It was apparent that the shear strength at points C, D and E were reduced significantly. Although liquefaction of the sample cannot be proven
at this stage with this apparatus is possible that the conditions existed for liquefaction to occur within these samples. Again, this theory will be verified with the addition of pressures transducers to the apparatus in the near future.

Another indication that liquefaction may have been the cause of the apparent loss of shear strength was that significant moisture migration was seen to occur, as seen in Figure 176. Moisture migration is an indication of significant densification causing changes in pore pressures within the sample.

![Moisture migration occurring during initial vibration within the mould](image)

*Figure 176 – Moisture migration occurring during initial vibration within the mould*

According to Werkmeister (2005), an unbound granular material, such as IOF, can be classified based on the response under repeated cyclic loading (Cerni et al., 2011; Werkmeister et al., 2005). Werkmeister’s ‘shakedown’ theory has three potential categories of response, which can be seen in Figure 177:

- **Plastic Shakedown** (Figure 177, Line 1), when the collective permanent strain rate decreases rapidly until it reaches a state of equilibrium. The response is resilient and does not produce permanent deformations and the material does not reach the failure criteria.
- **Plastic Creep** (Figure 177, Line 2), when the collective permanent strain rate is decreasing or constant. Although the deformation is not all resilient, the permanent deformation is acceptable. In this case, the material could reach the failure criteria under a great number of load cycles.
- **Incremental Collapse** (Figure 177, Line 3), when the collective permanent strain rate increases rapidly and the failure criteria is met after a low number of load cycles.
The Failure Threshold (FT) and the Critical Failure Curve (CFC), as seen in Figure 175, were between the plastic shakedown limit and plastic creep limit, respectively. The FT was the moisture content at which apparent shear strength loss commenced (penetration by the plunger began to occur) and the CFC was determined by the point of intersection of the tangents of the two dominant slopes of each curve and then averaging.

Using data from the IOFP, the sample of IOF showed an apparent loss of shear strength between Point B (1.5% GWC less than the MPFT TML) and Point C (MPFT TML). The sample also showed signs of significant changes in pore pressures, around Point C (MPFT TML).

10.3.5 Conclusion
The objective of this study was to investigate recent incidents during transportation on bulk carriers where liquefaction of the solid bulk cargo was suspected, and the impact these incidents had on the loss of human life and industry assets. In addition, the effectiveness of determining the Transportable Moisture Limit (TML) using the Modified Proctor/Fagerberg Test (MPFT) for Iron Ore Fines (IOF) was questioned and tested by developing an apparatus that was used to determine the shear strength boundaries of a sample of IOF. This apparatus is to be modified to confirm the results of this study by adding transducers to record the pore pressures within the samples under vibration.

The impact of the suspected liquefaction of solid bulk cargoes on human life and industry assets has been significant. It was determined during this study that 23 incidents were reported from 1988 to 2016 where liquefaction was the suspected cause, which resulted in 138 casualties. Furthermore, incidents continued to occur at nearly two per year even after the mandatory implementation of the International Maritime Solid Bulk Cargoes Code (IMSBC Code) in 2011. Due to this, it is recommended that the effectiveness of the test methods used to determine the TML of solid bulk cargoes be examined for specific solid bulk cargoes.
Based on the results from the IOF Plunger (IOFP), which was developed during this study, the sample of IOF tested depicted an apparent sudden loss of shear strength between Point B (1.5% GWC less than the MPFT TML) and Point C (MPFT TML). The sample also showed signs of significant changes in pore pressures, around Point C (MPFT TML), due to significant moisture migration occurring. The behaviour of the samples at these moisture contents shown relate to Werkmeister’s ‘shakedown theory’, which was an indication of the Failure Threshold (FT) and Critical Failure Curve (CFC) of the material.

The sample of iron ore fines tested in this study is not classified as ‘Group A’ or liquefiable according to the individual schedule for iron ore fines given in the 2016 IMSBC Code. This is due to the amount of Goethite that it contains, that begin above 35%, and therefore does not need to undergo TML testing using the MPFT. With this said, the initial cyclic energy applied was considered to produce the equivalent density as that produced by the compaction during the MPFT. This density has been shown by the developers of the test to be equivalent to that on board a bulk carrier. This indicated that the sample of IOF tested during this study had significantly reduced shear strength at the TML produced by the MPFT and therefore should be required to undergo testing using the MPFT if deemed an appropriate test.

It is to be noted that the reference to liquefaction in this study is not an indication that it is the definitive mode of failure that results in the loss of the vessels listed in this publication. The term liquefaction seems to be the general term used by industry and research associations to refer to the mode of failure that the cargo has experienced. It is questioned if this is the actual mode of failure or if it is another, such as; plastic shakedown, incremental collapse, general slope failure or even another not currently under investigation.

Further testing is to be performed to determine the state of the pore pressures within the samples of IOF to confirm the suspected boundaries referred to as the Failure Threshold (FT) and Critical Failure Curve (CFC) determined during this study. Additionally, further investigation is needed to determine why, after the mandatory implementation of the IMSBC Code, incidents of suspected liquefaction of solid bulk cargoes continue to occur.
### 10.3.6 Appendix A – Suspected Liquefaction Incidents (Table)

**Table 66 – Bulk carrier incidents from 1988 to 2016 involving suspected liquefaction of the solid bulk cargo being transported**

<table>
<thead>
<tr>
<th>Incident #</th>
<th>Vessel Name</th>
<th>IMO Number</th>
<th>DWT (tonnes)</th>
<th>Subclass</th>
<th>Date of Incident</th>
<th>Casualties / Total Crew</th>
<th>Loss of Vessel</th>
<th>Dismembarked</th>
<th>Destination</th>
<th>Incident Location / Last Location</th>
<th>Cargo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mega Taurus</td>
<td>7929279</td>
<td>30,413</td>
<td>Handysize</td>
<td>16 Dec 1988</td>
<td>20 / 20</td>
<td>Yes</td>
<td></td>
<td>Hinatuan, Philippines</td>
<td>Hachinohe, Japan</td>
<td>Nickel Ore</td>
</tr>
<tr>
<td>2</td>
<td>Oriental Angel Sea</td>
<td>8301620</td>
<td>21,373</td>
<td>Handysize</td>
<td>9 June 1990</td>
<td>0 / NA</td>
<td>No (Listed)</td>
<td></td>
<td>New Caledonia</td>
<td>New Caledonia at anchorage</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>Sea Prospect</td>
<td>9136709</td>
<td>21,297</td>
<td>Handysize</td>
<td>26 Aug 1998</td>
<td>10 / 21</td>
<td>Yes</td>
<td></td>
<td>Grebe Island Mine, Indonesia</td>
<td>Hiroshima, Japan</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>Padang Hawk</td>
<td>9109354</td>
<td>46,635</td>
<td>Handymax</td>
<td>26 July 1999</td>
<td>0 / 20</td>
<td>No (Listed)</td>
<td></td>
<td>Koaoua, New Caledonia</td>
<td>10 hours West travelling at 12.7 knots from Lat: -18.18N, Long: 153.93E</td>
<td>Nickel Ore</td>
</tr>
<tr>
<td>5</td>
<td>Hui Long</td>
<td>9037032</td>
<td>16,123</td>
<td>Handysize</td>
<td>20 May 2005</td>
<td>0 / 23</td>
<td>Yes</td>
<td></td>
<td>Hong Kong then Sungei Pakning, Indonesia</td>
<td>Kandla, India</td>
<td>Fluorspar</td>
</tr>
<tr>
<td>6</td>
<td>Jag Rahul</td>
<td>8028735</td>
<td>37,609</td>
<td>Handysize</td>
<td>1 Dec 2007</td>
<td>0 / NA</td>
<td>No (Listed)</td>
<td></td>
<td>Tanjung Buli, Indonesia</td>
<td>Ukraine</td>
<td>Ore</td>
</tr>
<tr>
<td>8</td>
<td>Chang Le Men</td>
<td>8104656</td>
<td>17,240</td>
<td>Handysize</td>
<td>7 Sept 2007</td>
<td>0 / 28</td>
<td>No (Listed)</td>
<td></td>
<td>Mangalore, India</td>
<td>China via Singapore Winds, China</td>
<td>Iron Ore</td>
</tr>
<tr>
<td>9</td>
<td>Asian Forest</td>
<td>9369112</td>
<td>14,434</td>
<td>Handysize</td>
<td>18 July 2009</td>
<td>0 / 18</td>
<td>Yes</td>
<td></td>
<td>Mangalore, India</td>
<td>7 miles off Mangalore, India</td>
<td>Iron Ore</td>
</tr>
<tr>
<td>10</td>
<td>Hodasco15</td>
<td>8312239</td>
<td>6,519</td>
<td>General Bulker</td>
<td>30 Aug 2009</td>
<td>0 / 18</td>
<td>Yes</td>
<td></td>
<td>Kolkata, India</td>
<td>Off Pulau Perak, Malaysia</td>
<td>Iron Ore</td>
</tr>
<tr>
<td>11</td>
<td>Black Rose</td>
<td>7602455</td>
<td>37,657</td>
<td>Handysize</td>
<td>9 Sept 2009</td>
<td>1 / 27</td>
<td>Yes</td>
<td></td>
<td>Paradip, India</td>
<td>3 miles off Paradip, India</td>
<td>Iron Ore</td>
</tr>
<tr>
<td>12</td>
<td>Jian Fu Star</td>
<td>8106379</td>
<td>45,108</td>
<td>Handymax</td>
<td>27 Oct 2010</td>
<td>13 / 25</td>
<td>Yes</td>
<td></td>
<td>Obi Island, Indonesia</td>
<td>Off Cape Eluanbi, Taiwan</td>
<td>Nickel Ore</td>
</tr>
<tr>
<td>13</td>
<td>Jianmao 9</td>
<td>7518915</td>
<td>34,456</td>
<td>Handysize</td>
<td>10 Nov 2010</td>
<td>0 / 26</td>
<td>Yes</td>
<td></td>
<td>Hong Kong</td>
<td>Lat: -15.42N, Long: 110.19E</td>
<td>N/A</td>
</tr>
<tr>
<td>14</td>
<td>Nasco Diamond</td>
<td>9467861</td>
<td>56,893</td>
<td>Handymax</td>
<td>09 Nov 2010</td>
<td>22 / 25</td>
<td>Yes</td>
<td></td>
<td>Lianyungang, China</td>
<td>Lat: -21.05N, Long: 123.50E</td>
<td>Nickel Ore</td>
</tr>
<tr>
<td>15</td>
<td>Hong Wei</td>
<td>9230139</td>
<td>50,149</td>
<td>Handymax</td>
<td>3 Dec 2010</td>
<td>10 / 24</td>
<td>Yes</td>
<td></td>
<td>Koloondale, Indonesia</td>
<td>100 miles South of Eluanbi Point, Taiwan</td>
<td>Nickel Ore</td>
</tr>
</tbody>
</table>
### Chapter 10 - Bulk Cargo Liquefaction Incidents during Marine Transportation and Possible Causes

<table>
<thead>
<tr>
<th>Incident Number</th>
<th>Vessel Name</th>
<th>IMO Number</th>
<th>Subclass</th>
<th>DWT</th>
<th>Vessel Type</th>
<th>Departure Port</th>
<th>Arrival Port</th>
<th>Event Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Bright Ruby</td>
<td>8604474</td>
<td>Handysize</td>
<td>26,589</td>
<td>25,652</td>
<td>Penang, Malaysia</td>
<td>Rizhao, China</td>
<td>16.33N, 114.00E</td>
</tr>
<tr>
<td>17</td>
<td>Vinalines Queen Sun Spirits</td>
<td>9290907</td>
<td>Handymax</td>
<td>56,040</td>
<td>56,107</td>
<td>Morowali, Indonesia</td>
<td>Ningde, China</td>
<td>North East of Luzon Island, Philippines</td>
</tr>
<tr>
<td>18</td>
<td>Harita Bauxite Trans Summer Bingo</td>
<td>8103664</td>
<td>Handymax</td>
<td>48,891</td>
<td>48,945</td>
<td>Leyte, Philippines</td>
<td>Ningbo, China</td>
<td>12 miles off Cape Bolinao, Philippines</td>
</tr>
<tr>
<td>19</td>
<td>Anna Bo</td>
<td>9385520</td>
<td>General Bulker</td>
<td>8,733</td>
<td>8,750</td>
<td>Subaim, Indonesia</td>
<td>Yangjiang, China</td>
<td>21.92N, 113.67E</td>
</tr>
<tr>
<td>20</td>
<td>Bulk Jupiter</td>
<td>9545716</td>
<td>Handymax</td>
<td>56,720</td>
<td>56,735</td>
<td>Indonesia</td>
<td>Ningde, China</td>
<td>9.02N, 109.26E</td>
</tr>
<tr>
<td>21</td>
<td>Alam Manis</td>
<td>9397836</td>
<td>Handymax</td>
<td>55,652</td>
<td>55,652</td>
<td>Kuantan, Malaysia</td>
<td>Qingdao, China</td>
<td>9.02N, 109.26E</td>
</tr>
</tbody>
</table>

**Note:** Incident number 7 was removed due to it being revealed it was not liquefaction. The numbers have remained unchanged due to these being referenced in Figure 178 to Figure 180.

**Sources:**
- The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005.
- Devanney, Undated.
- International Association of Classification Societies, 2002.
- Devanney, Undated.
- International Association of Classification Societies, 2002.
- (Australian Transport Safety Bureau, 2000).
- (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005).
- (Grant, 2008; Roberts, 2012).
- (Devanney, Undated; O'Coninnoile, 2007).
- (Corbett, 2013; Deccan Herald, 2009; Trade Winds, 2010).
- (Marine Buzz, 2009).
- (ClassNK’s Initiatives for the Safe Carriage of Nickel Ore, 2012).
- (Panama Maritime Authority - Maritime Accident Investigation Department, 2011b).
- (Dolphin Maritime and Aviation Services Ltd, 2010; Interargo, 2010; Lloyd’s List Asia, 2010; InterManager, 2013; Mareud, 2010; Maritime Accident Casebook, 2011; Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).
- (ClassNK’s Initiatives for the Safe Carriage of Nickel Ore, 2012).
- (Interargo, 2010; Maritime Accident Casebook, 2010; Panama Maritime Authority - Maritime Accident Investigation Department, 2011a; SeaNews Turkey, 2010a; (Andrei and Pazar, 2013; Maritime Bulletin, 2011).
- (gCaptain, 2012; Long, 2011).
- (gCaptain, 2013; Glen, 2013; Maritime Bulletin, 2013c).
- (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).
- (Hancock, 2013; The Times of India, 2013).
- (gCaptain, 2015a, 2015b; News, 2015; The Bahamas Maritime Authority, 2015).
- (Chan, 2015; Petrov, 2015).

**Key Points:**
- IMO number is a unique reference number for vessels.
- DWT, Dead Weight Tonnage is a measure of how much mass a vessel can safely carry. It does not include the weight of the vessel, ballast and fuel. The IMO number remains linked to the hull for life of the vessel.
10.3.7 Appendix B – Suspected Liquefaction Incidents (Localities)

Figure 178 – Locations of where bulk carriers disembarked that have been suspected of undergoing liquefaction from 1988 to 2016 (Source: Google Maps and Section 10.3.6)

Note: Although countries of origin are correct, some locations within those countries are approximate. Refer to Section 10.3.6 for more details.
Figure 179 – Locations of incidents, last location and voyage of bulk carriers that have been suspected of undergoing liquefaction from 1988 to 2016 (Source: Google Maps and Section 10.3.6)

**Note 1:** Although countries of origin are correct, some locations within those countries are approximate. Refer to Section 10.3.6 for more details.

**Note 2:** Voyages are based on approximate common trade routes taken by bulk carriers transporting solid bulk cargoes and the reported location the vessel was lost.

**Note 3:** The location of the incident involving the Jag Rahul is unknown. The incident is plotted in the figure half way through a typical voyage the vessel would take.
Figure 180 – Locations of loading ports, incidents, last location destination, voyage and intended voyage of bulk carriers that have been suspected of undergoing liquefaction from 1988 to 2016 (Source: Google Maps and Section 10.3.6)

Note 1: Although countries of origin are correct, some locations within those countries are approximate. Refer to Section 10.3.6 for more details.

Note 2: Voyages are based on approximate common trade routes taken by bulk carriers transporting solid bulk cargoes and the reported location the vessel was lost.

Note 3: The location of the incident involving the Jag Rahul is unknown. The incident is plotted in the figure half way through a typical voyage the vessel would take.
10.4 SUPPLEMENTARY RESULTS AND FIGURES

Supplementary results and figures in relation to the Iron Ore Fines Plunger (IOFP) and scale model testing can be seen in the related publications in Chapter 14 and Chapter 16. There are no additional supplementary results or figures relating to this manuscript.

10.5 SUMMARY AFTER THE FACT

As described previously in Chapter 9 Section 9.5, the preliminary results from the Iron Ore Fines Plunger (IOFP) gave the first indications that under significant dynamic loading iron ore fines exhibit a significant loss of shear strength less than the Transportable Moisture Limit (TML) obtained using the Modified Proctor/Fagerberg Test. It is noted, at this stage, that the conditions of dynamic loading applied during this stage of research do not represent that expected in the hold of a bulk carrier. During the time that this manuscript was being published, extensive testing using the scale model was being performed. These results are presented in Chapter 14 and Chapter 16.

The information obtained regarding the suspected liquefaction incidents provided this research with a key understanding of the types of cargoes most commonly involved, and the type of vessel most commonly involved. Understanding the proportion and frequency of incidents involving iron ore fines confirmed the significance of the problem, and knowing the type of vessel and route details opened up information regarding possible loading conditions the cargo may experience.

Another aspect that was of concern was the location the vessel was loaded with the cargo. There is an obvious trend that is occurring, but speculation can only be made about the exact factors that may increase incidents occurring from these locations. It was decided to probe deeper into some of the incident reports to determine exactly what may be the influencing factors.
CHAPTER 11 LIQUEFACTION INCIDENTS OF MINERAL CARGOES ON BULK CARRIERS

11.1 INTRODUCTION

The peer-reviewed manuscript presented in this chapter includes a review of the seven publicly available reports regarding incidents on board bulk carriers where liquefaction was the suspected cause. It was hoped that by analysing these reports the factors that influence a cargo to liquefy, or shift in another way, could be realized.

Exclusions made from this manuscript and not included in this chapter are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made continuous throughout this document.

11.2 CITATION

11.3 MANUSCRIPT CONTENTS

11.3.1 Abstract
Liquefaction is a frequently occurring problem taking place when transporting wet granular solid bulk cargoes on-board bulk carriers. Liquefaction of a solid bulk cargo can occur when excessive dynamic loading, induced by rough seas and vessel vibrations, is transmitted to the cargo. From 1988 to 2015, there has been 24 suspected liquefaction incidents reported, which resulted in 164 casualties and the loss of 18 vessels. The objective of this study is to investigate the collective causes of liquefaction of solid bulk cargoes on-board bulk carriers in order to make recommendations to prevent future incidents from occurring. This was achieved by analysing the seven available investigative reports relating to the incidents, focusing on the key findings and exploring the effect of excess moisture within the cargo. This study has placed significant emphasis on the importance of preventing ingress of water into the cargo during transportation, loading and storage. Recommendations have been given, based on the key findings from the reports, to reduce the potential for liquefaction incidents to occur.

11.3.2 Introduction
Liquefaction is a frequently occurring problem taking place when transporting wet granular solid bulk cargoes on-board bulk carriers (Cabai, 2011; Van Paassen et al., 2013; Zou et al., 2013). Similar to liquefaction of soils during earthquakes (Ishihara, 1985, 1993; Seed and Idriss, 1971, 1982), liquefaction of a solid bulk cargo occurs when excessive cyclic or dynamic loading, induced by rough seas and vessel vibrations, is transmitted to the cargo (Fagerberg and Stavang, 1971). Cargoes that are more likely to undergo liquefaction in the holds of bulk carriers are those that contain sufficient amounts of moisture and fine particles (Andrei and Pazara, 2013; Munro and Mohajerani, 2015; Rahman et al., 2014; Rahman and Lo, 2012).

Liquefaction, in soil mechanics, is a term used to describe the behaviour of a material that flows in a manner resembling a liquid when subjected to monotonic, cyclic or shock loading. This behaviour is caused by pore pressures changing within the material, which results in the loss of effective stress and therefore shear strength (Martin et al., 1975; Seed and Idriss, 1971; Terzaghi et al., 1996). Liquefaction does not cease until the loading is reduced causing the shear stresses acting on the mass to be as low as the reduced shear resistance (Sladen et al., 1985). Although further investigation is needed, some incidents attributed to liquefaction may also be more accurately described as cyclic instability, which is a form of unstable behaviour (strain softening) caused by a succession of dynamic load cycles (Baki et al., 2012; Mohamad and Dobry, 1986; Rahman et al., 2014).

If liquefaction of a solid bulk cargo occurs, it can cause the vessel to list and occasionally capsize (Grunau, 2012). During this study, it has been found that from 1988 to 2015, there has been 24 suspected liquefaction incidents reported, which resulted in 164 casualties and the loss of 18 vessels.

The International Maritime Solid Bulk Cargoes Code (IMSBC Code), published by the International Maritime Organization (IMO), is an internationally recognized code of safe practice to be followed when transporting hazardous solid bulk cargoes on-board bulk carriers (International Maritime Organization, 2013b). In 2011 the IMSBC Code, formally the Code of Safe Practice for Solid Bulk Cargoes (BC Code), was made mandatory under the SOLAS Convention (International Maritime Organization MSC85/26/Add.2, 2008). Included in Appendix 2 of the IMSBC Code are test methods to
be followed when a cargo is classified as ‘Group A’ or liquefiable (International Maritime Organization, 2013b). These test methods include the flow table, penetration and Proctor/Fagerberg tests, which are described in detail in related publications (Munro and Mohajerani, 2014, 2015, 2016b). The results from these tests provide the shipper with a ‘safe’ moisture content at which the cargo can be loaded without it being at risk of liquefying (International Maritime Organization, 2013b).

This ‘safe’ moisture content is known as the Transportable Moisture Limit (TML) and it’s inferred definition is ‘the maximum gross water content that a liquefiable cargo may contain without being at risk of liquefying while being transported in a bulk carrier’ (International Maritime Organization, 2013b). The Flow Moisture Point (FMP) is also determined using two of the three methods stated in the IMSBC Code. The TML is 90% of the FMP (International Maritime Organization, 2013b). Along with these test methods, other policies and procedures are included to reduce the occurrence of liquefaction incidents and ensure liquefiable cargoes do not get loaded on a bulk carrier if it exceeds its TML.

One final method in the IMSBC Code used to determine if a cargo is potentially liquefiable is the ‘Can Test’. If a Master has doubts in regard to the appearance or condition of the material, a simplified in-situ testing method for providing a rough idea on the possibility of flow may be carried out by half filling a cylindrical vessel of about 1 litre capacity with a sample of the cargo and striking it against a hard surface at least 25 times. If free moisture appears on the surface of the sample, additional laboratory tests should be conducted (International Maritime Organization, 2013b; Panama Maritime Authority - Maritime Accident Investigation Department, 2011b).

Some other physical properties that influence the liquefaction potential of ‘Group A’ cargoes are the; particle size, void ratio, degree of saturation, hydraulic conductivity and pore air/water pressure characteristics (Munro and Mohajerani, 2015; Rahman et al., 2014; Rahman and Lo, 2012). Additionally, some system variables are the; induced cyclic loading, drainage conditions and rate of loading. The moisture content is considered the major factor regarding the liquefaction potential of ‘Group A’ cargoes. It is noted that all the test methods given in the IMSBC Code use the moisture content of the cargo as a variable that can be monitored and adjusted accordingly to prevent cargoes from liquefying. Other physical properties of the cargo are not considered changeable to prevent liquefaction of the cargoes (International Maritime Organization, 2013b). This is because the majority of cargoes being transported on bulk carriers are considered products and therefore their physical properties are more or less unalterable.

The objective of this study is to investigate the collective causes of liquefaction of solid bulk cargoes on-board bulk carriers in order to make recommendations to prevent future incidents from occurring. This will be achieved by analysing the available investigative reports relating to the incidents, focusing on the key findings and exploring the effect of excess moisture within the cargo.

11.3.3 Case Studies

In order to make recommendations to prevent future liquefaction incidents from occurring, investigation reports will be utilised to summarize seven incidents including the conclusions and key findings. These seven investigation reports are the only publicly available reports of suspected liquefaction incidents from 1988 to 2015. The list given in Table 67 shows the major incidents that are investigated during this study along with the main vessel and incident details.
Table 67 – Major incidents investigated during this study along with the main vessel and incident details (Australian Transport Safety Bureau, 2000; Panama Maritime Authority - Maritime Accident Investigation Department, 2011a, 2011b, 2011c; The Bahamas Maritime Authority, 2015; The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005, 2015)

<table>
<thead>
<tr>
<th>Case Study #</th>
<th>Vessel Name</th>
<th>IMO Number</th>
<th>Date of Incident</th>
<th>Casualties / # Crew</th>
<th>Vessel Lost</th>
<th>Disembarked</th>
<th>Cargo</th>
<th>Cargo (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Padang Hawk</td>
<td>9109354</td>
<td>26 July 1999</td>
<td>0 / 20</td>
<td>No</td>
<td>Kouaoua, New Caledonia</td>
<td>Nickel Ore</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>Hui Long</td>
<td>9037032</td>
<td>20 May 2005</td>
<td>0 / 23</td>
<td>Yes</td>
<td>Sungei Pakning, Indonesia</td>
<td>Fluorspar</td>
<td>5,185</td>
</tr>
<tr>
<td>3</td>
<td>Jian Fu Star</td>
<td>8106379</td>
<td>27 Oct 2010</td>
<td>13 / 25</td>
<td>Yes</td>
<td>Obi Island, Indonesia</td>
<td>Nickel Ore</td>
<td>43,000</td>
</tr>
<tr>
<td>4</td>
<td>Nasco Diamond</td>
<td>9467861</td>
<td>09 Nov 2010</td>
<td>22 / 25</td>
<td>Yes</td>
<td>Kolonodale, Indonesia</td>
<td>Nickel Ore</td>
<td>55,150</td>
</tr>
<tr>
<td>5</td>
<td>Hong Wei</td>
<td>9230139</td>
<td>3 Dec 2010</td>
<td>10 / 24</td>
<td>Yes</td>
<td>Kolonodale, Indonesia</td>
<td>Nickel Ore</td>
<td>40,000</td>
</tr>
<tr>
<td>6</td>
<td>Trans Summer</td>
<td>9615468</td>
<td>14 Aug 2013</td>
<td>0 / 21</td>
<td>Yes</td>
<td>Subaim, Indonesia</td>
<td>Nickel Ore</td>
<td>54,067</td>
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<tr>
<td>7</td>
<td>Bulk Jupiter</td>
<td>9339947</td>
<td>02 Jan 2015</td>
<td>18 / 19</td>
<td>Yes</td>
<td>Kuantan, Malaysia</td>
<td>Bauxite</td>
<td>46,400</td>
</tr>
</tbody>
</table>

*a The IMO number is a distinctive reference number of a vessel (International Maritime Organisation, 2015).

It is noted that the terms ‘sea state’ and ‘wind force’, given herein, are stated using the Douglas and Beaufort scales respectively (Met Office, 2010). All the case study summaries and conclusions presented in Section 11.3.3 have been obtained from their respective investigation reports (Australian Transport Safety Bureau, 2000; Panama Maritime Authority - Maritime Accident Investigation Department, 2011a, 2011b, 2011c; The Bahamas Maritime Authority, 2015; The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005, 2015). By summarizing and analysing these incidents, we hope to determine trends or similarities that may be causing these incidents to occur.

11.3.3.1 Case Study 1 – Padang Hawk

Built in 1995, the Singapore flag Padang Hawk (IMO: 9109354) is a Handymax bulk carrier with a summer deadweight of 46,635 tonnes (United Nations Conference on Trade and Development (UNCTAD), 2014). The vessel, which has a length of 190 m, breadth of 31 m and summer draught of 12 m, has five cargo holds serviced by four on-board cranes (Australian Transport Safety Bureau, 2000). At the time of producing this report the Padang Hawk, now Panama flag Tong Ji Men, is still in active service (MarineTraffic, 2015c). The Padang Hawk along with its hold and tank layout can be seen in Figure 181 and Figure 182.
11.3.3.1.1 Summary of Incident

On 17 July 1999 at 1224, the Padang Hawk arrived at the port of Kouaoua, New Caledonia, seen in Figure 183, to begin loading a cargo of nickel ore from shore barges. Loading commenced at 1440 and was completed on 23 July by 2140. Although each day during loading soundings of the cargo holds for water were taken and no bilge water was recorded, the crew noticed that some ‘grabs’ of cargo had water running from them as they were lifted off the barges and into the holds (Australian Transport Safety Bureau, 2000).
The Padang Hawk departed Kouaoua at 2307 on the 23 July on a north-westerly course along the coast of New Caledonia. At 1700 on 24 July, the ships log book records that the bilges of all holds were pumped dry with the vessel rolling heavily in south-easterly swells. Just before 2400 on the same day, the Padang Hawk altered course north of Récifs d’Entrecasteaux. The vessel was rolling and pitching heavily when the wind was noted as being east-south-east, force 5, and the sea was described as rough as the Padang Hawk sailed west towards Townsville, Australia (Australian Transport Safety Bureau, 2000).

At 0900 on 25 July and 0830 on 26 July, the bilges in all holds were again pumped. The rough conditions caused the vessel to roll and pitch heavily, particularly from 1600 onwards on 25 July. At noon on 26 July, the Padang Hawk was about 100 nautical miles of Marion Reef, as seen in Figure 184. During the afternoon, the wind strength was logged at force 5 with regular notations in the logbook concerning the ship’s heavy rolling. Throughout the day, from time to time, seas broke over the deck and hatch covers. By 2000, the wind was logged at force 6–7 and the vessel was rolling heavily. The hold bilges were pumped at 2000 and again at 2100 (Australian Transport Safety Bureau, 2000).
A little before 2200 the Padang Hawk suddenly developed a 15-degree list to port. After reducing speed and altering the course to bring the wind and sea onto the port quarter, crew were sent to check the hatches and the state of the main deck. After noting that nothing was out of place, the crew opened access hatches to each of the holds. They found that the cargo of nickel ore in all the holds, except hold number 5, had settled and shifted to port. The cargo in the first three holds appeared to be semi-liquid, ‘like melted ice cream’, as one of the crew described it. Two images of the nickel ore in hold number 1 of the Padang Hawk can be seen in Figure 185 (Australian Transport Safety Bureau, 2000).

After using ballast to try to correct the list, a message was sent to the Australian Maritime Safety Authority (AMSA) via the ships agent in Townsville noting the condition of the ship, actions taken and reporting that the cargo had liquefied (Australian Transport Safety Bureau, 2000).

By early morning, the list had been reduced to about 5-degrees by using the vessel’s double bottom ballast tanks, which was recommended by the owners. The strong wind and heavy swell continued...
and seas broke regularly over the vessel’s quarter. The cargo hold bilges were pumped at regular intervals throughout the day (Australian Transport Safety Bureau, 2000).

Due to the consistently rough weather, at noon on 27 July the Master decided to maintain the course with the wind astern. This course took the Padang Hawk directly towards Grafton Passage. In the early hours of 28 July, the ship was approaching Grafton passage. By 0400, it was safely in the calmer waters inside the Great Barrier Reef and later that afternoon the vessel anchored off Townsville. Once a pilot boarded, the Padang Hawk was safely navigated and docked at Townsville by 1930 (Australian Transport Safety Bureau, 2000).

11.3.3.1.2 Investigation Conclusions

Investigations into the incident started immediately after the Padang Hawk arrived at Townsville, Australia. The following are the main conclusions from the investigation into the incident involving the Padang Hawk (Australian Transport Safety Bureau, 2000).

1. The cargo was loaded with excessive moisture content,
2. the vessel was subjected to heavy seas, which led to the cargo changing state from a solid to a viscous liquid in 4 of the 5 holds,
3. insufficient knowledge of the characteristics of nickel ore as a cargo and its propensity to become fluid when the moisture content is high and it is subjected to sufficient physical stress,
4. there is no test to specifically ascertain the Transportable Moisture Limit (TML) of nickel ore,
5. the owners/agent of the vessel did not include in the Master’s voyage instructions, the relevant information pertaining to the cargo moisture content, flow tests, and the Master’s right to refuse to load the cargo under the terms of the agreement between the buyer, Queensland Nickel Pty Ltd (QNPL), and the cargo sellers,
6. the ore seller did not provide the Master with the agreed data pertaining to the cargo’s moisture content and flow tests as required by the SOLAS Convention,
7. the Master loaded the nickel ore without insisting on the provision of the data concerning the moisture content and flow tests,
8. the mined nickel ore was stockpiled in areas open to the ingress of rainwater and
9. the agreement between QNPL and the seller did not stipulate a reasonable, maximum, acceptable moisture content, based on the nickel ore’s ability to be carried safely by sea.

Additionally, the flow table test, which is used to determine the TML of coal and ore concentrates (International Maritime Organization, 2013b), was performed on the cargo of nickel ore after the incident and the moisture content of the cargo was found to exceed the TML determined by the test (Australian Transport Safety Bureau, 2000).

11.3.3.2 Case Study 2 – Hui Long

Built in 1999, the Hong Kong flag Hui Long (IMO: 9037032) was a Handysize bulk carrier with a summer deadweight of 16,113 tonnes (United Nations Conference on Trade and Development (UNCTAD), 2014). The vessel, which had a length of 158 m and breadth of 23 m had four cargo holds serviced by three on-board cranes (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005). The Hui Long can be seen in Figure 186.
11.3.3.2.1 Summary of Incident
On 1 May 2005, the Hui Long arrived in Hong Kong from China and was loaded with 5,185 tonnes of fluorspar in hold number 1 and the lower part of hold number 3, as seen in the stowage plan in Figure 187. Loading was carried out by grabs from the barges that were moored alongside the Vessel (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005).
Figure 187 – Hui Long’s cargo stowage plan on departure from Sei Pakning (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005)

According to the weather and crew reports, there had been slight showers on the day of loading, which did not impair the loading of the cargo. After completion, samples from the two holds were taken and a certificate of moisture content was issued. The certificate indicated that the moisture content of the fluorspar cargo was at 9.8%. The certificate did not provide the details of the Transportable Moisture Limit (TML) of the fluorspar (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005).

The next day the vessel sailed to Singapore to unload a cargo of aluminium ingots and steel angle bars where it was reported that there had been intermittent rain showers during the cargo operation and that the crew would close the No. 2, 3 and 4 hatch covers when raining. The vessel departed Singapore on 11 May for Sei Pakning, Indonesia to load a cargo of wood pulp. Again, during loading, it was reported that there had been occasional rain showers and the ship’s crew had to close the No. 2, 3 and 4 hatch covers during the rain, as wood pulp cargo is susceptible to rainwater. After loading was completed on 14 May, the Hui Long departed Sei Pakning, Indonesia for India loaded with a deadweight of 11,244 tonnes including the 5,185 tonnes of fluorspar. The vessel was upright and in normal working condition on its departure and it was indicated that the vessel had no major structural problems (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005).

On 18 May, the Hui Long was proceeding off Sumatra on a westerly course. The weather was fine with moderate sea and south-westerly wind at force 5. Occasional moderate rolling of vessel movement was experienced. According to the Master, ship movement was normal and there was no severe rolling during the voyage (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005).

On 18 May at approximately 1535, the Hui Long suddenly developed a 15-degree list to port. The bridge navigating officer stated that the vessel was navigating normally with no irregularities and rolled moderately approximately 10 degrees to both sides before the list. After reporting the incident, the Master informed the engineers to upright the vessel by filling the starboard double bottom tanks. The crews were not able to upright the vessel with ballasting due to the severe listing (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005). An image of the Hui Long listing severely to port can be seen in Figure 188.
At 1602, as the list worsened to 40-degrees to port, the Master decided to abandon the vessel. At this time, the port deck edge of the vessel was immersed under the sea. A nearby container vessel and the management company in China was made aware of the situation (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005).

The nearby container vessel successfully rescued all crewmembers from the water and the life rafts. A salvage tug arrived at the scene the following day but the vessel sank 49 hours and 43 nautical miles north-east of the initial listing position. There was no casualties reported in the incident (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005).

11.3.3.2.2 Investigation Conclusions
The following are the main conclusions from the investigation into the sinking of the Hui Long (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005).

1. The exact cause of the sinking of ‘Hui Long’ could not be established,
2. after investigating the probable causes of the accident, it is believed to be the liquefaction of the fluorspar cargo inside holds number 1 and 3. The flow state of the fluorspar cargo might have caused the vessel to list, capsize and sink,
3. the Master appeared to have not followed the company’s cargo safety manual for loading a bulk cargo that may liquefy by accepting on-board for shipment of fluorspar cargo with the moisture content higher than the stipulated 8%,
4. the shipper has failed to provide the TML of the fluorspar cargo before the shipment as required by the Merchant Shipping (Safety) (Carriage of Cargoes) Regulation and the BC Code. While a norm of 10% TML for bulk fluorspar was used by the shipper without documentation support of any laboratory test. As such it is possible that the fluorspar cargo at moisture content of 9.8% had exceeded the actual TML and
5. the amount of sample taken by the survey firm would not be sufficient for a proper determination of moisture content as far as the BC Code is concerned.
11.3.3.3 Case Study 3 – Jian Fu Star
Built in 1982, the Panama flag Jian Fu Star (IMO: 8106379) was a Handymax bulk carrier with a deadweight of 45,107 tonnes (United Nations Conference on Trade and Development (UNCTAD), 2014). The vessel, which had a length of 190 m, breadth of 31 m and summer draught of 11 m, had five cargo holds serviced by four cranes (Panama Maritime Authority - Maritime Accident Investigation Department, 2011b). The Jian Fu Star, as seen in 2008 as Elene (MarineTraffic, 2015b), along with the hold and tank layout can be seen in Figure 189 and Figure 182.

11.3.3.3.1 Summary of Incident
On 16 October 2010 at approximately 1900, the Jian Fu Star arrived at an Obi Island port in Indonesia, one of which can be seen in Figure 190. Loading commenced on 17 October at 0200 and was completed on 20 October by approximately 1400. The Master and Chief Officer noted that the cargo was dry in appearance and to the touch, similar to previous loadings condition. Due to the visually dry appearance of the cargo, the Master and Chief Officer did not carry out any tests to determine its moisture content (Panama Maritime Authority - Maritime Accident Investigation Department, 2011b). The stowage plan for the Jian Fu Star for this voyage can be seen in Figure 191.
The vessel loaded 23,800 tonnes of nickel ore continuously depending on the inflow of barges and halting during periods of occasional showers. After the Master noted that the moisture content of the nickel ore was less than the shipper’s earlier declaration, the Jian Fu Star departed Obi Island, Indonesia on the 20 October at approximately 1800 bound for Lazhou, China (Panama Maritime Authority - Maritime Accident Investigation Department, 2011b).

During loading, there was no reports of damage to the bulk carrier by either the barges or grab cranes. The journey from Obi Island to just off Lazhou was uneventful and the weather was reported to be fine with calm sea states. On 26 October at approximately 1000, as the vessel continued towards Lazhou, the wind shifted to a strong northerly with a force of 5 to 6. By 1400 the wind had increased
to force 7 to 8 and sea conditions worsened causing the vessel to pitch heavily and roll moderately (Panama Maritime Authority - Maritime Accident Investigation Department, 2011b).

On 27 October at approximately 0700, as the sea remained rough and swell heavy, the vessel listed suddenly 5-degrees to port and did not upright itself. Procedures began to try to upright the vessel by reducing the port and increasing the starboard tank ballast along with transferring fuel from port to starboard. Even after these measures were implemented, the vessel's list increased to 10-degrees port (Panama Maritime Authority - Maritime Accident Investigation Department, 2011b).

At this time, the general alarm was raised and the Master notified the company in charge. During this time, the vessel’s list had increased dramatically to where the port deck was level with the sea. Due to the inevitable capsizing of the vessel, a distress signal was activated and the abandon ship alarm was sounded. The vessel sank within a 20-minute period from the initial list. Of the 25 crewmembers on-board the Jian Fu Star, 12 were rescued (Panama Maritime Authority - Maritime Accident Investigation Department, 2011b).

11.3.3.3.2 Investigation Conclusions
The following are the main conclusions from the investigation into the sinking of the Jian Fu Star (Panama Maritime Authority - Maritime Accident Investigation Department, 2011b).

1. The exact cause of the sinking of Jian Fu Star could not be established with absolutely certainty as the vessel had completely sunk,
2. the mined nickel ore was stockpiled in areas open to the ingress of rain water,
3. the cargo was loaded with suspected excessive moisture content,
4. the vessel was subjected to heavy seas, which led to the cargo changing state from a solid to a viscous liquid in all of its 5 holds,
5. insufficient knowledge of the characteristics of nickel ore as a cargo and its propensity to become fluid when the moisture content is high and it is subjected to sufficient physical stress,
6. it is highly believed the accident was a result of liquefaction of the nickel ore inside the cargo holds that caused the sudden list, capsize and sinking of the Jian Fu Star,
7. there is no test to specifically ascertain the Transportable Moisture Limit (TML) of nickel ore,
8. the owners/manager of the vessel did not have clear instruction on the care and handling of such cargoes as specified in its Safety Management System, especially relating to the procedures in accepting shipper’s laboratory certificate, self-basic testing of the cargo moisture content and the procedures in Master’s right to refuse to load the cargo under the terms of the agreement between the Chinese buyer and the cargo sellers,
9. the ore seller did provide the Master with data pertaining to the cargo’s moisture content and flow tests as required by SOLAS, but with respect to accuracy and authenticity of the laboratory data, this was very much in doubt,
10. the Master and Chief Officer appeared to have not followed strictly the IMSBC Code’s guideline and recommendation of carrying a basic ‘Can Test’ to determine and compared the stated cargo specification declaration supplied by the shipper,
11. the shipper might have failed to provide accurately the TML of the nickel ore before the shipment as required by the IMSBC Code.

11.3.3.4 Case Study 4 – Nasco Diamond
Built in 2009, the Panama flag Nasco Diamond (IMO: 9467861) was a Handymax bulk carrier with a summer deadweight of 56,893 tonnes (United Nations Conference on Trade and Development (UNCTAD), 2014). The vessel, which had a length of 186 m, breadth of 32 m and summer draught of
13 m, had five cargo holds serviced by four on-board cranes (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c). The Nasco Diamond can be seen in Figure 192.

![Figure 192 – The Nasco Diamond (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c)](image)

11.3.3.4.1 Summary of Incident

On 18 October 2010 at 2130, the Nasco Diamond arrived at Kolonodale, Central Sulawesi, Indonesia, seen in Figure 193, to begin loading a cargo of nickel ore from shore barges, similar to what is seen in Figure 194. Loading operations commenced at 2245 on 19 October. The same day, the flow table test was carried out on a sample of the cargo that was to be loaded on the Nasco Diamond. The representative sample that was tested was taken two days prior on 16 October (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).

The results of the test showed that the moisture content at time of sampling was 30.08% with a flow moisture point of 37.00% and resulting transportable moisture limit of 33.25%. It was noted that the barges carrying the nickel ore had no protection from the, ‘time to time, pouring’ rain during the passage and loading and that there was no sample taken for the determination of moisture content after 16 October (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).

![Figure 193 – Port of Kolonodale, Central Sulawesi, Indonesia (Source: Google Maps)](image)
During loading, the Master was unsatisfied with the condition of the nickel ore cargo that was being brought to the vessel by the barges. On 2 November, a ‘note of protest’ was prepared and within stated, “We find the cargo in [the 12th barge] is very wet and contains plenty of water. In view of the above fact, I, the Master of the MV “Nasco Diamond”, regret to submit this notice in advance to reject to receive this cargo, the ship, owner is not responsible for any loss.” (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c). Photographs were taken at this time and can be seen in Figure 195. The ‘note of protest’ was more or less ignored as the cargo was allowed to be loaded wet (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).

On 4 November at 1230, after the loading of 55,150 tonnes of nickel ore was complete, the Nasco Diamond departed Kolonodale, Indonesia. The stowage plan can be seen in Figure 196. The vessel was reported to be in normal working condition at the time of its departure (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).
The journey was uneventful until 9 November at 1111 when the Master reported to his respective supervisor that the vessel was listing 3-degrees to port. After inspections of all five holds, slurry was observed. It was noted that slurry was observed in the aft Section of hold number 1, in the aft Section of hold number 4 (approximately 50 to 60 cm depth) and in the aft Section of hold number 5 (approximately 20 to 40 cm depth). Hold numbers 2 and 3 were dry with no formation of slurry (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).

At this time, the wind was north-easterly with force 6 to 7, the sea was 3 meters in height and the vessel was rolling between 0-degrees and 7-degrees on the port side. The Master reported that his intent was to use ballast to try to correct the vessel’s list but was instructed to wait for further instructions (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).

At 1137, the Master was contacted by his respective supervisor, whom had gathered the company’s emergency response team, and it was suggested that he adjust his sailing course to head windward, so as to minimize the rolling of the vessel. It was also suggested he scoop the slurry into oil drums and, with a submersible pump placed in the drum, attempt to pump the slurry out of the vessel’s holds. Following that, the Master was also instructed to take the sounding of all the ballast and oil tanks and to get the assistance of all crew on-board to assist in scooping the slurry except for those on duty (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).

At 1217, the captain reported that the removal of the slurry was progressing and going well. At 1314, the Master reported that the submersible pump had been placed in a bamboo basket and was directly pumping the slurry from top of the cargo. At this time, the Master also reported that the surface of the cargo in the respective holds were uneven and all water from the bilges had been drained out (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).

Sometime between 1650 and 1720, after reporting that the vessel was now rolling between 5-degrees port to 2-degrees starboard, the captain reported that the situation is rather stable. From 1817 to 1825, the Master reported that the vessel was swaying uniformly about 2.5-degrees and the vessel was in stable condition with the sea state reduced to 2 meters (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).
At 2030, the emergency response team called the Master but there was no answer. From 2030 to 2041, the emergency response team kept calling while also checking the status of the vessel using the available satellite tracking. At 2230, after continuing calls went unanswered and tracking was lost, the emergency response team began search and rescue procedures (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).

On 10 November at 0951, the emergency response team was notified that a rescue plane located an oil slick on the sea surface and located two life rafts. At 2330, they were also notified that three life rafts were located by other rescue planes. The name on the life rafts could not be read at the distances they were seen but it was confirmed that they contained no survivors. On 11 November rescue ships from Taiwan and Japan found and rescued three crewmembers and retrieved two dead bodies. The rescue operations ceased on 13 November at 2200 leaving 22 crewmembers deceased or missing (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).

11.3.3.4.2 Investigation Conclusions
The following are the main conclusions from the investigation into the sinking of the Nasco Diamond (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c).

1. The exact cause of the sinking of Nasco Diamond could not be established,
2. the cargo as presented for loading was not in accordance with the Code of Safe Practice for Solid Bulk Cargoes (IMSBC Code). The cargo was loaded with excessive moisture content as evident from the damp cargo loaded from the barge and the Master’s ‘Note of Protest’,
3. the IMSBC Code was not adhered to as stated in Appendix 1,
   a. under ‘Carriage’: “The appearance of the surface of the cargo shall be checked regularly during voyage. If free water above the cargo or fluid state of the cargo is observed during voyage, the Master shall take appropriate actions to prevent cargo shifting and potential capsize of the ship, and give consideration to seeking emergency entry into a place of refuge” and
   b. under ‘Weather Precautions’: the moisture content of the cargo is more than the TML during voyage,
4. insufficient knowledge of the characteristics of nickel ore as a cargo and its propensity to become fluid when the moisture content is high and it is subjected to sufficient physical stress. The vessel was subjected to heavy seas, which led to the cargo changing state from a solid to a viscous liquid in 3 of the 5 holds,
5. on completion of loading, there was no sample taken to test to specifically ascertain the ‘transportable moisture limit’ of the nickel ore. The ore seller did not provide the Master with the agreed data pertaining to the cargo’s moisture content and flow tests as required by SOLAS & BC Code (IMSBC Code),
6. no evidence to indicate if the owners/agents of the vessel have included, in the Master’s voyage instruction, the relevant information pertaining to the cargo moisture content, flow tests, and the Master’s right to refuse to load the cargo under the terms of the agreement between the cargo buyer and cargo seller,
7. the Master loaded the nickel ore without insisting on the provision of the data concerning the moisture content and flow tests of the cargo on-board even after physically seeing the ore arriving in wetted condition,
8. the mined nickel ore was stockpiled in areas open to the ingress of rain water and that includes while being transported by the barge from the stockpile area to the vessel loading anchorage,
9. the vessel’s stability should have been calculated for the loaded condition leaving Kolonodale, Indonesian and subsequently checked prior to the pumping of ballast into the topside and double bottom tanks to correct the list, if any and
10. After investigation the probable causes of the accident, it is believed to be the liquefaction of the nickel ore cargo inside the No.1, 4 and No.5 holds. The flow state of the nickel ore cargo might have caused the vessel to list, capsize and sink.

11.3.3.5 Case Study 5 – Hong Wei

Built in 2001, the Panama flag Hong Wei (IMO: 9230139) was a Handymax bulk carrier with a deadweight of 50,149 tonnes (United Nations Conference on Trade and Development (UNCTAD), 2014). The vessel, which had a length of 181 m, breadth of 32 m and draught of 12 m, had five cargo holds serviced by four on-board cranes (Panama Maritime Authority - Maritime Accident Investigation Department, 2011a). The Hong Wei, as seen in 2006 as the Darya Dhyan (MarineTraffic, 2015a), can be seen in Figure 197.

![Figure 197 – The Hong Wei (Source: Silvio Roberto Smera) (ShipSpotting, 2006)](image)

11.3.3.5.1 Summary of Incident

On 6 November 2010 at 1820, the Hong Wei arrived at Kolonodale, Central Sulawesi, Indonesia, seen in Figure 193, to begin loading a cargo of 48,900 tonnes of nickel ore from shore barges, similar to what is seen in Figure 194 (Panama Maritime Authority - Maritime Accident Investigation Department, 2011a).

During loading, the Chief Engineer recalled that it rained during two occasions and the cargo loading operations were stopped during this time. Additionally, he could not recall if during inspections of the cargo by the Chief Officer it was found to be in dry conditions or not.

On 4 November, prior to the arrival of the Hong Wei at Kolonodale, Indonesia, a flow table test was carried out to determine the transportable moisture limit of the nickel ore cargo. The results of the test showed that the moisture content at time of sampling was 31.50% with a flow moisture point of 37.00% and resulting transportable moisture limit of 33.25%.
Loading operations were completed on 27 November at approximately 1800 and the vessel departed Kolonodale, Indonesia for Lanshan, China on the 28 November at approximately 0600. The cargo distribution of the Hong Wei can be seen in Table 68 (Panama Maritime Authority - Maritime Accident Investigation Department, 2011a).

<table>
<thead>
<tr>
<th>Cargo Hold Number</th>
<th>Quantity of Nickel Ore (Tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8,600</td>
</tr>
<tr>
<td>2</td>
<td>10,100</td>
</tr>
<tr>
<td>3</td>
<td>9,700</td>
</tr>
<tr>
<td>4</td>
<td>10,100</td>
</tr>
<tr>
<td>5</td>
<td>10,400</td>
</tr>
<tr>
<td>Total</td>
<td>48,900</td>
</tr>
</tbody>
</table>

The weather at the time of departure was fine with winds of force 3 and slight seas. It was reported that from 28 November to 2 December, the wind force gradually increased to force 4. The interviewed Bosun reported that every day, at around 1500 to 1600, he usually checked the cargo holds and that everything seemed normal (Panama Maritime Authority - Maritime Accident Investigation Department, 2011a).

On 3 December at approximately 1300, the Chief Engineer felt a hard shock and reported that the vessel moved from port to starboard heavily until the vessel returned to the semi-normal position. At approximately 1305, the Captain made an announcement requesting that the Bosun pump port top side tanks numbers 2, 3 and 4 to correct the list that was reported to be approximately 3-degrees to the starboard side (Panama Maritime Authority - Maritime Accident Investigation Department, 2011a).

While lifejackets were being donned, crewmembers left their posts and moved towards the upper decks. As the Captain tried to convince crewmembers to return to their respective places of work, the list of the vessel increased to 6-degrees starboard. As the Chief Engineer made his way to the main deck, he saw the vessel’s bow deck nearly touching the sea surface and it was at this moment the abandon ship signal sounded (Panama Maritime Authority - Maritime Accident Investigation Department, 2011a).

Some of the crew went to Port side to try to release the Lifeboat but despite the efforts, it could not be released due to the now 20-degree list to the starboard side. The Chief Engineer lost hold of the railing and went into the sea with multiple crewmembers who were either in life rafts or also in the sea (Panama Maritime Authority - Maritime Accident Investigation Department, 2011a).

At approximately 1800, a search and rescue helicopter rescued the Chief Engineer and another crewmember while another vessel rescued 12 more. 10 crewmembers are still missing and presumed dead (Panama Maritime Authority - Maritime Accident Investigation Department, 2011a).

11.3.3.5.2 Investigation Conclusions
The following are the main conclusions from the investigation into the sinking of the Hong Wei (Panama Maritime Authority - Maritime Accident Investigation Department, 2011a).
1. Many mines in the regions where these cargoes are available to carry are very basic and are situated in very remote locations, making it hard for surveyors and experts to attend them. Moreover, it is not easy to arrange for cargo samples to be tested independently due to the lack of reliable laboratories in such countries,
2. the nickel ore is mined from open quarries and stored in open areas where stockpiles are susceptible to heavy rainfall and high humidity prior to shipment. In some cases, the ore is transported directly from the mine to the vessel,
3. the “solar drying” of stockpiles has limited effect and rarely does more than dry the surface area of the ore. No other processing is involved. The ore is typically loaded into barges and transhipped to bulk carriers waiting at anchor. Although the cargo presented for shipment may appear to be dry, this is not a guide as to whether the cargo is actually safe to carry,
4. nickel ore is non-homogenous cargo and particle sizes vary considerably. This creates problems for laboratories when trying to ascertain the flow moisture point from which the transport moisture limit is calculated. Local test facilities in these problem areas are not able to complete the testing required by the new IMSBC Code. The required shipping documentation, actual moisture content and transport moisture limit may therefore be very inaccurate,
5. the non-homogenous nature of nickel ore means that cargo loaded in different holds may be inconsistent from one hold to the next with respect to the flow moisture point of cargo in such different holds and
6. in summary, the evidence suggest that the direct cause of this accident was the loss of stability as a result of cargo liquefaction and shift in bad weather.

11.3.3.6 Case Study 6 – Trans Summer
Built in 2012, the Hong Kong flag Trans Summer (IMO: 9615468) was a Handymax bulk carrier with a summer deadweight of 56,824 tonnes (United Nations Conference on Trade and Development (UNCTAD), 2014). The vessel, which had a length of 190 m, breadth of 31 m and summer draught of 13 m, had five cargo holds serviced by four on-board cranes (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015). The Trans Summer can be seen in Figure 198.
11.3.3.6.1 Summary of Incident

On 15 July 2013, the Trans Summer arrived at Subaim, Indonesia, seen in Figure 199, to begin loading a cargo of nickel ore from shore barges. Prior to arrival, on 10 July, a precaution notice was sent to the Master reminding him to pay particular attention to the possible high moisture content of the nickel ore cargo. Moreover, the ‘Can Test’ should be conducted on each barge so as to satisfy himself before loading the cargo on-board (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).

![Figure 199 – Port of Subaim, Indonesia (Source: Google Maps)](image)

Loading commenced on 17 July at 1230 after the Chief Officer and Chief Engineer inspected the nickel ore mine. Although the Master had already received a cargo declaration together with a moisture certificate issued by shipper, the Chief Officer and Chief Engineer did not verify the conditions of cargo stockpiles, nor were they aware whether the cargo stockpiles would be covered by tarpaulins to prevent wetting. The cargo declaration showed that the moisture content at time of sampling was 33.87% and had a flow moisture point of 38.66% with a resulting transportable moisture limit of 34.79% (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).

It was noted that it rained frequently during the loading of cargo. To avoid rainwater wetting the cargo, the loading operation was suspended during these times. The crew on-board the vessel closed the cargo hold hatches while the stevedores on the barges covered the cargo using tarpaulins (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).

A ‘Can Test’ was performed on each barge prior to transfer to the Trans Summer. The ‘Can Test’ samples were taken from approximately 1 m below the cargo surface. If the ‘Can Test’ failed, the moisture content was determined and if the moisture content was found to exceed the transportable moisture limit then the cargo was rejected. The results of all the cargo moisture content tests were recorded and sent to the vessels owner (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).
Subsequently, all documents on the vessel including the above records were lost in the accident. The information regarding the cargo loading sequences was retrieved from emails exchanged between the Trans Summer and the vessels owner, as seen in Table 69 (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).

Table 69 – The loading sequence of the Trans Summer (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015)

<table>
<thead>
<tr>
<th>Date</th>
<th>Stoppage Due to Rain (Hours)</th>
<th>Loaded (Tonnes)</th>
<th>‘Can Test’(s)</th>
<th>Moisture Content Test</th>
<th>Cargo Rejected</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>17/07</td>
<td>1500-2400</td>
<td>310</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>MC certificate received.</td>
</tr>
<tr>
<td>18/07</td>
<td>0000-0300, 1700-1900</td>
<td>4800</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19/07</td>
<td>1600-2100</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>No Loading operation.</td>
</tr>
<tr>
<td>20/07</td>
<td>1300-1630</td>
<td>1283</td>
<td>1 (Fail)</td>
<td>-</td>
<td>Rejected one.</td>
<td>-</td>
</tr>
<tr>
<td>21/07</td>
<td>0030-0230, 0800-1040</td>
<td>808</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>22/07</td>
<td>1430-1530, 2255-2330</td>
<td>1830</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>23/07</td>
<td>1630-1730, 1855-1930</td>
<td>1588</td>
<td>1 (Fail)</td>
<td>-</td>
<td>Rejected one was towed back.</td>
<td>MC certificate received. did not check.</td>
</tr>
<tr>
<td>24/07</td>
<td>1730-2140</td>
<td>2204</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>25/07</td>
<td>0210-0525, 1820-1930, 2100-2250</td>
<td>2657</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>26/07</td>
<td>0300-0800, 1315-1505, 2000-2320</td>
<td>5587</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>27/07</td>
<td>-</td>
<td>2833</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>28/07</td>
<td>-</td>
<td>6394</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>0220-0745 stop due to Wet cargo.</td>
</tr>
<tr>
<td>29/07</td>
<td>-</td>
<td>2213</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30/07</td>
<td>1200-2400</td>
<td>1281</td>
<td>1</td>
<td>-</td>
<td>MC Certificate received.</td>
<td></td>
</tr>
<tr>
<td>31/07</td>
<td>0000-1000, 1150-1220, 1640-1720, 2115-2400</td>
<td>5549</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>01/08</td>
<td>-</td>
<td>1382</td>
<td>1</td>
<td>1 (MC 35.53% &gt; TML)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>02/08</td>
<td>-</td>
<td>4896</td>
<td>1</td>
<td>1 (MC 37% &gt; TML)</td>
<td>No information. At 0907 hours Company enquiry of why the cargo was loaded on-board. Rechecked by 'Can Test'. Cargo was loaded o/b.</td>
<td></td>
</tr>
<tr>
<td>03/08</td>
<td>-</td>
<td>3040</td>
<td>3</td>
<td>1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>04/08</td>
<td>1340-1800</td>
<td>1809</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>05/08</td>
<td>0800-1500, 1525-1640, 1800-2010</td>
<td>1839</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>06/08</td>
<td>Completed Loading</td>
<td>2488</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>0010-0800 stop due to Wet cargo.</td>
</tr>
<tr>
<td>Total</td>
<td>26 Stoppages</td>
<td>54750</td>
<td>19</td>
<td>7</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

As seen in Table 69, on 23 July a moisture content certificate was received however, nobody on-board the vessel checked the cargo declaration and certificate. As a consequence, they did not know the moisture content of cargo loaded into the cargo holds from 24 to 30 July. On 30 July, the moisture content certificate was checked by the crew and it was sent to the company. It showed that the moisture content at time of sampling was 33.88%, had a flow moisture point of 38.69% and a resulting transportable moisture limit of 34.80%. Table 69 revealed that the vessel accepted cargo on two
occasions with a moisture content exceeding the transportable moisture limit (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).

The loading was completed on 6 August with the distribution of cargo in the holds shown in Table 70. On 7 August at approximately 1342, the vessel departed Subaim, Indonesia bound for her discharge port in Yangjiang, China. Everything was found normal upon departure with the stability of the vessel intact (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).

Table 70 – Cargo distribution of the Trans Summer when departing Subaim, Indonesia (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015)

<table>
<thead>
<tr>
<th>Cargo Hold Number</th>
<th>Quantity of Nickel Ore (Tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10,708</td>
</tr>
<tr>
<td>2</td>
<td>11,602</td>
</tr>
<tr>
<td>3</td>
<td>9,948</td>
</tr>
<tr>
<td>4</td>
<td>11,159</td>
</tr>
<tr>
<td>5</td>
<td>11,333</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>54,750</strong></td>
</tr>
</tbody>
</table>

During the voyage, on 9 August, the cargo in hold number 4 was inspected and found to be normal. No further inspections were performed. On the same day, the Master was informed to monitor a tropical depression developing in the Philippines. On 10 August, the tropical depression developed into typhoon ‘Utor’, which was predicted to make landfall close to the Trans Summer’s discharge port in Yangjiang, China. Typhoon precautionary measures were then executed by the crew (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).

On 12 August at 1540, the Master altered course towards Wanshan QuanDao, China (about 100 miles from Yangjiang) to shelter from the typhoon. On 13 August at 2000, after anchoring 2 nautical miles off the coast, easterly winds increased to force 8 to 9, and wave height increased to approximately 5 to 6 meters. The rolling and yawing of the vessel at this time was 10-degrees with increasing periods (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).

Early morning on 14 August, the wind was continuing at force 9 blowing in an easterly direction and the vessel was yawing about 10-degrees and rolling about 7 to 8-degrees. At 0757, the wind was now blowing from the southeast at force 9 with wave heights about 4 to 6 meters. The distance to typhoon centre was about 120 nautical miles. At 1000, the wind force intensified to force 10 with wave heights up to 7 meters. At 1010, a high wave rushed from the starboard side causing the vessel to heel port side more than 20-degrees immersing the deck edge in water. The vessel then rolled back and stayed listing about 10-degrees to port. The listing to port then increased to 15-degrees soon afterwards and persisted (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).

Ballast was then used to try to correct the list but it was mistakenly pumped into the starboard top tanks instead of the double bottom tanks causing the vessels centre of gravity to increase. At 1030, when the vessel listed to port about 17-degrees, the second officer transmitted a distress signal under the Master’s order and life rafts and the lifeboat were prepared for launching. The Master announced abandon ship at 1105 the same day (The Hong Kong Special Administrative Region - Marine
Department - Marine Accident Investigation Section, 2015). The track of ‘Utor’ on 14 August at 1200 can be seen in Figure 200.

![Figure 200 – Track of ‘Utor’ on 14 August at 1200 (Predicted track in red) (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015)](image)

As the vessel listed to port more than 22-degrees, the Master ordered all crewmembers to jump into the sea from the stern deck and board the inflated life rafts. As rescue operations commenced, the vessel listed to port more than 90-degrees and subsequently sank on 14 August at 1156. Views from a rescue helicopter can be seen in Figure 201 and Figure 202. The vessel had dredged the anchor more than half a nautical mile north-west from its original position.
Figure 201 – View from rescue helicopter as the Trans Summer listed 45-degrees to port (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015)

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Figure 202 – View from rescue helicopter as the Trans Summer listed 90-degrees to port (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015)

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Fortunately, helicopters and vessels sent to the location of the Trans Summer rescued all crewmembers, but the deck log along with other statutory documents were lost at sea. (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).

11.3.3.6.2 Investigation Conclusions
The following are the main conclusions from the investigation into the sinking of the Trans Summer (The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2015).

1. The requirements of IMSBC Code for the cargo of nickel ore, under group A & B, was not strictly followed. It was loaded despite moisture content exceeded its Transportable Moisture Limit,
2. the safety shipboard procedures for loading and carriage of nickel ore were not followed. The relevant procedures were:
   a. the procedure for handling of cargo,
   b. the instruction of handling of bulk cargo which may liquefy,
   c. the requirement of cargo care at sea,
   d. the instruction for preventing strong wind and
   e. the voyage instruction,
3. liquefaction of cargo inside cargo holds while the anchored vessel experienced rolling at the anchorage, compounded by worsening weather and sea condition due to approaching of typhoon and mistakenly pumping water into ballast tank,
4. the Master’s assessment to select the shelter for the vessel to anchor was not appropriate. The place selected by the Master could shelter the wind from the north only. The vessel could not shelter from the south-easterly strong wind and waves when the typhoon “Utor” was passing the south of the vessel,
5. the moisture content certificate was issued by the shipper instead of local administration or independent organization (or authorized organization) and
6. the crew was not trained and therefore not competent to carry out Oven Drying Testing on-board to verify the moisture content of the cargo before loading.

11.3.3.7 Case Study 7 – Bulk Jupiter
Built in 2006, the Bahama flag Bulk Jupiter (IMO: 9339947) was a Handymax bulk carrier with a summer deadweight of 56,009 tonnes (United Nations Conference on Trade and Development (UNCTAD), 2014). The vessel, which had a length of 190 m, breadth of 32 m and draught of 13 m, had five cargo holds serviced by four on-board cranes (The Bahamas Maritime Authority, 2015). The Bulk Jupiter can be seen in Figure 203.
11.3.3.7.1 Summary of Incident

On 12 December 2014, the Bulk Jupiter arrived at the port of Kuantan, Malaysia, seen in Figure 204, to begin loading a cargo of bauxite from a berth. The cargo loading operations were delayed due to heavy and prolonged rainfall until 17 December at 2100, at which point loading of hold numbers 1, 3, 4 and 5 commenced. Loading of hold number 2 commenced on 18 December (The Bahamas Maritime Authority, 2015).

The East coast of Malaysia had endured record-breaking rainfall over the month of December, recording the highest monthly rainfall in the history of Kuantan at 1806.4mm over a 22-day period, as seen in Figure 205. The loading operations continued for an extended period of time due to heavy rain and technical delays. During periods of rain, vessels generally close their hatch covers to prevent any moisture from entering cargo holds and maintain the cargo in a dry condition. However, any cargo left on the quayside is left uncovered and therefore exposed to the elements. It is very likely that the moisture content of the bauxite increased during this time (The Bahamas Maritime Authority, 2015).
Loading of Bauxite onto bulk carriers at the Port of Kuantan is achieved using the on-board cranes, as seen in Figure 206. The bauxite is transported to the port on load trucks where they either store the cargo in stockpiles or storage facilities or transport the bauxite directly to the quayside. Noted in the investigation was that during transport and storage the bauxite is generally not covered to protect it from rain (The Bahamas Maritime Authority, 2015).

There are a number of mines dotted around the Port of Kuantan with varying sizes of operations. It was also noted that there was also no covered storage facility at these mines that affords any protection from the rain or surface water runoff (The Bahamas Maritime Authority, 2015). At the time of loading there was no transportable moisture limit test performed on the bauxite as in the IMSBC Code, under the individual schedule for bauxite, it did not state the cargo was potentially liquefiable (International Maritime Organization, 2013b).
On 30 December at 2124, the Bulk Jupiter left Kuantan, Malaysia bound for Qingdao, China with 46,400 tonnes of bauxite on-board and stability intact. After clearing the breakwater, the vessel was observed to be rolling about 2 to 3-degrees in low swell. The pilot did not note any abnormal behaviour in the way the vessel handled while she was being pulled off the berth or while being manoeuvred through the port and channel (The Bahamas Maritime Authority, 2015).

On 31 December, part way into the voyage, the weather deteriorated. Wind was forecast north-east at a force of 6 to 7, wind speed 24 to 34 knots, sea state 4 to 6 and with an average wave height of 2.2 m. On 1 January, the Master received a weather forecast that included alternate waypoints for the vessel to travel to reduce the exposure to gale force winds and waves between 2.5 to 4m from a tropical storm in the North East (The Bahamas Maritime Authority, 2015). The route of the Bulk Jupiter and location the bulk carrier was lost can be seen in Figure 207.

On 2 January 2015 at approximately 0600, the Chief Cook awoke and noted the weather was starting to deteriorate and the vessel was rolling more heavily than the previous day. At approximately 0640, the general alarm was sounded followed by an announcement by the Master directing all crew to proceed to the bridge. The Chief Cook made his way to the bridge but was told by fellow crewmembers to instead proceed to the port side lifeboat (The Bahamas Maritime Authority, 2015).

At 0654, a distress signal was sent out by the Bulk Jupiter, which initiated search and rescue operations. As the Chief Cook returned to his cabin to collect some belongings, he felt the vessel suddenly start to roll more heavily, particularly to starboard. As he left his cabin, the vessel suffered a black out and emergency lights illuminated. The vessel then stopped rolling and adopted a 45-degree
list to the starboard side. After meeting the Master, they both abandoned the vessel on the starboard side (The Bahamas Maritime Authority, 2015).

The Bulk Jupiter founded southeast of Vietnam between the time of the distress signal and 0700. As the search for survivors continued throughout the day, at 1556, the Chief Cook was recovered. Search and rescue operations ceased on the 06 January. The Chief Cook was the only survivor of the 19 crewmembers on-board (The Bahamas Maritime Authority, 2015).

Bauxite cargo in the hold of another bulk carrier, the Orchid Island, which left the Port of Kuantan on 1 January 2015, shortly after the Bulk Jupiter, can be seen in Figure 208. This cargo of bauxite was suspected to have liquefied during the voyage. Note the extensive ‘splatter’ on the sides of the cargo hold. An additional photo, seen as Figure 209, taken from the Medi Okinawa shows bauxite on the quayside open to the elements. The Medi Okinawa arrived at Kuantan shortly before the Bulk Jupiter but sailed on 21 January 2015, after discharging the cargo of bauxite that was loaded because the cargo failed to meet the description contained in the declaration provided (The Bahamas Maritime Authority, 2015).

Figure 208 – View of bauxite cargo in hold number 4 of the Orchid Island after voyage from Kuantan, Malaysia to Qingdao, China (The Bahamas Maritime Authority, 2015)
11.3.3.7.2 Investigation Conclusions
The following are the main conclusions from the investigation into the sinking of the Bulk Jupiter (The Bahamas Maritime Authority, 2015).

1. There is significant documentary evidence to identify that the 46,400t of bauxite loaded over the course of the 13-day period had an average moisture content of 21.3%. Despite this, there is no physical evidence to confirm what caused the vessel to adopt an unrecoverable list to starboard and subsequent capsize,

2. It was found that the cargo declarations were considered generic, including the declared 10% moisture content of the cargo. This was found when comparisons were made between the Bulk Jupiter’s cargo declaration and declarations of the bulk carriers Orchid Island and Medi Okinawa,

3. Communications between the Master and the Company ship manager indicated the Master had a lack of understanding of the practical method for determining excessive moisture content of a bulk cargo, specifically the ‘Can Test’,

4. In total 186.55 hours of loading was lost due to rainfall - the equivalent of 7 days of loading over the period. The infrastructure available to adequately store and transport bauxite in Kuantan increased the exposure of the bauxite to the elements. Despite the crew’s diligent response to the rain by continually opening and closing the hatch covers to reduce the ingress of water, the cargo remained exposed whilst on the quayside, in stockpiles and in the trucks,

5. An independent inspection was not requested by the Master to verify the properties of the cargo prior to loading on-board. Considering the extreme weather conditions and storage
facilities available it was acknowledged that the cargo was very wet and that measures to protect the cargo on shore from further rain were not effective in preventing further wetting. The absence of an independent inspection resulted in the cargo being loaded without its physical properties and moisture content being verified against the parameters of the IMSBC Code schedule or the cargo declaration form,

6. every 48 hours a report should be generated and provided to the Charterers if any water had been drained from the bilges during the transit in accordance with the Charterers Voyage Instructions. No correspondence has been received from the Charterers and therefore it cannot be determined whether the cargo was draining free water and/or whether anyone on-board was aware and was taking action to discharge any water accumulating in the hold bilges,

7. the previous class and special survey inspections indicate no structural integrity failures; the vessel had fulfilled diligently all prior certification conformity requirements and as such the likelihood of a catastrophic structural failure is considered low,

8. having presumed that the probability of structural failure is low, as a singular causal event, it can be concluded most probable that either liquefaction or a free surface effect induced an unrecoverable list. When considering the conditions in the order that they occurred, there can only be very few circumstances that cause a vessel to capsize so quickly with minimal warning. The reliability of the information provided on the cargo declaration, in particular the composition of cargo, the probability of liquefaction occurring is considered high. A further causal event, for which would only occur if the cargo is sufficiently compacted is a free surface effect generated on top of the cargo. Notwithstanding this, if the cargo had liquefied, a free surface effect will also occur, with similar catastrophic effect. Another related phenomenon associated with both liquefaction and free surface effect occurs when the cargo slides to one side of the vessel and fails to return to where it came from. This particular effect would be inevitable once the angle of heel is greater than the angle of repose of the cargo, if untrimmed, or if the cohesion between the particles of the cargo is insufficient when an angle of heel is induced.

11.3.4 Discussion and Recommendations

As discussed in Section 11.3.2, there are many factors that influence the liquefaction potential of cargoes. Although this is the case, the moisture content is one that can change significantly during extraction, storage and transportation. It can change significantly based on the implemented procedures and the actions of the people involved in these processes. Despite the fact that some reports indicate that excess moisture within the cargo is only assumed to have been the cause of the incident, we will assume that in all cases excess moisture within the cargo was the cause of the incident.

Determining if a cargo is safe to transport is relatively simple if the correct sampling and testing techniques are implemented. The importance of sampling is commonly overlooked but is the most imperative aspect of any laboratory testing (Gard, 2012). If the sample does not represent the cargo being transported then the results will be misleading. There are many techniques for sampling stockpiles depending on the type of material and standards being followed (i.e. iron ore (International Standards Organization, 1998)). Section 4.6 of the IMSBC Code outlines sampling procedures that are to be followed when sampling stockpiles consigned to vessels (International Maritime Organization, 2013b). It is recommended these sampling techniques be used when determining the moisture content and transportable moisture limit of a cargo.

Once a representative sample of the cargo has been obtained, prior to the arrival of a vessel, it is recommended to determine both the average moisture content and transportable moisture limit of
the stockpile. For bauxite and nickel ore, there are no test methods specifically designed to determine the transportable moisture limit. Until such a test is developed, it is recommended to utilize either the Penetration test or Flow Table test stated in Appendix 2 of the IMSBC Code (International Maritime Organization, 2013b). These tests are recommended as they measure the direct liquefaction potential with visual observations (Munro and Mohajerani, 2014, 2015). Like iron ore fines and coal, it is recommended that a test be developed specifically designed for determining the transportable moisture limit of bauxite and nickel ore and the IMSBC Code specify mandatory testing of all variations of these cargoes (Australian Coal Association Research Program, 2014; Australian Coal Association Research Program (ACARP), 2014b; International Maritime Organization, 2012a, 2013a, 2015d). From the reports, it is clear that the ingress of water into the cargo is a major problem during transportation, storage and loading, prior to a vessels departure from port. It is commonly reported that trucks and barges are not equipped with tarpaulins to protect the cargo from rain. Additionally, stockpiles at the mines and quayside also lack this essential equipment. Cargoes such as nickel ore and bauxite can contain a significant amount of fine particles (Gard, 2014; UK P&I Club, 2015). This property can also increase the cargoes’ hygroscopic properties (Xinwei et al., 2013). Protective equipment should be easily accessible and readily available for use when rain is forecast. Masters should insist on checking if this protective equipment is available, as if this equipment is unavailable it can be an indication of poor practices at the site and therefore the Master should be extra vigilant. ‘Solar drying’ of stockpiles of cargo is an ineffective method for rapidly reducing the moisture content. The method merely dries the surface of the stockpile leaving the core of the stockpile unaffected (Britannia - The Britannia Steam Ship Insurance Association Limited, 2015; The American Club, 2010). If ‘solar drying’ is to be carried out, it is recommended that the cargo be evenly spread on a pad and frequently turned over using a bulldozer or excavator to increase the rate of evaporation and distribution of desiccation. Drying or dewatering a cargo can take some time to accomplish, therefore, prior to arrival of a vessel, it is recommended that the moisture content of the cargo is determined and compared with the transportable moisture limit in order to decide if drying is needed. Moisture content testing is inexpensive when compared to the cost that will be incurred if a vessel is lost due to a cargo liquefying or shifting. After the arrival of a vessel, prior to loading, the exact moisture content of the cargo should be known. Section 4.5 of the IMSBC Code states that the interval between moisture content sampling should not be more than seven days prior to loading (International Maritime Organization, 2013b). This statement can be misleading as the moisture content of a cargo can change significantly within seven days. If rainfall has occurred during this time or the air humidity has been high, it is highly recommended that a few hours prior to loading additional moisture content tests be performed for confirmation. It is recommended that an accredited independent testing laboratory is available to perform the required moisture content and transportable moisture limit testing. These laboratories may be located at the mine or port and be under the supervision of the International Maritime Organization and funded by the export company. After testing, if the Master suspects that a cargo may contain a moisture content that exceeds the transportable moisture limit then it is recommended that a ‘Can Test’ is also performed on the cargo. The ‘Can Test’ is an in-situ complementary test procedure for determining the liquefaction potential of a cargo given in the IMSBC Code (International Maritime Organization, 2013b). The ‘Can Test’
provides an estimate on whether the cargo may exceed the transportable moisture limit. Masters should be familiar with the ‘Can Test’ and moisture content test if they are frequently transporting potentially liquefiable cargoes. The ‘Can Test’ is usually the last line of defence for preventing cargoes exceeding the transportable moisture limit being loaded onto a bulk carrier. Failure of this test indicates the cargo it not safe to transport and should be rejected unless it is proven that the cargo has a moisture content less than the transportable moisture limit. Even then, extra precautions should be taken and the validity of the transportable moisture limit test be questioned.

Once a cargo is loaded onto a bulk carrier, it is still susceptible to the ingress of moisture. During loading, it is highly recommended that when rain is forecast all cargo holds be closed. The ingress of water into the holds can sometimes be removed by bilge pumps, but due to some cargoes ability to retain moisture it can be preserved within and migrate out during transportation.

During transportation, dynamic loading, caused by the ocean waves and vessel vibrations, can cause a cargo to densify. Dynamic Loading can reduce the voids in the cargo in turn increasing the degree of saturation and changing pore pressures. A cargo that is highly saturated may be at risk of liquefying and shifting within the hold of a bulk carrier (Koromila et al., 2013). In Appendix 1 of the IMSBC Code, it is recommended that cargoes be checked regularly to make sure that there are no changes in the state of the material. The IMSBC Code states, “The appearance of the surface of the cargo shall be checked regularly during a voyage. If free water above the cargo or fluid state of the cargo is observed during a voyage, the Master shall take appropriate actions to prevent cargo shifting and potential capsize of the ship, and give consideration to seeking emergency entry into a place of refuge” (International Maritime Organization, 2013b).

As the degree of saturation of a cargo increases, so does the degree to which it can densify. Densification may cause excess moisture to migrate to the surface. It has been proven that this process occurs gradually with the speed related to the magnitude and time of dynamic loading. It is recommended that regular check on the cargo be made, with frequently increasing checks being performed if the vessel experiences rough sea states.

11.3.5 Conclusion
The objective of this study was to investigate the collective causes of liquefaction of solid bulk cargoes on-board bulk carriers in order to make recommendations to prevent future incidents from occurring. This was achieved by analysing the available investigative reports relating to the incidents, focusing on the key findings and exploring the effect of excess moisture within the cargo. This study placed significant emphasis on the importance of preventing ingress of water into the cargo during transportation, loading and storage.

Although the International Maritime Solid Bulk Cargoes Code (IMSBC Code) was implemented on a mandatory basis from January 2011, incidents involving liquefaction of mineral bulk cargoes continue to occur.

The findings of this study indicate that liquefaction incidents on-board bulk carriers are caused by a combination of below par procedural implementation along with insufficient knowledge about liquefaction of cargoes and the possible consequences of transporting them with a high moisture content. Sampling and testing techniques, that may not be mandatory, are necessary in order to reduce liquefaction incidents from occurring.
Many mines where bauxite and nickel ore are being extracted are very basic and situated in remote locations. This makes it hard for surveyors and experts to attend them. Hence, it is not easy to arrange for cargo samples to be tested independently due to the lack of reliable laboratories in these remote areas. Due to this, the responsibility falls onto the mine operators, port authority and Master of the vessel to make sure the test results are valid and are representative of the cargo and that all necessary precautions are taken to reduce the potential for the cargo to liquefy.

Although it is not mandatory to determine the transportable moisture limit of certain bauxite and nickel ore cargoes, it is highly recommended to do so as incidents are continuing to occur when transporting these cargoes on bulk carriers. Additionally, although a cargo may appear dry, it could contain excessive moisture and become saturated under dynamic loading. It is essential that the moisture content of a cargo is kept low to reduce the risk of liquefaction or cargo shift and that further research is performed to determine the physical properties and system variables that increase the liquefaction potential of these cargoes.
11.4 SUPPLEMENTARY RESULTS AND FIGURES

There are no supplementary results or figures relating to this manuscript.

11.5 SUMMARY AFTER THE FACT

The review of the seven investigation reports presented in this manuscript showed key aspects of loading and transport of solid bulk cargoes that would be used to design and develop the test methods further on in this research.

Similar to the manuscript presented previously in Chapter 10, the exact loading conditions, routing during transport and the described and recorded behaviour of the cargoes, before during and after the foundering of the vessels, were indications of the possible phenomenon that may have occurred, including liquefaction.

Up to this point, research mainly focussed on the review of elements relating to the liquefaction of solid bulk cargoes. Resulting from the newly found knowledge presented up to know, a major shift was made to focus on the design, development, and utilization of standard and unique apparatus and procedures to test hypotheses that came about during the preliminary research.
CHAPTER 12 ANALYSING THE FAILURE MODE OF IRON ORE FINES UNDER REPEATED LOAD TRIAXIAL TESTING TO DETERMINE LIKELIHOOD OF A CARGO SHIFTING DURING MARINE TRANSPORTATION

12.1 INTRODUCTION

The following manuscript, which is currently under review, includes an investigation into the strength of iron ore fines under cyclic loading. This is the first area of research performed using a repeated load or cyclic triaxial apparatus. It presents the hypothesis that cargoes of iron ore fines may not be undergoing liquefaction, but, instead, may be exhibiting a certain type of shearing failure.

It is to be pointed out here that this investigation was a preliminary study performed to become familiar with the concept of the triaxial apparatus, procedure, and theory. The purpose of performing this preliminary study was to prepare for the installation of a new cyclic triaxial specifically designed for the testing of soils. This new triaxial apparatus was used further on in this research and is described in more detail in Chapter 15.

Exclusions made from this manuscript and not included in this chapter are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made continuous throughout this document.

12.2 CITATION

12.3 MANUSCRIPT CONTENTS

12.3.1 Abstract
Recently industry and research associations have developed a test to determine the transportable moisture limit of iron ore fines. The transportable moisture limit is the maximum gross water content that a cargo can contain, without being at risk of liquefying, while being transported in the holds of bulk carriers. Liquefaction of a solid bulk cargo can occur when excessive cyclic loading is transmitted to the cargo in the hold of a bulk carrier, resulting in the centre of gravity of the vessel shifting. The objective of this study was to determine the validity of a new hypothesis that some bulk carrier incidents, where the cause was reported to be liquefaction, are incorrect and can be more accurately described as shear failure of the cargo. Using a repeated load triaxial apparatus, the unsaturated and undrained cyclic behaviour of iron ore fines were studied in order to determine whether cyclic stresses applied to the samples resulted in shear failure rather than liquefaction. The study concluded, that under the applied undrained loading conditions, the behaviour of the majority of the samples tested during this study, was not indicative of a material undergoing liquefaction. It was shown that the cyclic stresses were most likely causing shear failure, which could result in the transporting vessel listing and possibly capsizing. Future studies will investigate the effect pore pressures have on the strength of iron ore fines.

12.3.2 Introduction
Similar to liquefaction of soils during earthquakes (Ishihara, 1985, 1993; Seed and Idriss, 1971, 1982), liquefaction of a solid bulk cargo can occur when excessive cyclic loading, induced by rough seas and vessel vibrations, is transmitted to the cargo in the hold of a bulk carrier (Fagerberg and Stavang, 1971). If liquefaction of a solid bulk cargo takes place it can cause the bulk carrier to list and possibly capsize (Grunau, 2012). Cargoes that are more likely to undergo liquefaction are those that contain sufficient amounts of moisture and fine particles (Andrei and Pazara, 2013; International Maritime Organization, 2013b).

Recently industry and research associations have developed a test to determine the Transportable Moisture Limit (TML) of iron ore fines (International Maritime Organization, 2013a; Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e). The TML is inferred as the maximum allowable gross water content that a cargo may contain, without being at risk of liquefying, while being transported in the holds of bulk carriers (International Maritime Organization, 2013b). The International Maritime Solid Bulk Cargoes Code (IMSBC Code) is an internationally recognized code of safe practice, published by the International Maritime Organization, which is to be followed when transporting potentially hazardous solid bulk cargoes (International Maritime Organization, 2013b). The new test, referred to as the Modified Proctor/Fagerberg test for iron ore fines (MPFT), has been included as an amendment in the 2015 edition of the IMSBC Code and is to be entered into force on the 1 January 2017 (International Maritime Organization, 2013a, 2015d, 2015e). More details regarding the IMSBC Code, the newly developed MPFT and liquefaction of solid bulk cargoes can be seen in related publications (Munro and Mohajerani, 2014, 2015, 2016b, 2016c, 2017a).

12.3.3 Hypothesis
A recently published paper, which summarizes and discusses the key findings of seven investigation reports into suspected liquefaction incidents of solid bulk cargoes on bulk carriers, has indicated that
liquefaction may not be the cause of all the reported incidents (Munro and Mohajerani, 2016a, 2017a). Identified, but not directly discussed within the paper, is that some incidents occur shortly after the vessel departs with no significant cyclic loading be applied to the cargo (Australian Transport Safety Bureau, 2000; Panama Maritime Authority - Maritime Accident Investigation Department, 2011a, 2011b, 2011c; The Bahamas Maritime Authority, 2015; The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005, 2015).

Bulk carriers transporting specific types of solid bulk cargoes are required to perform trimming according to Section 5 of the 2013 IMSBC Code. Trimming ultimately “reduces the likelihood of the cargo shifting” (International Maritime Organization, 2013b). Trimming is commonly achieved by using crane grabs to level and press the surface of the cargo in the holds. Although the Master has the right to request that a cargo of iron ore fines undergo trimming, according to Section 5 of the 2013 IMSBC Code as well as the new voluntarily implemented individual schedule for iron ore fines, trimming is not mandatory as iron ore fines is considered to be a cohesive cargo (International Maritime Organization, 2013b, 2015e).

Figure 210 and Figure 211 show illustrations depicting a typical cargo hold of a Capesize subclass of bulk carrier. Figure 210 (left) shows an untrimmed cargo at an angle of heel of 10 to 15 degrees and Figure 211 (left) shows a trimmed cargo at an angle of heel of 15 to 20 degrees. Both figures (right) also show what would possibly occur to the cargo if it was to shift during transportation (Bell, 1968; Bishop, 1955; Budhu, 2011; Janbu, 1973; Sarma, 1975; Spencer, 1967).

![Figure 210 – Untrimmed cargo at an angle of heel of 10-15 degrees in a Capesize subclass bulk carrier before (left) and after (right) a cargo shift](image_url)
If a cargo was to shift during transportation, trimming would hypothetically increase the angle needed, as well as decrease the amount of material that is likely to shift, altering the centre of gravity of the bulk carrier (Munro and Mohajerani, 2017f). Of the seven suspected liquefaction incidents, where investigation reports are available, only three cargoes were said to be trimmed before they departed, one of which was only partially trimmed. Four of the seven incidents also mentioned a sudden list shortly after the vessel departed with no mention of significant cyclic loading being created by the ocean waves (Australian Transport Safety Bureau, 2000; Panama Maritime Authority - Maritime Accident Investigation Department, 2011a, 2011b, 2011c; The Bahamas Maritime Authority, 2015; The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005, 2015).

Other incidents where the full investigation reports are not available also indicate that they may have occurred a short time after departing with no significant cyclic loading being applied (Munro and Mohajerani, 2017a). Two of these incidents that are prominent involve the bulk carriers M.V. Chang Le Men and M.V. Asian Forest where they both listed shortly after leaving Mangalore, India, whilst carrying iron ore fines. The listing of the M.V. Asian Forest, as seen in Figure 212, resulted in the capsizing of the vessel (Corbett, 2013; Deccan Herald, 2009; Devanney, Undated; Munro and Mohajerani, 2017a; O’Cinneide, 2007; Trade Winds, 2010). It is assumed the minimal time from the vessels departing combined with the apparently negligible cyclic loading, indicate that these cargoes may have experienced stresses that caused shear failure of the cargo resulting in the cargo shifting rather than liquefaction.
During transportation, a solid bulk cargo such as iron ore fines undergoes both static and dynamic compaction. Static compaction is caused by the loading technique and self-weight of the material and dynamic compaction is caused by the cyclic loading during transport. In this paper ‘dynamic compaction’ is used to refer to the increase in density, or decrease in void ratio, of an unsaturated cargo under cyclic loading. This is caused by air and water within the pores being expelled resulting in a reduction in voids. The emphasis being on both the air and water and not solely water as is the only medium in a saturated material undergoing consolidation. Consolidation is usually referred to as the reduction in volume of a saturated soil caused by applied stresses expelling moisture from the voids of the soil (Terzaghi, 1943).

Eq. 19 shows the widely accepted equation used to determine the shear strength of a soil. This was derived by Karl Terzaghi, and is commonly referred to as the Mohr-Coulomb failure criterion (Terzaghi, 1942). It expresses that the shear strength ($\tau$) of a granular material is a function of its friction angle ($\phi'$), cohesion ($c'$) and applied effective normal stress (or simply effective stress, $\sigma'$);

$$\tau = c' + \sigma' \tan \phi'$$  \hspace{1cm} (Eq. 19)

Eq. 20 shows Bishop’s equation for effective stress of a soil, which is used as a variable in Eq. 19 (Bishop, 1959). We have chosen to introduce this equation for effective stress as it includes the common variables comparable in most unsaturated effective stress proposals (Bishop, 1959; D.G. Fredlund et al., 1978; Vanapalli et al., 1996) and also it is easier to dissect for explanation. Bishop’s equation for effective stress introduces the pore air pressure ($u_a$), pore water pressure ($u_w$) and the total normal stress ($\sigma$) variables along with the parameter ($\chi$), which is a value between 0 and 1 relating to the degree of saturation (where 1 is fully-saturated);

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w)$$  \hspace{1cm} (Eq. 20)

According to Eq. 20, in fully saturated soils (when $\chi = 1$), the reduction in effective stress is directly related to pore water pressure overcoming the total normal stress (i.e. $\sigma' = \sigma - u_w$). In unsaturated soils, the reduction in the effective stress is dependent on the applied total normal stress and matric suction ($u_a - u_w$), caused by the degree the soil is saturated, being overcome by the pore air pressure. The lower the degree of saturation, the more the pore air pressure affects the effective stress of the material.
Although pore air pressure and pore water pressure affect one another, the theoretical effective stress of soils with the same applied total normal stress and pore water pressure will decrease as the pore air pressure increases and the effective stress of soils with the same applied total normal stress and pore air pressure will decrease as the pore water pressure decreases.

A cargo of iron ore fines that has a void ratio and moisture content similar to that produced at the TML, as defined by the MPFT (see Figure 215), and with the physical properties seen in Section 12.3.4.1, would contain approximately 8% air voids. Using the typical dimensions of a cargo of iron ore fines in the hold of a Capesize bulk carrier, 35 x 25 x 17 m (Iron Ore Technical Working Group, 2013c), the cargo was shown to contain approximately 500 m$^3$ of air. This amount of air is significant to overcome the binding stresses. Under these conditions it is assumed that the pore air pressure within the cargo would have a considerable effect on the behaviour of the cargo under cyclic loading.

In a previous publication, a typical sample of iron ore fines was tested under varying pressures from 1 kPa to 600 kPa and found to have a hydraulic conductivity of $1 \times 10^{-5}$ m/s to $2 \times 10^{-8}$ m/s (Munro and Mohajerani, 2016d). Under the higher pressures typically expected in a cargo iron ore fines, the values were considered to be low with poor drainage (i.e. low intrinsic permeability) (Holtz and Kovacs, 1981; Lambe and Whitman, 1969; Terzaghi and Peck, 1967). Due to the low intrinsic permeability, it is assumed that the ability the entrained air within the main body of the partially saturated cargo has to permeate outwards is significantly reduced, decreasing the ability for pore pressures to dissipate (Al-Jibury, 1961; Tuli et al., 2005).

It is noted that although both related to the reduction in the effective stress of a material, the difference between shear failure and liquefaction must be defined (Zen et al., 1998). In this paper liquefaction is assumed to be occurring when the shear resistance of the material is reduced to nothing due to excess pore pressures causing a reduction in friction between the particles of a mass of the material (i.e. reducing effective stress). Shear failure is assumed to have occurred when the shear resistance is seen to be overcome or mobilized along a plane of failure. The interaction between the particles (i.e. internal friction angle and cohesion, variables in Eq. 19) can be affected by properties of the material, such as moisture content and density.

It is theorized that shortly after loading unsaturated cargoes of iron ore fines that have not undergone significant dynamic compaction experience shear failure rather than liquefaction. The conditions in the hold of a vessel lead us to believe that parts of the cargo are undrained due to the low intrinsic permeability of the material under the pressures expected in the hold. Due to the reduced effective stress, cause by the inability for pore pressures to dissipate, the cargo undergoes shear failure in a similar way to that observed during slope failures in soil mechanics (Budhu, 2011; Das, 2013). This shearing of the cargo is what causes a dramatic shift in the centre of gravity of the bulk carrier ultimately leading to the vessel listing and conceivably capsizing.

The objective of this study is to determine the validity of the hypothesis that some bulk carrier incidents, where the cause was reported to be liquefaction, are incorrect and can be more accurately described as shear failure which resulted in slope failure of the cargo. Using a Repeated Load Triaxial (RLT) apparatus, the unsaturated and undrained cyclic behaviour of iron ore fines will be studied in order to determine whether the cyclic stresses applied to the samples ultimately cause shear failure rather than liquefaction as investigation reports indicate.
12.3.4 Material and Method

12.3.4.1 Material

A number of samples of iron ore fines were tested during previous research to determine the physical properties of a typical cargo (Munro and Mohajerani, 2015). Sample MA004, seen in Figure 213, was chosen for this study because it was considered a typical cargo of iron ore fines commonly transported on bulk carriers. The physical properties of this sample and results from the Modified Proctor/Fagerberg test are shown in Table 71, Figure 214 and Figure 215.

The moisture contents shown in Table 71 have been reported according to the relevant standard. In AS 1289, the moisture content is reported in Net Water Content by Weight (NWC), shown as Eq. 21 (Standards Australia, 2000). In the IMSBC Code and MSC 95/22/Add.2, the moisture content, including the Transportable Moisture Limit (TML), is reported in Gross Water Content by Weight (GWC), shown as Eq. 22 (International Maritime Organization, 2013b, 2015e). In geotechnical engineering and soil mechanics, the NWC is commonly used whereas in most other cases, including metallurgy and the transportation of solid bulk cargoes, GWC is favoured. Both the GWC and NWC are shown in Table 71 for convenience.

\[
NWC = w_N = \frac{\text{Mass of Moisture}}{\text{Mass of Dry Material}} \times 100 \quad \text{(Eq. 21)}
\]

\[
GWC = w_G = \frac{\text{Mass of Moisture}}{\text{Mass of Wet Material}} \times 100 \quad \text{(Eq. 22)}
\]

Table 71 – Physical properties of the iron ore fines sample used during this study

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard/Apparatus</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Identification</td>
<td>N/A</td>
<td>MA004</td>
</tr>
<tr>
<td>Atterberg Limits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Limit</td>
<td>AS1289.3.1.2 (Standards Australia, 2009a)</td>
<td>17% NWC or 15% GWC</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>AS1289.3.2.1 (Standards Australia, 2009b)</td>
<td>16% NWC or 14% GWC</td>
</tr>
</tbody>
</table>
Chapter 12 - Analysing the Failure Mode of Iron Ore Fines under Repeated Load Triaxial Testing to Determine Likelihood of a Cargo Shifting during Marine Transportation

Plasticity Index

- AS1289.3.3.1 (Standards Australia, 2009c)
  - 1% NWC/GWC \(^b\)

Particle Size Distribution \(^a\)

- Gravel (>2.36 mm)
  - AS1289.3.6.1 (Standards Australia, 2009d)
  - 51%
- Sand (75 μm – 2.36 mm)
  - AS1289.3.6.1 (Standards Australia, 2009d)
  - 38%
- Silt (2 μm – 75 μm)
  - Mastersizer Aero 3000
  - 9%
- Clay (<2 μm)
  - Mastersizer Aero 3000
  - 1%

Classification

- AS1726 (Standards Australia, 1993)
  - Borderline between poorly graded gravel and silty gravel (GP-GM)

Coefficient of Curvature (C\(_c\))

- N/A
  - 3.2

Coefficient of Uniformity (C\(_u\))

- N/A
  - 44.7

Particle Density, G\(_s\)

- AS1289.3.5.1 (Standards Australia, 2006)
  - 4.15 t/m\(^3\)

Modified Proctor/Fagerberg TML

- MSC 95/22/Add.2 (International Maritime Organization, 2015e)
  - 10.9% GWC or 12.2% NWC at 80% Saturation (OMC occurring at 96% Saturation) \(^bc\)

Quantitative X-Ray Diffraction

- Hematite (Fe\(_2\)O\(_3\))
  - X’Pert Pro PW3040
  - 36% Total Weight
- Goethite (FeOOH)
  - X’Pert Pro PW3040
  - 62% Total Weight \(^d\)

\(^a\) A graphical representation of the particle size distribution can be seen in Figure 214.

\(^b\) The reported moisture content unit, according to the relevant standard, is presented first (i.e. GWC or NWC).

\(^c\) The compaction curve and TML produced during the Modified Proctor/Fagerberg test can be seen in Figure 215.

\(^d\) According to MSC 95/22/Add.2, if a cargo of iron ore fines has more than 35% goethite total weight then the schedule for iron ore should be followed and the cargo does not need to undergo Modified Proctor/Fagerberg testing and is considered unable to liquefy (International Maritime Organization, 2015e).

---

**Figure 214 – Particle size distribution of the iron ore fines sample used during this study**
12.3.4.2 Method

In order to determine the unsaturated and undrained cyclic behaviour of the iron ore fines samples and investigate the hypothesis given in Section 12.3.3, an original procedure was developed using the Repeated Load Triaxial (RLT) apparatus shown in Figure 216. The RLT, utilized for this study, is commonly used in pavement design and soil mechanics to determine the permanent deformation and resilient modulus of both fine grained and granular materials under repeated loading. Some common standards used to determine either or both of these properties are AASHTO Designation: T 307-99 (2007) (The American Association of State Highway and Transportation Officials (AASHTO), 2007), LTPP Protocol P46 (U.S. Department of Transportation, 1996) and AG:PT/T053-07 (ASTM and AusRoads, 2007).

The 14kN Pneumatic Universal Testing Machine (UTM-14P) was employed to perform the RLT testing (IPC Global, 2016). An image and schematic of the RLT apparatus can be seen in Figure 216 and Figure 217. The UTM-14P was connected to a data acquisition unit, which was fully automated to apply pre-programmed stresses to a cylindrical sample of iron ore fines.
Figure 216 – 14kN pneumatic universal testing machine and data acquisition unit employed to perform the RLT testing

Figure 217 – Schematic of apparatus employed to perform RLT testing and initial sample dimensions
The existing software used to perform the RLT tests was UTS027 AG:PT/T053 Triaxial Stress Stage Modulus Test (v 2.07b). This software was adjusted accordingly to apply a calculated load combination at a typical cycle period that cargoes of iron ore fines were expected to undergo while being transported on bulk carriers.

Calculations were performed to determine a suitable load combination for the RLT test. It was assumed that initial failure may occur in the upper regions of a cargo due to this being the region least compacted. The additional acceleration that a cargo of iron ore fines was expected to experience during transportation was reported not to exceed 1 G (9.81 m/s²) (Iron Ore Technical Working Group, 2013b; Munro and Mohajerani, 2016d, 2017c). It was therefore assumed that it would be likely that failure would initially occur in the top 2 m under an additional 1 G of acceleration.

During the development of the Modified Proctor/Fagerberg Test (MPFT), it was noted that the “Capesize [subclass] vessels have a natural roll period of 10 seconds or 0.1 Hz” (Iron Ore Technical Working Group, 2013b). Due to restrictions within the software, this cycle period could not be used. It was therefore decided to use a total cycle period of 1 second with a load period of 0.5 seconds, which is the closest values that could be used with the available software. Although not representative of conditions on a bulk carrier, due to the samples being undrained dissipation of pore pressure will not occur therefore the cyclic period is not considered critical. Additionally, the smaller cycle period allowed for more load applications, over a shorter period of time, and was considered to be conservative.

The load combination, number of cycles and period of loading that was used during the RLT test can be seen in Table 72 and Figure 218. Additionally, a loading diagram of the sample in the RLT apparatus is depicted in Figure 219 and a graphical representation of the calculations used to determine the load combinations can be seen in Figure 220. The internal friction angle and bulk density shown in Figure 220 was the average determined during a previous study on a similar material transported in a bulk carrier from the same geographic region (Iron Ore Technical Working Group, 2013c).

<table>
<thead>
<tr>
<th>Confining Stress (kPa, (\sigma_3))</th>
<th>Contact Stress (kPa, (\sigma_c))</th>
<th>Deviator Stress (kPa, (\sigma_d))</th>
<th>Major Principal Stress (kPa, (\sigma_1))</th>
<th>Number of Cycles</th>
<th>Load Period (Seconds)</th>
<th>Total Cycle Period (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>20</td>
<td>10</td>
<td>70</td>
<td>10,000</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Figure 218 – Graphical representation of the stresses applied during the RLT test

Figure 219 – Loading diagram of sample with (a) and without (b) the applied deviator stress ($\sigma_d$) causing permanent ($H_1$) and resilient ($H_r$) deformation
The procedure that was used to test the samples was modified from AG:PT/T053 (ASTM and AusRoads, 2007). Initially, the sample of iron ore fines was split into 17 subsamples of approximately 5 kg and varying amounts of moisture was added to each. Each sample was then compacted into a split mould and membrane where the final dimensions of the samples were measured. Each sample had a diameter of approximately 100 mm and was 185 mm high. The height of the sample was 185 mm in height instead of the common 200 mm as the 200 mm high split mould that was used needed to have a porous plate placed within the base prior to compaction.

Varying compaction energies were used to produce a range of densities that the material may exhibit in the hold of a bulk carrier. These expected densities were assumed based on a recent study where a hammer with a drop height of 150 mm and weight of 150 g was shown to produce that of iron ore fines in the hold of a bulk carrier (Iron Ore Technical Working Group, 2013a, 2013c, 2013e). The densities achieved can be seen in Figure 224.

After the split mould was removed from the compacted sample the triaxial chamber was then placed over the sample and airtightness was ensured. Using air as the medium, 40 kPa confining pressure was applied to the sample and then the test commenced under undrained conditions. The test was performed under undrained conditions as it is assumed that no dissipation of pore pressures occur due to the low intrinsic permeability of the material, as discussed in Section 12.3.3.

Testing concluded when either failure of the sample occurred, 5% double amplitude (peak-to-peak) strain was exceeded, or 10,000 load applications were applied. 5% double amplitude strain was used to define failure as researchers have found that if exceeded while testing a sandy material a large redistribution of density may be observed that makes results questionable (American Society for Testing and Materials, 2013; Gilbert, 1984). After testing, the samples were then removed from the membrane in order to determine the total mass of the material that was tested and the precise moisture content. This procedure was repeated on all 17 samples identified in Table 73.
12.3.5 Experimental Results

In order to identify the samples of iron ore fines that were tested, each was given a unique identification number (ID). The ID of each sample along with the initial conditions calculated prior to testing are shown in Table 73. Also shown in Table 73, is the number of cycles that the sample survived before either the failure criteria was met (5% double amplitude strain was exceeded) or 10,000 cycles was reached (survived).

The load combination used during the RLT testing can be seen in Table 72 and typical images and stress versus strain graphs for each failure group can be seen from Figure 221 to Figure 223. It is noted that the data shown from Figure 221 to Figure 223 has been condensed based on the average deviator stress and maximum deformation. The total cycles per cycle shown is displayed on each figure.

<table>
<thead>
<tr>
<th>Unique sample Identification Number, ID</th>
<th>Gross Water Content by Weight, ( w_G ) (%)</th>
<th>Net Water Content by Weight, ( w_N ) (%)</th>
<th>Void Ratio, ( e )</th>
<th>Dry Density, ( \rho_d ) (t/m(^3))</th>
<th>Degree of Saturation, ( S ) (%)</th>
<th>Failure Cycles, ( N_f ) or Survived (^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.21</td>
<td>7.77</td>
<td>0.81</td>
<td>2.29</td>
<td>39.82</td>
<td>136</td>
</tr>
<tr>
<td>2</td>
<td>9.70</td>
<td>10.74</td>
<td>0.78</td>
<td>2.33</td>
<td>57.01</td>
<td>325</td>
</tr>
<tr>
<td>3</td>
<td>7.69</td>
<td>8.33</td>
<td>0.89</td>
<td>2.19</td>
<td>38.80</td>
<td>340</td>
</tr>
<tr>
<td>4</td>
<td>10.93</td>
<td>12.26</td>
<td>0.65</td>
<td>2.51</td>
<td>77.86</td>
<td>449</td>
</tr>
<tr>
<td>5</td>
<td>10.43</td>
<td>11.65</td>
<td>0.66</td>
<td>2.49</td>
<td>72.77</td>
<td>589</td>
</tr>
<tr>
<td>6</td>
<td>8.79</td>
<td>9.64</td>
<td>0.70</td>
<td>2.44</td>
<td>56.88</td>
<td>629</td>
</tr>
<tr>
<td>7</td>
<td>7.75</td>
<td>8.40</td>
<td>0.75</td>
<td>2.38</td>
<td>46.64</td>
<td>1415</td>
</tr>
<tr>
<td>8</td>
<td>9.32</td>
<td>10.27</td>
<td>0.59</td>
<td>2.60</td>
<td>71.79</td>
<td>8387</td>
</tr>
<tr>
<td>9</td>
<td>12.44</td>
<td>14.21</td>
<td>0.64</td>
<td>2.53</td>
<td>91.85</td>
<td>9076</td>
</tr>
<tr>
<td>10</td>
<td>11.67</td>
<td>13.21</td>
<td>0.60</td>
<td>2.59</td>
<td>90.82</td>
<td>Survived</td>
</tr>
<tr>
<td>11</td>
<td>7.56</td>
<td>8.18</td>
<td>0.72</td>
<td>2.42</td>
<td>47.45</td>
<td>Survived</td>
</tr>
<tr>
<td>12</td>
<td>9.36</td>
<td>10.33</td>
<td>0.62</td>
<td>2.56</td>
<td>69.14</td>
<td>Survived</td>
</tr>
<tr>
<td>13</td>
<td>11.69</td>
<td>13.24</td>
<td>0.57</td>
<td>2.64</td>
<td>96.57</td>
<td>Survived</td>
</tr>
<tr>
<td>14</td>
<td>11.78</td>
<td>13.36</td>
<td>0.59</td>
<td>2.61</td>
<td>93.98</td>
<td>Survived</td>
</tr>
<tr>
<td>15</td>
<td>10.79</td>
<td>12.09</td>
<td>0.59</td>
<td>2.62</td>
<td>85.74</td>
<td>Survived</td>
</tr>
<tr>
<td>16</td>
<td>11.50</td>
<td>13.00</td>
<td>0.59</td>
<td>2.61</td>
<td>91.67</td>
<td>Survived</td>
</tr>
<tr>
<td>17</td>
<td>12.61</td>
<td>14.43</td>
<td>0.63</td>
<td>2.55</td>
<td>95.70</td>
<td>Survived</td>
</tr>
</tbody>
</table>

\(^a\) If the sample survived testing 10,000 cycles were reached
Chapter 12 - Analysing the Failure Mode of Iron Ore Fines under Repeated Load Triaxial Testing to Determine Likelihood of a Cargo Shifting during Marine Transportation

Figure 221 – A typical averaged stress versus strain graph and image of a sample that failed under less than 1,000 cycles

Figure 222 – A typical averaged stress versus strain graph and image of a sample that failed between 1,000 and 10,000 cycles
Figure 223 – A typical averaged stress versus strain graph and image of a sample that survived 10,000 cycles

Shown in Figure 224 and Figure 225 are the graphical representations of the tabulated data shown in Table 73. For comparison, this data can be seen alongside the compaction curve from the Modified Proctor/Fagerberg Test (MPFT) and resulting Transportable Moisture Limit (TML) in Figure 224.

Figure 224 – sample failure conditions in relation to the void ratio, gross water content, degree of saturation and MPFT results
The results indicate that there is a trend for samples tested with a high moisture content yet low void ratio to survive the applied stresses and for samples with a low moisture content yet high void ratio to meet the set failure criteria (5% double amplitude strain). As previously shown in Eq. 20, increasing the degree of saturation results in a reduction in the effect that pore air pressure has on the effective stress. The majority of the samples with high levels of saturation did not meet the failure criteria. This is attributed simply to the decrease in void ratio or increase in density of the same samples.

Liquefaction of a soil is related to both void ratio and increase degree of saturation (Bishop, 1959). The samples that are likely undergoing shear failure are those with low cohesion and friction between the particles. The behaviour of the samples of iron ore fines that can be seen in Figure 224 is not indicative of a material undergoing liquefaction, as described in Section 12.3.3. This is due to the reduced particle friction and cohesion, caused by the high void ratio, being overcome by the applied stresses.

The permanent deformation and strain of each sample throughout the duration of each test can be seen in Figure 226. The samples show two distinct behaviours. These can be seen as the sample that failed at less than 1,000 cycles and the sample that survived 10,000 cycles. Only three samples shown ‘intermediate’ failure between 1,000 and 10,000 cycles.

Figure 225 – Initial void ratio versus failure conditions of the test samples along with the void ratio at the MPFT TML
According to Werkmeister (2005), an unbound granular material, such as iron ore fines, can be classified based on the response under repeated cyclic loading (Cerni et al., 2011; Werkmeister et al., 2005). Werkmeister’s ‘shakedown’ theory has three potential categories of response:

- **Plastic Shakedown** (Figure 227, Line 1), when the collective permanent strain rate decreases rapidly until it reaches a state of equilibrium. The response is resilient and does not produce permanent deformations and the material does not reach the failure criteria.
- **Plastic Creep** (Figure 227, Line 2), when the collective permanent strain rate is decreasing or constant. Although the deformation is not all resilient, the permanent deformation is acceptable. In this case, the material could reach the failure criteria under a great number of cycles.
• *Incremental Collapse* (Figure 227, Line 3), when the collective permanent strain rate increases rapidly and the failure criteria is met after a low number of cycles.

According to the ‘shakedown’ theory, the samples that failed at less than 1,000 load cycles show ‘incremental collapse’ and the samples that survived testing show ‘plastic shakedown’ with the three others showing signs of ‘plastic creep’. The shakedown theory is essentially an extended theory of elastoplasticity and not an indication of liquefaction but rather an indication of a materials apparent strength under cyclic loading (Triantafyllidis, 2004). ‘Incremental collapse’ can be described, in terms for this study, as the material incrementally shearing each cycle due to the shear resistance being overcome with no signs of the initial strength expected prior to liquefaction.

As explained in Section 12.3.3, the physical properties the samples exhibit directly relate to the shear strength and liquefaction potential of a soil. Figure 228 and Figure 229 show the moisture content and the degree of saturation versus failure conditions of the tested samples. It is noted that every sample that failed during testing, except for sample 9, failed at or below the Modified Proctor/Fagerberg Test (MPFT) TML and 80% degree of saturation, which is the point used to determine the MPFT TML (International Maritime Organization, 2013b, 2015e). Liquefaction of these samples is unlikely to be the cause of failure due to all but one failing on the safe side of the TML. In soil mechanics, it is commonly expected that with the increase of moisture content and saturation comes a reduction in the strength. This is not the behaviour seen in Figure 228 and Figure 229 as due to compaction used during sample preparation, with the increase in moisture content and saturation came an increase in density.

*Figure 228 – Initial gross water content versus failure conditions of the test samples along with the MPFT TML*
The trend in Figure 229 is similar to that shown in Figure 228. It shows that as the degree of saturation increases towards 100%, the samples tended to gain shear strength and survive the RLT testing. Although failure can be attributed to both the saturation conditions and void ratio, which collectively increase, as mentioned previously, the potential for materials with similar void ratios to liquefy should theoretically increase as the degree of saturation increases (Bishop, 1959).

Figure 230 illustrates the relationship between the volume of air and failure conditions of the tested samples. Similar to Figure 228 and Figure 229, Figure 230 demonstrates that as the volume of air within the samples increase, the samples are more likely to undergo ‘incremental collapse’ or shear failure under unsaturated and undrained conditions. Additionally, failure is seen to occur to sample with a volume of air greater than the equivalent value used to determine the MPFT TML ($V_a = 8\%$), which is the opposite of what should be occurring due to liquefaction.
Chapter 12 - Analysing the Failure Mode of Iron Ore Fines under Repeated Load Triaxial Testing to Determine Likelihood of a Cargo Shifting during Marine Transportation

The majority of the results seen in this study can be linked to case studies where failure of the cargo occurs after a somewhat short period of time after a bulk carrier departs where there is insignificant time for dynamic compaction of the unsaturated cargo to occur (Australian Transport Safety Bureau, 2000; Munro and Mohajerani, 2016a; Panama Maritime Authority - Maritime Accident Investigation Department, 2011a, 2011b, 2011c; The Bahamas Maritime Authority, 2015; The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005, 2015). The results interpreted during this study have led to the assumption that the samples that failed within 1,000 cycles did not undergo liquefaction, but instead the excessive cyclic stresses caused the resistance shear strength of particle to particle interaction to be overcome and shear failure to occur.

12.3.6 Conclusion

The objective of this study was to determine the validity of a new hypothesis that some bulk carrier incidents, where the cause was reported to be liquefaction, are incorrect and can be more accurately described as shear failure which resulted in slope failure of the cargo. Using a Repeated Load Triaxial (RLT) apparatus, the unsaturated and undrained cyclic behaviour of iron ore fines was studied in order to determine whether the cyclic stresses applied to the samples were ultimately causing shear failure rather than liquefaction as investigation reports indicate.

The behaviour of the samples seen in this study can be associated with case studies where failure of the cargo of iron ore fines occurs shortly after a bulk carrier departs and there has been insignificant time for dynamic compaction of the cargo to occur. The results show that every sample that failed during the RLT testing, except one, did so at or below the Modified Proctor/Fagerberg Test (MPFT) Transportable Moisture Limit (TML) as well as 80% saturation, which is the point used to determine the MPFT TML, which is inferred as a safe moisture content where the liquefaction potential is minimal.
According to the shakedown theory, ‘incremental collapse’ of the samples can be seen to be occurring as the material undergoes small amounts of shearing each cycle due to the shear resistance being overcome. The interpretation of the results has led to the assumption that the samples that failed did not undergo liquefaction, but instead the excessive cyclic stresses caused incremental collapse. Under these conditions liquefaction was assumed to be improbable especially when under poor conditions of high moisture and saturation, where liquefaction would be more likely to occur, resulted in the samples surviving.

In conclusion, the behaviour of the samples of the samples of iron ore fines used in this study, is not indicative of a material undergoing liquefaction. If a cargo is initially in a loose state in the hold of a bulk carrier it may shear and shift after a relatively low number of cyclic load applications. Although the results agreed with the hypothesis being analysed, this study does not rule out that under certain circumstances a cargo of iron ore fines may undergo liquefaction. Future studies will investigate the effect pore pressures have on the strength of iron ore fines using an advanced triaxial apparatus.
Chapter 12 - Analysing the Failure Mode of Iron Ore Fines under Repeated Load Triaxial Testing to Determine Likelihood of a Cargo Shifting during Marine Transportation

12.4 SUPPLEMENTARY RESULTS AND FIGURES

There are no supplementary results or figures relating to this manuscript.

12.5 SUMMARY AFTER THE FACT

This initial study into the behaviour of iron ore fines under cyclic loading was important in order to understand the unsaturated behaviour of iron ore fines under cyclic loading using increasingly representative loading conditions to what may be experienced by a cargo during marine transportation.

The triaxial apparatus, such as the one used in this study, usually tests fully saturated samples. It was decided that because of the inability for the apparatus to measure pore pressure within the sample, it was not necessary for the samples to be saturated. This allowed us to perform testing that we would otherwise be unable to perform with the new apparatus, which required the samples to be fully saturated.

During these tests, knowledge was also gained in respect of the theory and procedures related to cyclic triaxial testing of soils. This knowledge was necessary in order to install and prepare the new cyclic triaxial system that was specifically designed for the testing of soils, and prepare new procedures for the replication of marine transportation. This new triaxial apparatus was used further on in this research and described in more detail in Chapter 15. While installing and preparing this new apparatus, computation modelling was undertaken to further understand the stability of the cargo using static analysis techniques.
CHAPTER 13 SLOPE STABILITY EVALUATION OF IRON ORE FINES DURING MARINE TRANSPORTATION IN BULK CARRIERS

13.1 INTRODUCTION

This peer-reviewed manuscript takes a slightly alternative look at the stability of cargoes. It focuses on analysing the strength of the material in terms of slope failure under varying angles of heel, which may be caused by the sea state being traversed. The translational and rotational slope analysis performed assumes static conditions, not cyclic as has so far been described. This seems applicable under some circumstances as typical wave motions produce loading at very low frequencies, i.e. 0.1 Hz (Iron Ore Technical Working Group, 2013b).

Exclusions made from this manuscript and not included in this chapter are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made continuous throughout this document.

13.2 CITATION

13.3 MANUSCRIPT CONTENTS

13.3.1 Abstract
A commodity, such as iron ore fines, shifting in the hold of a bulk carrier can lead to the vessel listing or capsizing. The objective of this study is to investigate the factors of safety pertaining to slope failure for both untrimmed and trimmed cargoes of iron ore fines during marine transportation. In order to determine the shear strength parameters needed to perform this analysis, triaxial testing was performed on samples of iron ore fines under varying densities and moisture contents. Using the shear strength parameters of the material, the Morgenstern-Price method of slices and infinite slope analysis, referred to as rotational and translational slope stability analyses, were used to determine the factors of safety against slope failure. The study concludes that, considering a factor of safety of 1.5, an untrimmed cargo of iron ore fines is unstable at angles of heel that bulk carriers are expected to experience during a typical voyage. If the cargo is trimmed it is shown to be significantly more stable. The results support the recommendation that it becomes mandatory for cargoes of iron ore fines to undergo trimming in order to reduce the chance of slope failure occurring, which may result in the loss of human life and industry assets.

13.3.2 Introduction
A solid bulk cargo, such as iron ore fines, shifting in the hold of a bulk carrier can lead to the transporting vessel listing and possibly capsizing. Most incidents where cargoes shift during transportation can be attributed to the occurrence of one of four distinct failure modes. Three of these failure modes, referred to as slope failures, can be seen in Figure 231. All four failure modes relate to the reduction in shear strength between the particles of a solid bulk cargo.

The first failure mode, liquefaction, is significantly more likely to occur in a cargo that contains sufficient amounts of fine particles and moisture (International Maritime Organization, 2013b). Liquefaction occurs when there is a reduction in the shear strength, and, therefore, the effective stress within a cargo. This can occur in the cargo either partially or as a whole, propagating rapidly from a single point of origin. Described in further detail in related publications (Munro and Mohajerani, 2014, 2015, 2016a, 2016b, 2016c, 2016d, 2017a, 2017c), liquefaction is more accurately described as “a phenomenon wherein a mass of soil loses a large percentage of its shear resistance, when subjected to monotonic, cyclic or shock loading, and flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance” (Sladen et al., 1985).

The second failure mode, sliding en masse, occurs when the shear strength and friction along the stratum between the cargo and the hold is overcome by external forces and the entire cargo mass shifts as a single entity in the hold; thus en masse. The third and fourth failure modes, herein referred to as rotational and translational slope failure, can occur when a slip plane develops due to the internal resisting shear strength of the cargo being exceeded by the resultant stresses being applied (i.e. equilibrium being overcome) (Budhu, 2011; Das, 2013).
The consequence of all failure modes, if the transporting vessel acquires an asymmetric resulting moment, is one of buoyancy, commonly resulting with the vessel listing to either port or starboard. The International Maritime Solid Bulk Cargoes Code (IMSBC Code), published by the International Maritime Organization, is an internationally recognised and mandatorily implemented code of safe practice that is to be followed when shipping hazardous solid bulk cargoes. To prevent cargoes from shifting, the IMSBC Code provides procedures to be followed if shifting of the cargo within the hold is considered to be a possibility (Sladen et al., 1985).

To prevent “Group A” cargoes, that are listed as liquefiable in Appendix 4, from undergoing liquefaction, sections 7 and 8 of the IMSBC Code state that laboratory testing must be performed to determine the maximum safe moisture content that the cargo may contain so that it is not considered to be at risk of liquefying during transportation. To prevent slope failure from occurring, sections 5 and 6 of the IMSBC Code mandate procedures for trimming cohesionless cargoes that are listed in Appendix 3 of the code. The IMSBC Code notes that the possibility of shear failure and shifting of a cargo is increased when the cargo being transported has minimal cohesion between the particles (Sladen et al., 1985).

Regardless of the cause of the cargo shifting, for a bulk carrier to list or capsize, the mass of the cargo that has shifted must result in an overturning moment, \( M_O \), which exceeds the restoring moment, \( M_R \). These moments, which are off-centred forces, are caused by both buoyancy, which is an upward force applied by the sea that opposes the weight of the vessel, and gravity, which is the downwards force of the vessel on the sea itself. The conditions that are considered to be unstable are shown in Figure 158 (right) in which the centre of buoyancy of the hull, B, stays inwards of the centre of gravity of the vessel, G.

The location of the metacentre is critical to the stability of the vessel. The metacentre is considered to be the intersection between two theoretical lines, both drawn through the centres of buoyancy; one when the vessel is vertical and one when the vessel is tilted. When the resulting metacentre, M, is below the centre of gravity, as seen in Figure 158 (right), the overturning moment, \( M_O \), exceeds the restoring moment, \( M_R \), causing instability. Under these conditions the bulk carrier develops a list and may capsize if preventative measures are not taken. Listing vessels can often be righted by using ballast, but due to the weight of iron ore fines it sometimes requires more ballast than what is available and further shifting of the cargo may cause the vessel to capsize. A bulk carrier transporting a cargo of iron ore fines that has shifted can be seen in Figure 233.
A cargo that is now considered “Group A” or liquefiable but is not considered cohesionless is iron ore fines (International Maritime Organization, 2015e). Recent studies have shown that slope failure within a cargo of iron ore fines, as shown in Figure 231 (middle) and (right), is a possibility because of the low cohesion of the material. These same studies have hinted that the causes of some incidents may be due to slope failure rather than liquefaction, as is suggested in the incident reports (Munro and Mohajerani, 2016a, 2017a; TML Testing Wiki, 2015).

Iron ore fines is a finer, less valuable by-product of iron ore produced after initial grading of the extracted ore. Iron ore fines commonly has particle sizes less than 6.3 mm and an iron content of approximately 50%. After separation, iron ore fines are stockpiled and shipped to places, such as China, to be further refined. Iron ore fines can be loaded onto bulk carriers using many methods, most commonly being conveyors and bucket grab cranes. Due to the wide variety of differing types of iron
ore fines (Munro and Mohajerani, 2015) along with the many loading methods and sequences. The initial conditions of the cargo within the hold of the bulk carrier is hard to estimate especially since the heights of the cargoes can vary significantly based on the size of the vessel and may even undergo trimming, or flattening, prior to the vessel disembarking.

The objective of this study is to investigate the factors of safety against slope failure of iron ore fines being transported on bulk carriers under both untrimmed and trimmed conditions. In order to determine these factors of safety, triaxial testing was performed under varying densities and moisture contents to obtain the range of shear strength parameters expected during marine transportation. Using these shear strength parameters, the Morgenstern-Price method of slices and infinite slope analysis, referred to as rotational and translational slope stability analyses, were then used to determine the factors of safety against slope failure for iron ore fines being transported under varying conditions.

13.3.3 Material and Methods

13.3.3.1 Material

Although iron ore fines can have significantly varying properties, a number of samples of iron ore fines were tested during a related study in order to determine the physical properties of a typical cargo (Munro and Mohajerani, 2015). The sample identified as MA004, which can be seen in Figure 213, was chosen for this study because it was considered to be a typical cargo of iron ore fines that is commonly transported on bulk carriers. The physical properties of this sample can be seen in Table 74 and Figure 214.

![Figure 234 – Typical iron ore fines sample used during this study (sample MA004)](image)

The moisture contents shown in Table 74 have been reported according to the relevant standard. In geotechnical engineering and soil mechanics, the Net Water Content by Weight (NWC) is commonly used, whereas, in most other cases, including metallurgy and the transportation of solid bulk cargoes, the Gross Water Content by Weight (GWC) is favoured. Both the GWC and NWC are shown in Table 74 for convenience and the relevant calculations are shown in Eq. 23 and Eq. 24.

\[ NWC = w = \frac{\text{Mass of Moisture}}{\text{Mass of Dry Material}} \times 100 \]  \hspace{1cm} (Eq. 23)
\[ GWC = w^1 = \frac{\text{Mass of Moisture}}{\text{Mass of Wet Material}} \times 100 \quad (\text{Eq. 24}) \]

Table 74 – Physical properties of the iron ore fines sample used during this study

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard/ Apparatus</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Identification</td>
<td>N/A</td>
<td>MA004</td>
</tr>
<tr>
<td>IMSBC Code Schedule Applied</td>
<td>MSC 95/22/Add.2 (International Maritime Organization, 2015e)</td>
<td>Iron ore (as cargo contains more than 35% goethite)</td>
</tr>
<tr>
<td>Atterberg Limits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Limit</td>
<td>AS1289.3.1.2 (Standards Australia, 2009a)</td>
<td>17% NWC or 15% GWC (^b)</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>AS1289.3.2.1 (Standards Australia, 2009b)</td>
<td>16% NWC or 14% GWC (^b)</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>AS1289.3.3.1 (Standards Australia, 2009c)</td>
<td>1% NWC/GWC (^b)</td>
</tr>
<tr>
<td>Particle Size Distribution (^a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel (&gt;2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>51%</td>
</tr>
<tr>
<td>Sand (75 μm – 2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>38%</td>
</tr>
<tr>
<td>Silt (2 μm – 75 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>9%</td>
</tr>
<tr>
<td>Clay (&lt;2 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>1%</td>
</tr>
<tr>
<td>Classification</td>
<td>AS1726 (Standards Australia, 1993)</td>
<td>Poorly graded gravel to silty gravel (GP-GM)</td>
</tr>
<tr>
<td>Coefficient of Curvature ((C_c))</td>
<td>N/A</td>
<td>3.2</td>
</tr>
<tr>
<td>Coefficient of Uniformity ((C_u))</td>
<td>N/A</td>
<td>44.7</td>
</tr>
<tr>
<td>Particle Density, (G_s)</td>
<td>AS1289.3.5.1 (Standards Australia, 2006)</td>
<td>4.15 t/m(^3)</td>
</tr>
<tr>
<td>Quantitative X-Ray Diffraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hematite ((\text{Fe}_2\text{O}_3))</td>
<td>X’Pert Pro PW3040</td>
<td>36% Total Weight</td>
</tr>
<tr>
<td>Goethite ((\text{FeOOH}))</td>
<td>X’Pert Pro PW3040</td>
<td>62% Total Weight</td>
</tr>
</tbody>
</table>

\(^a\) The graphical representation of the particle size distribution can be seen in Figure 214.

\(^b\) The reported moisture content unit, according to the relevant standard, is presented first (i.e. GWC or NWC).

Figure 235 – Particle size distribution of the iron ore fines sample used during this study
13.3.3.2 Methods

13.3.3.2.1 Triaxial Testing
The 14kN Pneumatic Universal Testing Machine (UTM-14P), seen in Figure 216, was employed to perform triaxial testing on samples of iron ore fines. The widely accepted 3-point monotonic shear test (British Standard, 1990) was performed using the apparatus on unsaturated samples of iron ore fines under drained conditions at varying densities and moisture contents. These conditions are considered to be characteristic of what can be expected in the hold of a typical bulk carrier.

From the 3-point monotonic shear tests the shear strength parameters, including the internal friction angles and cohesion factors of the samples, were determined. These variables were needed, along with the bulk density during testing, in order to perform the rotational and translational slope stability analyses.

The hammer chosen to perform the compaction of the samples into a split mould prior to testing was a 150 g hammer with a drop height of 150 mm. The samples of iron ore fines were compacted in 5 layers, and, depending on the final density that was to be achieved, between 20 and 40 drops of the hammer were used for each layer. The compaction produced a range of typical initial densities that were expected to occur in the hold of a bulk carrier. The range of densities tested can be seen in Table 73 and Figure 243.

The 150 g hammer with a drop height of 150 mm was chosen as during recent research it was shown to produce a similar density to that of iron ore fines in the hold of a bulk carrier (International Maritime Organization, 2015e; Iron Ore Technical Working Group, 2013a). The Modified Proctor/Fagerberg Test, outlined in Appendix 2 of the IMSBC Code (International Maritime Organization, 2016), utilises this hammer to determine a safe transportable moisture content in order to prevent a cargo of iron ore fines from liquefying. The procedure involves compacting a sample in five layers into a 1 litre cylindrical mould. This compaction is performed at varying moisture contents to produce a compaction curve. The compaction curve is presented by plotting void ratio against gross water
content alongside varying degrees of saturation. The safe moisture content is taken from where the compaction curve intersects the degree of saturation equal to 80%. Additional details regarding this test is provided in related publications (Munro and Mohajerani, 2014, 2015, 2016b, 2016c).

13.3.3.2.2 Slope Stability Analysis

During this study, two common types of slope failure analysis, rotational and translational, were performed using the shear strength parameters obtained during the triaxial testing. Rotational and translational analysis were performed in order to determine the factors of safety against slope failure for the iron ore fines described in Section 13.3.3.1.

A method known as the Morgenstern-Price method of slices was used to perform the rotational analysis (Morgenstern and Price, 1965). The Morgenstern-Price method is one of many referred to as a the ‘method of slices’. The ‘method of slices’ also refers to other similar methods based on the limit equilibrium of circular slip surfaces, such as those developed by Spencer (1967), Bishop (1955), Bell (1968), Janbu (1973) and Sarma (1975) (Bell, 1968; Bishop, 1955; Budhu, 2011; Janbu, 1973; Sarma, 1975; Spencer, 1967). Figure 237 shows a hypothetical failure surface along with a free-body diagram of a slice used for general slope stability analysis as per the ‘method of slices’.

![Slope Stability Analysis Diagram](By Fona (Own work) [Public domain], via Wikimedia Commons)

The program chosen to perform this analysis was Geo-Slope International’s GeoStudio SLOPE/W (2012 Edition), herein referred to as SLOPE/W (Geo-Slope International, 2016; Geo-Slope International Ltd, 2015). The Morgenstern-Price method was chosen for a number of reasons, including:

1. it is widely accepted in geotechnics and therefore commonly used for geotechnical engineering purposes,
2. it considers both the shear and normal interslice forces, and
3. it satisfies both the moment and force equilibrium.

The method was developed by Morgenstern and Price (1965) and has similarities to the Spencer method (1967); however, unlike the Spencer method it allows for various user-specified interslice force functions (Geo-Slope International Ltd, 2015; Morgenstern and Price, 1965; Spencer, 1967). Using the constant interslice function makes the Morgenstern-Price method identical to the Spencer
method, but, in this study, the half-sine interslice function was used to more accurately calculate the resulting factors of safety (Morgenstern and Price, 1965).

Along with the rotational analysis, infinite slope analysis, herein referred to as translational analysis, was also performed. The translational analysis used is also a limit equilibrium method, but instead of using a circular slip surface, as assumed in the rotational analysis, it uses a planar slip surface (Budhu, 2011). This failure mode is more common in a coarse grained cohesionless material, similar to the sample of iron ore fines tested.

Eq. 25 and Eq. 26 are the modified formulas used to perform the translational analysis. The equations illustrate the assumed addition of the resisting cohesion force, \( C_b/W_j \sin \alpha_s \), which is not explicitly represented in the original infinite slope analysis equation for non-cohesive materials (Budhu, 2011).

The translational analysis enabled the minimum factors of safety to be determined based on the position of the weakest slip plane, and these results were compared with the results from the rotational analysis.

\[
FS = \frac{C_b + N_j \tan \phi}{T_j} = \frac{C_b}{W_j \sin \alpha_s} + \frac{W_j \cos \alpha_s \tan \phi}{W_j \sin \alpha_s} \quad \text{(Eq. 25)}
\]

\[
FS = \frac{C_b}{W_j \sin \alpha_s} + \frac{\tan \phi}{\tan \alpha_s} \quad \text{(Eq. 26)}
\]

Where:
- \( FS = \) Factor of Safety
- \( C = \) Cohesion Factor (kN/m²)
- \( b_j = \) Width of Slice (m)
- \( N_j = W_j \cos \alpha_s = \) Normal Force on Slip Plane (kN/m)
- \( T_j = W_j \sin \alpha_s = \) Mobilized Shear Resistance of Soil (kN/m)
- \( W_j = z_j b_j \gamma_b = \) Weight of Slice (kN/m)
- \( \alpha_s = \) Slope Angle from Horizontal (°)
- \( \phi = \) Internal Friction Angle (°)
- \( z_j = \) Height of Slice (m)
- \( \gamma_b = \rho_b g = \) Bulk Unit Weight (kN/m³)
- \( \rho_b = \) Bulk Density (t/m³)
- \( g = \) Acceleration due to Gravity (~9.807 m/s²)

During this study, static slope stability analysis was performed rather than dynamic analysis because recent studies have shown that the average frequency of cyclic loading applied to a bulk carrier by the sea state being traversed was lengthy at 0.1Hz (1 cycle per 10 seconds), and only produced a relatively low peak acceleration of approximately 10 m/s² (Iron Ore Technical Working Group, 2013b). Due to this finding, an assumption was made for this study that, due to the lengthy cycle and low peak acceleration, the loading transferred to the cargo is typically considered insignificant.

Both the rotational and translational analysis were performed on hypothetical trimmed and untrimmed cargoes at varying angles of heel, \( \alpha \). The cargoes and conditions analysed are depicted in Figure 238 and Table 75. The hold dimensions used during analysis were those of a typical Capesize subclass of bulk carrier (Iron Ore Technical Working Group, 2013c). These dimensions were used due to the majority of iron ore fines being transported using this subclass of bulk carrier (Munro and Mohajerani, 2016b). The cargo was also assumed to be uniform and homogeneous.
Table 75 – The angles of heel used to perform the trimmed and untrimmed slope stability analysis

<table>
<thead>
<tr>
<th>Angle of Heel, α (°)</th>
<th>Rotational Analysis</th>
<th>Translational Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trimmed</td>
<td>Untrimmed</td>
</tr>
<tr>
<td>0</td>
<td>-</td>
<td>✓</td>
</tr>
<tr>
<td>10</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>20</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>30</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>40</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>50</td>
<td>✓</td>
<td>-</td>
</tr>
<tr>
<td>60</td>
<td>✓</td>
<td>-</td>
</tr>
</tbody>
</table>

A typical figure, including the cargo dimensions, that was used during the trimmed and untrimmed rotational analysis can be seen in Figure 239 and Figure 240. It is noted that the corner fillets of the hold and the depth of the cargo are not governing factors during the trimmed rotational analysis.
The cargo dimensions used during the trimmed and untrimmed translational analysis can be seen in Figure 241 and Figure 242. It is noted that the width of the slice (width of hold), $b_j$, and the height of the slice, $z_j$, have been assumed to be the typical maximum width and height of the cargo.

*Assuming maximum trimmed cargo height ($z_j$) based on maximum untrimmed cargo height of 16.5m (Munro and Mohajerani, 2017c). It is noted that the cargo height is not a major factor when determining the factors of safety using translational analysis unlike other properties, such as the internal friction angle. (Not to scale)
13.3.4 Experimental Results

13.3.4.1 Triaxial Testing

The following are the results from the triaxial testing performed in order to determine the strength parameters needed to analyse the slope stability of a cargo of iron ore fines described in Section 13.3.3.1. Prior to the triaxial test, each sample was given a Unique Identification Number (ID). The ID of the samples along with the initial and final physical properties that were measured are shown in Table 73 and Figure 243.
Table 76 – The initial and final physical properties of the samples tested

<table>
<thead>
<tr>
<th>Unique sample Identification Number, ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Wet Density, $\rho_b$ (t/m³)</td>
<td>2.55</td>
<td>2.90</td>
<td>2.93</td>
<td>2.95</td>
<td>2.74</td>
<td>2.60</td>
<td>2.50</td>
<td>2.79</td>
<td>2.71</td>
</tr>
<tr>
<td>Initial Dry Density, $\rho_d$ (t/m³)</td>
<td>2.32</td>
<td>2.57</td>
<td>2.58</td>
<td>2.62</td>
<td>2.49</td>
<td>2.41</td>
<td>2.27</td>
<td>2.49</td>
<td>2.43</td>
</tr>
<tr>
<td>Initial Void Ratio, e</td>
<td>0.79</td>
<td>0.62</td>
<td>0.61</td>
<td>0.59</td>
<td>0.67</td>
<td>0.72</td>
<td>0.83</td>
<td>0.67</td>
<td>0.71</td>
</tr>
<tr>
<td>Initial Gross Water Content, $w^1$ (%)</td>
<td>9.11</td>
<td>11.53</td>
<td>11.97</td>
<td>11.45</td>
<td>9.17</td>
<td>7.23</td>
<td>9.23</td>
<td>10.72</td>
<td>10.51</td>
</tr>
<tr>
<td>Initial Degree of Saturation, S (%)</td>
<td>52</td>
<td>88</td>
<td>92</td>
<td>91</td>
<td>63</td>
<td>45</td>
<td>51</td>
<td>75</td>
<td>69</td>
</tr>
<tr>
<td>Initial Volume of Air, $V_a$ (%)</td>
<td>21</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>15</td>
<td>23</td>
<td>22</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Final Gross Water Content, $w^1$ (%)</td>
<td>9.11</td>
<td>9.79</td>
<td>9.60</td>
<td>9.87</td>
<td>8.86</td>
<td>7.20</td>
<td>8.84</td>
<td>10.28</td>
<td>9.76</td>
</tr>
</tbody>
</table>

The physical properties of the samples tested are considered to exhibit the range of properties that a cargo of iron ore fines with the physical properties described in Section 13.3.3.1 could possess while being transported. The samples are said to be either before or after transportation by looking at a curve produced by performing the Modified Proctor/Fagerberg test (MPFT) on the same sample of iron ore fines. The curve produced by the MPFT is shown in Figure 243 as ‘typical cargo density before transportation’ because the hammer is said to produce a density similar to the average of that of a cargo iron ore fines before transportation (International Maritime Organization, 2015e; Iron Ore Technical Working Group, 2013a). More information regarding the MPFT can be seen in related publications (Munro and Mohajerani, 2014, 2015, 2016b, 2016c).

Table 77 shows the results from the 3-point monotonic shear test that was performed on each sample of iron ore fines using the triaxial apparatus. Additionally, a typical total failure envelope along with the resulting Mohr’s circles, produced from the triaxial tests, is shown in Figure 244.

Table 77 – The 3-point monotonic shear test conditions and results produced during the triaxial testing

<table>
<thead>
<tr>
<th>Unique sample Identification Number, ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triaxial Shear Test 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Confining Stress, $\sigma_3$ (kPa)</td>
<td>35</td>
<td>35</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>----</td>
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<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td></td>
</tr>
<tr>
<td>Maximum Deviator Stress, $(\Delta\sigma_f)$ (kPa)</td>
<td>232</td>
<td>253</td>
<td>159</td>
<td>163</td>
<td>194</td>
<td>160</td>
<td>124</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>Major Principal Stress, $\sigma_1$ (kPa)</td>
<td>267</td>
<td>288</td>
<td>174</td>
<td>178</td>
<td>209</td>
<td>175</td>
<td>139</td>
<td>198</td>
<td></td>
</tr>
</tbody>
</table>

**Triaxial Shear Test 2:**

<table>
<thead>
<tr>
<th>Confining Stress, $\sigma_3$ (kPa)</th>
<th>50</th>
<th>45</th>
<th>35</th>
<th>35</th>
<th>35</th>
<th>35</th>
<th>35</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Deviator Stress, $(\Delta\sigma_f)$ (kPa)</td>
<td>300</td>
<td>320</td>
<td>241</td>
<td>229</td>
<td>270</td>
<td>230</td>
<td>185</td>
<td>306</td>
</tr>
<tr>
<td>Major Principal Stress, $\sigma_1$ (kPa)</td>
<td>350</td>
<td>365</td>
<td>276</td>
<td>264</td>
<td>305</td>
<td>265</td>
<td>220</td>
<td>341</td>
</tr>
</tbody>
</table>

**Triaxial Shear Test 3:**

<table>
<thead>
<tr>
<th>Confining Stress, $\sigma_3$ (kPa)</th>
<th>- 1</th>
<th>55</th>
<th>55</th>
<th>55</th>
<th>55</th>
<th>55</th>
<th>55</th>
<th>55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Deviator Stress, $(\Delta\sigma_f)$ (kPa)</td>
<td>- 1</td>
<td>383</td>
<td>364</td>
<td>346</td>
<td>364</td>
<td>325</td>
<td>261</td>
<td>419</td>
</tr>
<tr>
<td>Major Principal Stress, $\sigma_1$ (kPa)</td>
<td>- 1</td>
<td>438</td>
<td>419</td>
<td>401</td>
<td>419</td>
<td>380</td>
<td>316</td>
<td>474</td>
</tr>
</tbody>
</table>

**Resulting Shear Strength Parameters:**

<table>
<thead>
<tr>
<th>Internal Friction Angle, $\phi$ (°)</th>
<th>43</th>
<th>49</th>
<th>46</th>
<th>44</th>
<th>43</th>
<th>42</th>
<th>39</th>
<th>48</th>
<th>44</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesion, $c$ (kPa)</td>
<td>18</td>
<td>6</td>
<td>17</td>
<td>20</td>
<td>28</td>
<td>21</td>
<td>17</td>
<td>18</td>
<td>21</td>
</tr>
</tbody>
</table>

1 sample failed before the third shear test was completed due to the higher confining pressures initially used. The third shear test was used for verification of the total failure envelope. Due to the accuracy of the other tests this sample was included without the verification.

![Mohr’s circles and the resulting total failure envelope of a typical sample (sample 8)](image)

The resulting shear strength parameters produced from the triaxial testing are considered to be typical of that for iron ore fines (Iron Ore Technical Working Group, 2013c; H. Wang et al., 2016). It is noted that due to the high internal friction angles, the cohesion factors have a relatively low effect on the shear strength of the material.

### 13.3.4.2 Slope Stability Analysis

In order to determine the factors of safety when transporting a cargo of the described iron ore fines on a bulk carrier, slope stability analysis was carried out, as described in Section 13.3.3.2.2. Table 78 shows the tabulated results from the rotational analysis and Figure 245 shows a graphical representation of the average factors of safety, and upper and lower boundaries for the iron ore fines.
described in Section 13.3.3.1. The average computational results from SLOPE/W can be seen in Section 13.3.6.

Table 78 – The results of the rotational slope stability analysis for each of the samples of iron ore fines

<table>
<thead>
<tr>
<th>Unique sample Identification Number, ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trimmed Rotational Analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle of Heel, α (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>7.2</td>
<td>7.7</td>
<td>7.5</td>
<td>7.3</td>
<td>7.7</td>
<td>7.3</td>
<td>6.4</td>
<td>8.2</td>
<td>7.5</td>
<td>7.4</td>
</tr>
<tr>
<td>20</td>
<td>3.7</td>
<td>3.8</td>
<td>3.8</td>
<td>4.0</td>
<td>3.8</td>
<td>3.3</td>
<td>4.2</td>
<td>3.9</td>
<td>3.8</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>2.4</td>
<td>2.4</td>
<td>2.5</td>
<td>2.4</td>
<td>2.5</td>
<td>2.1</td>
<td>2.7</td>
<td>2.5</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1.6</td>
<td>1.7</td>
<td>1.7</td>
<td>1.8</td>
<td>1.7</td>
<td>1.5</td>
<td>1.9</td>
<td>1.7</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>1.3</td>
<td>1.2</td>
<td>1.3</td>
<td>1.4</td>
<td>1.3</td>
<td>1.1</td>
<td>1.4</td>
<td>1.3</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>1.0</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
<td>1.1</td>
<td>0.9</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Angle of Heel at Failure (FS = 1), αf (°)</td>
<td>61</td>
<td>58</td>
<td>62</td>
<td>61</td>
<td>66</td>
<td>62</td>
<td>55</td>
<td>67</td>
<td>64</td>
<td>62 a</td>
</tr>
<tr>
<td>Untrimmed Rotational Analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle of Heel, α (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.3</td>
<td>2.0</td>
<td>2.3</td>
<td>2.3</td>
<td>2.5</td>
<td>2.3</td>
<td>2.0</td>
<td>2.5</td>
<td>2.4</td>
<td>2.3</td>
</tr>
<tr>
<td>10</td>
<td>1.7</td>
<td>1.5</td>
<td>1.7</td>
<td>1.7</td>
<td>1.8</td>
<td>1.7</td>
<td>1.5</td>
<td>1.9</td>
<td>1.8</td>
<td>1.7</td>
</tr>
<tr>
<td>20</td>
<td>1.2</td>
<td>1.2</td>
<td>1.3</td>
<td>1.3</td>
<td>1.4</td>
<td>1.3</td>
<td>1.1</td>
<td>1.4</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>30</td>
<td>1.0</td>
<td>0.9</td>
<td>1.0</td>
<td>1.0</td>
<td>1.1</td>
<td>1.0</td>
<td>0.9</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>40</td>
<td>0.7</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
<td>1.0</td>
<td>0.8</td>
<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Angle of Heel at Failure (FS = 1), αf (°)</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>28</td>
<td>36</td>
<td>30</td>
<td>25</td>
<td>31</td>
<td>30</td>
<td>30 a</td>
</tr>
</tbody>
</table>

*Noting the high coefficient of determinations (R²) shown in Figure 245, the average angle of heel at failure is based on the trend lines produced from the data rather than the data itself.
The rotational analysis, produced using the Morgenstern-Price method of slices, shows a significant increase in the angle of heel at failure, $\alpha_f$, between an untrimmed and trimmed cargo. Figure 245, and the figures thereafter, show the average maximum and the maximum angles of heel that bulk carriers may experience. As these angles vary for each individual bulk carrier, a reasonable expectation of the maximum survivable angles had to be determined.

During a previous study, seven investigation reports into cargo shifts were summarised and discussed (Munro and Mohajerani, 2016a). The study noted the actions and observations made by the crew and rescuers relating to the angles of heel of bulk carriers before, during and after the events. To summarise, the Hui Long, Trans Summer and Nasco Diamond investigation reports indicate that the bulk carriers experienced a 10-degree roll caused by the sea state prior to the vessels listing (Panama Maritime Authority - Maritime Accident Investigation Department, 2011c; The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005, 2015). The Hui Long, Trans Summer and Padang Hawk investigation reports indicate that, once the cargo shift had occurred, the vessels developed a permanent 15-degree list after the initial rolling moment (Australian Transport Safety Bureau, 2000; The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005, 2015).

Noting that, under the International Convention for the Safety of Life at Sea (SOLAS Convention), all lifeboats must be “capable of being safely launched under ... list of up to 20-degrees”, The crew of the Hui Long, Trans Summer, Jian Fu Star and Bulk Jupiter abandoned their vessels at approximately 40-degrees, 20-degrees, 45-degrees and 45-degrees, respectively (Panama Maritime Authority - Maritime
Accident Investigation Department, 2011b; The Bahamas Maritime Authority, 2015; The Hong Kong Special Administrative Region - Marine Department - Marine Accident Investigation Section, 2005, 2015).

Additional studies recorded the maximum roll angles of a bulk carrier transporting iron ore fines being 10-degrees while traversing typical sea states and also determined roll angles of up to 35-degrees while analysing theoretical extreme sea states (Iron Ore Technical Working Group, 2013b, 2013c, 2013e). Also, in relation to the marine transportation of coal, a recent study has shown that a Handy size bulk carrier sailing through beam seas under a 95th percentile storm will produce a maximum angle of heel of 29-degrees (International Maritime Organization, 2015b).

Noting that the angles of heel produced during rolling are suspected of causing the cargo to shift, it was decided to adopt the maximum expected angle of heel as being 35-degrees, as vessels did not report roll angles exceeding this value, only listing angles. Additionally, using the maximum calculated angle of heel from the individual Handy size bulk carrier, the average maximum angle of heel adopted during this study was 29-degrees (International Maritime Organization, 2015b).

Considering the maximum angle of heel that a bulk carrier may experience as being 35-degrees, the rotational analysis shows that a bulk carrier transporting an untrimmed cargo could traverse through a sea state producing an angle of heel of approximately 30-degrees. Comparing this to an angle of heel at failure for a fully trimmed cargo of 62-degrees, analysis shows that trimming significantly increases the factor of safety against rotational failure during normal operation.

As described in Section 13.3.3.2.2 translational analysis was also performed in conjunction with the rotational analysis. Table 79 and Figure 246 show the tabulated results from the translational analysis and a graphical representation of the average factors of safety along with upper and lower boundaries for the iron ore fines described in Section 13.3.3.1.

Table 79 – The results of the translational slope stability analysis for each of the samples of iron ore fines

| Unique sample Identification Number, ID | Trimmed Translational Analysis | | | | | | | | | Average |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Angle of Heel, $\alpha$ (°) | Factor of Safety, $FS$, for $z_j = 12m$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 10 | 5.7 | 7.4 | 6.1 | 5.8 | 5.8 | 5.6 | 5.0 | 6.7 | 5.9 | 6.0 |
| 20 | 2.8 | 3.8 | 3.0 | 2.8 | 2.8 | 2.7 | 2.4 | 3.3 | 2.9 | 2.9 |
| 30 | 1.8 | 2.4 | 1.9 | 1.8 | 1.8 | 1.7 | 1.5 | 2.1 | 1.8 | 1.9 |
| 40 | 1.2 | 1.7 | 1.3 | 1.2 | 1.2 | 1.1 | 1.1 | 1.4 | 1.3 | 1.3 |
| 50 | 0.9 | 1.3 | 0.9 | 0.9 | 0.9 | 0.8 | 1.0 | 0.9 | 0.9 | 0.9 |
| 60 | 0.6 | 1.0 | 0.7 | 0.6 | 0.6 | 0.5 | 0.7 | 0.6 | 0.7 | 0.7 |

| Angle of Heel at Failure ($FS = 1$), $\alpha_f$ (°) | 44 | 62 | 47 | 45 | 42 | 44 | 40 | 50 | 46 | 46 |

| Untrimmed Translational Analysis | | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Angle of Heel, $\alpha$ (°) | Factor of Safety, $FS$, for $z_j = 2.9m$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 0 | 1.5 | 2.3 | 1.6 | 1.5 | 1.7 | 1.5 | 1.4 | 1.7 | 1.6 | 1.6 |
| 10 | 1.1 | 1.7 | 1.1 | 1.1 | 1.3 | 1.2 | 1.0 | 1.2 | 1.2 | 1.2 |
| 20 | 0.8 | 1.3 | 0.8 | 0.8 | 1.0 | 0.9 | 0.8 | 0.9 | 0.9 | 0.9 |
| 30 | 0.6 | 1.0 | 0.6 | 0.6 | 0.7 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 |

| Angle of Heel at Failure ($FS = 1$), $\alpha_f$ (°) | 14 | 0.8 | 14 | 14 | 18 | 15 | 10 | 17 | 16 | 14 |

Michael Colin Munro – July 2017
Noting the high coefficient of determinations ($R^2$) shown in Figure 246, the average angle of heel at failure is based on the trend lines produced from the data rather than the data itself.

Similar to the rotational analysis, the translational analysis shows a significant increase in the angle of heel at failure between an untrimmed and trimmed cargo. When compared to the rotational analysis, the translational analysis produced an angle of heel at failure 16-degrees lower for both the trimmed and untrimmed cargo, which were 46-degrees and 14-degrees, respectively.

The results shown depict the average untrimmed angle of heel at failure to be 14-degrees. This value can be validated by looking at the aforementioned case studies in which the founding of bulk carriers seems to commence when the vessels experience an angle of heel of approximately this degree.

Rotational slope failure commonly occurs in a fine-grained material with cohesion, and, therefore, it is considered that the infinite slope or translational analysis governs the resulting factors of safety. Hence, the lower factor of safety produced by the translational analysis, shown in Table 79 and Figure 246, is assumed to more accurately depict the cargo or iron ore fines in question.

In soil mechanics, a factor of safety of 1 is rarely perceived as safe and never used for design considerations. This is due to a factor of safety of 1 being the point at which the material is considered to be undergoing failure. In geotechnical engineering, a factor of safety of 1.5 is commonly used during slope stability analysis (Budhu, 2011). As expected, if a factor of safety of 1.5 is used for analysis, the angle of heel at failure decreases significantly, as seen in Table 80 and Figure 247.
Table 80 – The average angle of heel at failure for varying factors of safety

<table>
<thead>
<tr>
<th>Factor of Safety, FS</th>
<th>Rotational Analysis</th>
<th>Translational Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trimmed</td>
<td>Untrimmed</td>
</tr>
<tr>
<td>1</td>
<td>62</td>
<td>30</td>
</tr>
<tr>
<td>1.1</td>
<td>57</td>
<td>26</td>
</tr>
<tr>
<td>1.2</td>
<td>53</td>
<td>23</td>
</tr>
<tr>
<td>1.3</td>
<td>49</td>
<td>20</td>
</tr>
<tr>
<td>1.4</td>
<td>46</td>
<td>17</td>
</tr>
<tr>
<td>1.5</td>
<td>43</td>
<td>15</td>
</tr>
<tr>
<td>1.6</td>
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<td>12</td>
</tr>
<tr>
<td>1.7</td>
<td>39</td>
<td>10</td>
</tr>
<tr>
<td>1.8</td>
<td>37</td>
<td>8</td>
</tr>
<tr>
<td>1.9</td>
<td>35</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>34</td>
<td>4</td>
</tr>
</tbody>
</table>

Considering the safer operating factor of safety of 1.5, the values indicate that an untrimmed cargo for the iron ore fines, as described in Section 13.3.3.1, would be considered unstable under all expected angles of heel during operation. If trimmed, the cargo would be considered stable unless angles of heel above the average maximum are experienced.

The translational analysis shown in Table 80 and Figure 247 indicate that if a cargo is untrimmed and a conservative safety factor of 1.5 is utilized, the angle of heel at failure would be 1-degree, or assumed to be unstable under all conditions. Even utilizing a factor of safety of 1.2 the angle of heel at failure would only increase to 8-degrees, which is a common angle of heel experienced during a typical voyage of bulk carriers transporting iron ore fines. Depending on the factor of safety that is considered reasonable to account for uncertainties during analysis, the expected safe angle of heel will increase or decrease accordingly.
If a factor of safety of 1.5 was to be used, it would be recommended to increase the density of the trimmed cargo by compaction during loading to increase the internal friction angle, and, therefore, the angle of heel at failure. Overall, the results confirm that an untrimmed cargo of iron ore fines, as described in Section 13.3.3.1, would become unstable at the expected angle of heel while a trimmed cargo would be unlikely to reach the same unstable conditions in the hold of a bulk carrier.

13.3.5 Conclusion
The objective of this study was to investigate the factors of safety against the rotational and translational slope failure of iron ore fines being transported on bulk carriers under both untrimmed and trimmed conditions. In order to determine these factors of safety, triaxial testing was performed under varying densities and moisture contents to obtain a range of shear strength parameters expected during marine transportation. Using these shear strength parameters, the Morgenstern-Price method of slices and infinite slope analysis, referred to as rotational and translational slope stability analyses, were then used to determine the factors of safety against slope failure for iron ore fines being transported under varying conditions.

The results from this study indicate that if the cargo of iron ore fines is untrimmed it would become unstable at the angles of heel that bulk carriers are expected to experience during a typical voyage. By examining the translational analysis, which is considered to govern the factors of safety, the slope angle at failure is validated by investigating case studies. If trimmed, the cargo was shown to be significantly more stable using both the rotational and translational analysis. If a factor of safety of 1.5 was used, it would be recommended to increase the density of the trimmed cargo by compaction during loading to increase the internal friction angle, and, therefore, the angle of heel at failure to above 35-degrees.

The cumulative effect of a cargo having a low slope angle from the horizontal and increased density is an increased factor of safety against slope failure. Based on the results it is recommended that it become mandatory for cargoes of iron ore fines to undergo trimming, if not fully, partially, in order to decrease the slope angle of the cargo from horizontal and increase the density. Trimming will also decrease the amount of material that is likely to shift, if slope failure occurs, altering the buoyancy of the bulk carrier. Additionally, due to its inherently low cohesion depicted in this study, it is recommended that iron ore fines be listed as a non-cohesive cargo in Appendix 3, Section 1.1 of the International Maritime Solid Bulk Cargoes Code (IMSBC Code), and tested accordingly.

The results are based on the assumption that there is no significant dynamic loading applied to the cargo. If dynamic loading is significant, analysis would show that the factors of safety would significantly reduce. It is noted that the results may vary significantly depending on the physical properties of the cargo of iron ore fines being transported.

Future research is recommended in order to determine the range of strength parameters for iron ore fines with varying properties as well as the strength parameters relating to the resistance that cargoes of iron ore fines have against sliding en masse as well as under dynamic loading.
13.3.6 Appendix A – Average Rotational Analysis Computational Results
The trimmed and untrimmed cargo dimensions along with the average computational results for the rotational analysis (method of slices), including the minimum factor of safety, are shown from Figure 248 to Figure 258. As discussed in Section 13.3.3.2.2, the results were produced using Geo-Slope International’s GeoStudio SLOPE/W (2012 Edition) and are discussed in detail in Section 13.3.4.2.

Figure 248 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 10-degree angle of heel rotational analysis (method of slices)

Figure 249 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 20-degree angle of heel rotational analysis (method of slices)
Figure 250 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 30-degree angle of heel rotational analysis (method of slices)

Figure 251 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 40-degree angle of heel rotational analysis (method of slices)
Figure 252 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 50-degree angle of heel rotational analysis (method of slices)
Figure 253 – Trimmed cargo dimensions and resulting average minimum factor of safety from the 60-degree angle of heel rotational analysis (method of slices)
Figure 254 – Untrimmed cargo dimensions and resulting average minimum factor of safety from the 0-degree angle of heel rotational analysis (method of slices)

Figure 255 – Untrimmed cargo dimensions and resulting average minimum factor of safety from the 10-degree angle of heel rotational analysis (method of slices)
Figure 256 – Untrimmed cargo dimensions and resulting average minimum factor of safety from the 20-degree angle of heel rotational analysis (method of slices)

Figure 257 – Untrimmed cargo dimensions and resulting average minimum factor of safety from the 30-degree angle of heel rotational analysis (method of slices)
Figure 258 – Untrimmed cargo dimensions and resulting average minimum factor of safety from the 40-degree angle of heel rotational analysis (method of slices)
13.4 SUPPLEMENTARY RESULTS AND FIGURES

The supplementary results for the manuscript presented in Chapter 13 are given in Appendix D.

13.5 SUMMARY AFTER THE FACT

This manuscript provides a firm depiction of the shear strength of a cargo of iron ore fines considering static loading. The results indicate what could be considered the minimum safety characteristics, as the addition of cyclic loading or increased motions will likely reduce the angle of heel needed for the cargo to shift.

The analysis performed also gives an understanding of the cargo strength when trimmed and untrimmed. It is beginning to become obvious that there are definite advantages and disadvantages of having a trimmed or untrimmed cargo of iron ore fines.

The next stage of this research that was undertaken was completing the preliminary scale model testing using the new and unique scale model apparatus that was designed and developed during this study.
CHAPTER 14 CYCLIC BEHAVIOUR OF IRON ORE FINES ON BOARD BULK CARRIERS: SCALE MODEL ANALYSIS

14.1 INTRODUCTION

The peer-reviewed manuscript presented in this chapter introduces the new and unique scale model and apparatus that was designed and developed during this study. At this stage, the main aspects of the apparatus had been constructed, and testing was required to determine any further changes that may need to be made. The preliminary testing was undertaken while further equipment was being obtained that was needed to monitor parameters, such as the pore air and water pressures within the specimens.

Also covered in this manuscript is additional details regarding the Iron Ore Fines Plunger (IOFP). The IOFP was used to determine the apparent shear strength of the same samples of iron ore fines. In conjunction with the results from the monitoring of variables during the scale model testing, it was expected to obtain some confirmation or correlation of the strength characteristics.

Exclusions made from this manuscript and not included in this chapter are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made continuous throughout this document.

14.2 CITATION

14.3 MANUSCRIPT CONTENTS

14.3.1 Abstract

Solid bulk cargoes have been known to liquefy in the holds of bulk carriers since the loss of the Bengal in 1910. Due to the increased demand for iron ore fines over the past 20 years, export industries have experienced further incidents where liquefaction of the cargo was the suspected cause. The objective of this study was to develop a scale model of bulk carrier hold in order to investigate the variability of the physical properties of iron ore fines, which govern the liquefaction potential under cyclic loading. Additionally, by associating the theory of liquefaction of partially saturated soils to the cyclic behaviour of the samples, the apparent shear strength of the samples will be determined. During this study, a scale model along with an iron ore fines plunger were developed and utilised. The physical properties of the samples of iron ore fines were monitored during the scale model test and the point at which moisture migration began to occur was determined. The boundary where the material showed a significant loss of shear strength, referred to as the critical failure curve, was also determined using the iron ore fines plunger. After consistent results were shown using both methods, the moisture content at which the sample was considered potentially liquefiable was concluded and compared with the results from the current test method used to reduce liquefaction incidents on bulk carriers.

14.3.2 Background

Since the loss of the Bengal in 1910, solid bulk cargoes have been known to liquefy while being transported in the holds of bulk carriers (Sandvik and Rein, 1992). Numerous studies have been performed since then to determine the liquefaction potential of solid bulk cargoes that have been suspected of undergoing liquefaction at sea (i.e. (Australian Coal Association Research Program (ACARP), 2014b; Fagerberg and Stavang, 1971; Iron Ore Technical Working Group, 2013a; Jian-Ping, 2011; Munro and Mohajerani, 2015, 2016b, 2016d; Tanaka and Ura, 1989; T Ura, 1992)). Standard bulk carrier holds are not designed to transport liquids. When liquefaction of a solid bulk cargo occurs, the sheer weight of the unconstrained cargo shifting in the hold can cause a change in the buoyancy of the bulk carrier, which can result in the vessel listing or capsizing.

There has been an increase in the demand for Iron Ore Fines (IOF) from China and South Korea in the past 20 years. Export countries such as Indonesia, Malaysia, India and the Philippines have had an increase in incidents involving bulk carriers transporting IOF, where liquefaction has been the suspected cause. In fact, liquefaction of IOF has been suspected of being the cause of at least eight cargo shifts over the last eight years, six of which have resulted in total loss of the vessel, as seen in Table 43 and Figure 259.

Table 81 – Recent incidents involving bulk carriers transporting IOF

<table>
<thead>
<tr>
<th>Vessel Name</th>
<th>Subclass</th>
<th>Total Loss</th>
<th>Lives Lost</th>
<th>Date</th>
<th>Origin</th>
<th>Destination</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Chang Le Men</em></td>
<td>Handysize</td>
<td>No (Listed)</td>
<td>0</td>
<td>07/09/2007</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td><em>Asian Forest</em></td>
<td>Handysize</td>
<td>Yes</td>
<td>0</td>
<td>17/07/2009</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>#Hodasco 15</td>
<td>General Bulker</td>
<td>Yes</td>
<td>0</td>
<td>30/08/2009</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td><em>Black Rose</em></td>
<td>Handysize</td>
<td>Yes</td>
<td>1</td>
<td>09/09/2009</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>#Bright Ruby</td>
<td>Handysize</td>
<td>Yes</td>
<td>6</td>
<td>21/11/2011</td>
<td>Malaysia</td>
<td>China</td>
</tr>
<tr>
<td><em>Sun Spirits</em></td>
<td>Handysize</td>
<td>Yes</td>
<td>0</td>
<td>22/01/2012</td>
<td>Philippines</td>
<td>China</td>
</tr>
<tr>
<td><em>Bingo</em></td>
<td>General Bulker</td>
<td>Yes</td>
<td>0</td>
<td>12/10/2013</td>
<td>India</td>
<td>China</td>
</tr>
<tr>
<td>#Anna Bo (Figure 259)</td>
<td>Handymax</td>
<td>No (Listed)</td>
<td>0</td>
<td>04/12/2013</td>
<td>Indonesia</td>
<td>China</td>
</tr>
</tbody>
</table>

Source: * (Munro and Mohajerani, 2016b), # (Andrei and Pazara, 2013), ‡ (United Nations Conference on Trade and Development (UNCTAD), 2014)
Due to these recent incidents, research and industry institutions have begun to determine the conditions under which IOF liquefies and test methods that can be used to reduce their occurrence. The test that was recently introduced to determine the maximum moisture content that IOF can be transported, without being at risk of liquefaction, is the Modified Proctor/Fagerberg Test for IOF (MPFT) (International Maritime Organization, 2015d).

### 14.3.2.1 Modified Proctor/Fagerberg Test for Iron Ore Fines (MPFT)

Not to be confused with the Modified Proctor/Fagerberg Test for coal (Australian Coal Association Research Program (ACARP), 2014a), the Modified Proctor/Fagerberg Test for Iron Ore Fines (MPFT) is the current test method, amended in the 2015 International Maritime Solid Bulk Cargoes Code (IMSBC Code), that is used to determine the Transportable Moisture Limit (TML) of Iron Ore Fines (IOF) (International Maritime Organization, 2013a, 2015d). The IMSBC Code infers that the TML is the maximum Gross Water Content by weight (GWC) that a cargo of IOF may contain without being at risk of liquefying (International Maritime Organization, 2013b).

The MPFT procedure and individual IOF schedule describe the properties that classify it as such and subsequent requirements for TML testing. For iron ore to be classified as IOF, it must contain at least 10% of fine particles less than 1 mm and at least 50% of particles less than 10 mm, as well as have a goethite content of less than 35% by mass (International Maritime Organization, 2013a, 2015d). During the research into the MPFT, it was determined that iron ore with a goethite content of more than 35% of its mass did not need to undergo TML testing as the goethite could retain more water within the particles, thus restricting the amount of free water and reducing its liquefaction potential. This was established through laboratory tests that included triaxial testing (Iron Ore Technical Working Group, 2013c).

The MPFT procedure involves compacting a sample of IOF into a standard litre compaction mould at varying moisture contents to produce a compaction curve with a minimum of five data points. The compaction is executed in five layers by dropping a 150 g hammer, 25 times, through a guided pipe from a height of 150 mm. For each point, the GWC and void ratio is calculated and plotted on a graph along with the corresponding Degree of Saturation (S). The resulting GWC is then interpreted from the graph, where S equals 80%; this value is referred to as the TML (International Maritime Organization, 2015d).
Organization, 2013a, 2015d). The MPFT requires the particle density to produce the corresponding $S$ (e.g. AS1289 3.5.1 (Standards Australia, 2006)).

The density produced by the MPFT compaction procedure is considered to be equivalent to the density of IOF in the hold of a bulk carrier (Iron Ore Technical Working Group, 2013a). A typical compaction curve of IOF, produced during this study using the MPFT, can be seen in Figure 260 and the MPFT apparatus, including the 150 g hammer and standard litre compaction mould can be seen in Figure 261.

![Figure 260 – MPFT compaction curve and TML produced during this study on the sample of IOF](image)

*Figure 260 – MPFT compaction curve and TML produced during this study on the sample of IOF*
14.3.2.2 Liquefaction of Unsaturated Soils

A comprehensive literature review was carried out on the liquefaction potential of unsaturated granular soils to develop a scale model to determine the liquefaction potential of Iron Ore Fines (IOF) and to assist in achieving the objectives of this research.

The term ‘liquefies’ was first used when referring to the failure of the Calaveras Dam in 1918 (Hazen, 1920). Liquefaction is a term used to describe when the shear strength of a soil is reduced to near zero under cyclic, static or shock loading, which results in the soil behaving like a liquid. Under load, the shear strength of a soil can be reduced to near zero by preventing water drainage momentarily that effects the pore pressures between the particles of the soil (Eseller-Bayat et al., 2013). An illustration of the behaviour of partially saturated cohesionless soils before, during and after liquefaction can be seen in Figure 262. Sladen et al. (1985) gives a more precise definition of liquefaction:

“Liquefaction is a phenomenon wherein a mass of soil loses a large percentage of its shear resistance, when subjected to monotonic, cyclic or shock loading, and flows in a manner resembling a liquid until the shear stresses acting on the mass are as low as the reduced shear resistance.” (Sladen et al., 1985)
The latest version of the classification system by Robertson and Fear (Robertson and Fear, 1996) to define soil liquefaction and as summarized by Rauch (Rauch, 1997) can be seen in Table 82. Their classification system recognised that various mechanisms could be involved in the liquefaction potential of soils.

**Table 82 – The classification system by Robertson and Fear (Robertson and Fear, 1996) to define soil liquefaction, as summarized by Rauch (Rauch, 1997)**

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) Flow Liquefaction</td>
<td>Used to describe the undrained flow of a saturated, contractive soil when the static shear stress exceeds the residual strength of the soil. Failure may be triggered by cyclic or monotonic shear loading.</td>
</tr>
<tr>
<td>B) Cyclic Softening</td>
<td>Used to describe large deformations occurring during cyclic shear due to pore pressure build-up in soils that would tend to dilate in undrained, monotonic shear. Cyclic softening, where deformations do not continue after cyclic loading, can be further classified in two categories (See below)</td>
</tr>
<tr>
<td>B1) Cyclic Liquefaction</td>
<td>Occurs when cyclic shear stresses exceed the initial, static shear stress to produce a stress reversal. A condition of zero effective stress may be achieved during which large deformations may occur.</td>
</tr>
<tr>
<td>B2) Cyclic Mobility</td>
<td>Occurs when cyclic loads do not yield a shear stress reversal and a condition of zero effective stress does not develop. Deformations accumulate in each cycle of shear stress.</td>
</tr>
</tbody>
</table>
Additionally, some incidents attributed to liquefaction may be more accurately described as cyclic instability, which is a form of unstable behaviour (strain softening) caused by a succession of dynamic load cycles (Baki et al., 2012; Mohamad and Dobry, 1986; Rahman et al., 2014).

The theory behind the liquefaction of soils began with Terzaghi’s principal of effective stress, which was developed during his research on soil consolidation (Terzaghi, 1925, 1943). Eq. 27 shows that effective stress ($\sigma'$) is considered to be a function of normal stress ($\sigma$) and pore water pressure ($u_w$):

$$\sigma' = \sigma - u_w$$  \hspace{1cm} (Eq. 27)

Eq. 28 was derived from Coulomb (Coulomb, 1776) by Terzaghi (Terzaghi, 1942) and is commonly referred to as the Mohr-Coulomb failure criterion in soil mechanics. It expresses that shear stress ($\tau$) of a soil is a function of effective stress ($\sigma'$), friction angle ($\phi'$) and a cohesion factor ($c'$):

$$\tau = \sigma' \tan \phi' + c'$$  \hspace{1cm} (Eq. 28)

The expression depicts that when the effective stress of a cohesionless soil is reduced to near zero, the shear strength subsequently nears zero. As shear stress was found to be a function of effective stress, attempts were made in the 1950s to develop an expression for the effective stress of an unsaturated soil. Croney et al. suggested that the effective normal stress of an unsaturated soil ($\sigma'$) could be expressed as a function of the total normal stress ($\sigma$), a holding or bonding factor ($\beta'$) and pore water pressure ($u_w$), as seen in Eq. 29 (Croney et al., 1958):

$$\sigma' = \sigma - \beta' u_w$$  \hspace{1cm} (Eq. 29)

The first person to suggest an expression for effective normal stress ($\sigma'$), with both pore air pressure ($u_a$) and pore water pressure ($u_w$) variables was Bishop, as seen in Eq. 30 (Baker and Frydman, 2009; Bishop, 1959). The difference between pore air pressure ($u_a$) and pore water pressure ($u_w$) is referred to as matric suction ($u_m$, i.e. $u_m = u_a - u_w$). Bishop also included a parameter, $\chi$, which is a value between 0 and 1 relating to the degree of saturation:

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w)$$  \hspace{1cm} (Eq. 30)

According to Eq. 30, in fully saturated soils (where $\chi = 1$), the reduction in effective stress is directly related to the increase in pore water pressure, as seen as Terzaghi’s principal of effective stress (Eq. 27). In the 1960s attempts such as Croney’s and Bishop’s, to create an equation for effective stress of an unsaturated soil, were disparaged (e.g. (Jennings and Burland, 1962)).

Further improvements to the Mohr-Coulomb failure criterion (Eq. 28) have also been proposed. Eq. 31 (Bishop, 1959), Eq. 32 (D.G. Fredlund et al., 1978) and Eq. 33 (Vanapalli et al., 1996) are some examples of popular proposals:

$$\tau = (\sigma_n - u_a) \tan \phi' + (u_a - u_w) [\chi \tan \phi'] + c'$$  \hspace{1cm} (Eq. 31)

$$\tau = (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi b + c'$$  \hspace{1cm} (Eq. 32)

$$\tau = [c' + (\sigma_n - u_a) \tan \phi'] + (u_a - u_w) [(\theta b) \tan \phi']$$  \hspace{1cm} (Eq. 33)
In these equations, shear stress was expressed as a function of net normal stress on the plane of failure at failure \((\sigma_n - u_a)\), a parameter dependent on the degree of saturation assumed to vary between 0 and 1 \((\psi)\), normalized volumetric water content \((\Theta)\), the angle linking the rate of change of shear strength with matric suction \((\phi_b)\), and a factor of plasticity \((k, \text{close to 1 in sandy soils, and greater than 1 as plasticity increases})\).

Along with recent improvements to the Mohr-Coulomb failure criterion, Bishop’s equation for the effective stress of an unsaturated soil \((\text{Eq. 30})\) has also been scrutinised. Bishop’s expression indicates that \(\chi\), which is related to the degree of saturation, increases with matric suction, which implies that effective stress and subsequently shear stress increases forever. It has now been proven this is not always the case \((\text{e.g. (J. K. M. Gan and Fredlund, 1996; Md.Noor and Anderson, 2006; Toll et al., 2000))}\). Khalili and Khabbaz \((\text{Khalili and Khabbaz, 1998})\) and Geiser \((\text{Geiser, 2000})\) agreed that Bishop’s parameter, \(\chi\), is a function of the ratio of the existing suction \((s)\), to the suction at which air would enter saturated soil \((s_e)\), where the parameter, \(k\), varies from -0.65 to -0.4 and commonly taken as -0.55 \((\text{Geoffrey E Blight, 2013})\), as seen in \(\text{Eq. 34}\) and \(\text{Eq. 35}\):

\[
\chi = \left[\frac{s}{s_e}\right]^k \quad s \geq s_e \quad (\text{Eq. 34})
\]

\[
\chi = 1 \quad s < s_e \quad (\text{Eq. 35})
\]

When the degree of saturation in an unsaturated soil is low, then soil suction or negative pore water pressure was assumed to occur within. As soils become close to being saturated, soil suction is reduced and allows moisture migration to occur, which results in densification and a reduction in void ratio. By considering the basic functions of effective stress, as seen in \(\text{Eq. 27}\) to \(\text{Eq. 35}\), it could be deduced that the liquefaction potential of a soil is directly related to the ability the material has to normalise changes in pore air and water pressures.

The ability for soils to dissipate pore pressures rapidly, the hydraulic conductivity, or permeability, of the soil has to allow this to occur. A previous study showed that a typical sample of IOF has a hydraulic conductivity of \(1 \times 10^{-5}\) m/s to \(2 \times 10^{-8}\) m/s \((\text{Munro and Mohajerani, 2016d})\), values which are considered to be low with poor drainage \((\text{Holtz and Kovacs, 1981; Lambe and Whitman, 1969; Terzaghi and Peck, 1967})\).

Lambe and Whitman \((1969)\) proposed additional physical properties that influenced the hydraulic conductivity of soils, such as particle size, void ratio, composition, fabric and the degree of saturation \((\text{Lambe and Whitman, 1969})\). This study analysed variations in the physical properties that influence the hydraulic conductivity of IOF, including the moisture content, void ratio, dry density and the degree of saturation, to determine their influence on the liquefaction potential of IOF.

14.3.3 Objective

The objective of this study was to develop a scale model of bulk carrier hold in order to investigate the variability of the physical properties of Iron Ore Fines (IOF), which govern the liquefaction potential under cyclic loading. These physical properties include the moisture content, void ratio, dry density, degree of saturation and angle of repose. Additionally, by associating the theory of liquefaction of
Chapter 14 - Cyclic Behaviour of Iron Ore Fines on board Bulk Carriers: Scale Model Analysis

Michael Colin Munro – July 2017

partially saturated soils to the cyclic behaviour of the samples, the apparent shear strength of the samples will be determined.

14.3.4 Materials and Methods

14.3.4.1 Materials

The sample of Iron Ore Fines (IOF) used during this study, identified as sample MA003 and seen in Figure 263 was obtained from Western Australia. The physical properties of the IOF sample and the standards to which these properties were obtained can be seen in Table 83 and Figure 214.

The physical properties of the IOF sample was determined using the standard AS 1289 – Method of testing soils for engineering purposes (Standards Australia, 2000) and the Transportable Moisture Limit (TML) values were determined using the appropriate method stated in either the 2013 IMSBC Code (International Maritime Organization, 2013b) or the circular DSC.1/Circ.71 (International Maritime Organization, 2013a). More Information regarding the TML tests stated in the IMSBC Code can be found in two related publications (Munro and Mohajerani, 2015, 2016b).

The moisture contents seen in Table 83 have been reported according to the relevant standard. In AS 1289, the moisture content, including the Optimum Moisture Content (OMC), is reported in Net Water Content (NWC) by weight as the percentage of the mass of moisture to the mass of dry material (Standards Australia, 2000). In the IMSBC Code (International Maritime Organization, 2013b) and the circular DSC.1/Circ.71 (International Maritime Organization, 2013a), the moisture content, including TML, is reported in Gross Water Content (GWC) by weight as the percentage of the mass of moisture to the total mass of wet material. In geotechnical engineering and soil mechanics, NWC is commonly used whereas in most other cases, including metallurgy and the transportation of solid bulk cargoes, GWC is favoured. Both GWC and NWC are shown in Table 83 for convenience.

Table 83 – Physical properties of the IOF sample used during this study

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard/ Apparatus</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Cargo</td>
<td>Circular DSC.1/Circ.71 (International Maritime Organization, 2013a) or MSC 95/3/Add.1 (International Maritime Organization, 2015d)</td>
<td>Iron Ore Fines</td>
</tr>
<tr>
<td>Atterberg Limits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Limit</td>
<td>AS1289.3.1.2 (Standards Australia, 2009a)</td>
<td>18% NWC or 15.3% GWC *</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>AS1289.3.2.1 (Standards Australia, 2009b)</td>
<td>17% NWC or 14.5% GWC *</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>AS1289.3.3.1 (Standards Australia, 2009c)</td>
<td>1% NWC/GWC *</td>
</tr>
<tr>
<td>Particle Size Distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel (&gt;2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>27%</td>
</tr>
<tr>
<td>Sand (75 μm – 2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>50%</td>
</tr>
<tr>
<td>Silt (2 μm – 75 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>19%</td>
</tr>
<tr>
<td>Clay (&lt;2 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>3%</td>
</tr>
<tr>
<td>Classification</td>
<td>AS1726 (Standards Australia, 1993)</td>
<td>Silty Sand (SM)</td>
</tr>
<tr>
<td>Coefficient of Curvature (Cc)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>1.1</td>
</tr>
<tr>
<td>Coefficient of Uniformity (Cu)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>91</td>
</tr>
<tr>
<td>Particle Density</td>
<td>AS1289.3.5.1 (Standards Australia, 2006)</td>
<td>4.36 t/m³</td>
</tr>
<tr>
<td>Method</td>
<td>Standard/Specification</td>
<td>MDD (t/m³)</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>-------------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Standard Proctor Compaction MDD and OMC</td>
<td>AS1289.5.1.1 (Standards Australia, 2003b)</td>
<td>2.76</td>
</tr>
<tr>
<td>Modified Proctor Compaction MDD and OMC</td>
<td>AS1289.5.2.1 (Standards Australia, 2003c)</td>
<td>2.89</td>
</tr>
<tr>
<td>Minimum Dry Density</td>
<td>AS1289.5.5.1 (Standards Australia, 1998)</td>
<td>2.27</td>
</tr>
<tr>
<td>Maximum Dry Density</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Proctor/Fagerberg TML</td>
<td>(International Maritime Organization, 2013b)</td>
<td>11.4%</td>
</tr>
<tr>
<td>Flow Table TML (35kg.f)</td>
<td>(International Maritime Organization, 2013b)</td>
<td>10.3%</td>
</tr>
<tr>
<td>Modified Proctor/Fagerberg TML</td>
<td>Circular DSC.1/Circ.71 (International Maritime Organization, 2013a) or MSC 95/3/Add.1 (International Maritime Organization, 2015d)</td>
<td>12.8%</td>
</tr>
</tbody>
</table>

Note: GWC = Gross Water Content, MDD = Maximum Dry Density, NWC = Net Water Content, OMC = Optimum Moisture Content, TML = Transportable Moisture Limit.

a The reported moisture content unit, according to the relevant standard, is presented first (i.e. GWC or NWC).

b The compaction curve produced during this test can be seen in Figure 260.

Figure 263 – The sample of IOF used during this study
Sample MA003 was chosen for this study because it was considered a typical sample of IOF commonly transported on bulk carriers from Australia. The physical properties of sample MA003 was within the range of typical properties of IOF determined in a related publication (Munro and Mohajerani, 2015).

14.3.4.2 Apparatus
14.3.4.2.1 Scaled Cyclic Testing (SCT)
A scale model of a bulk carrier hold, constructed primarily of 20 mm acrylic and 10 mm steel, was developed to achieve the objectives of this research including performing, what has been termed for this study, Scaled Cyclic Testing (SCT). The dimensions of the scale model were based on a typical capesize bulk carrier as the holds of these carriers were found to transport at sea 92% of iron ore by tonnage in 2012 (Iron Ore Technical Working Group, 2013b).

The dimensions of the capesize bulk carrier hold that were used to determine the size of the scale model were 35 x 25 m, with a height of just over 21 m. The height of a typical cargo of Iron Ore Fines (IOF) in a capesize bulk carrier hold is approximately 17 m (Iron Ore Technical Working Group, 2013c). As seen in Figure 265, the final inner dimensions used for the scale model were 410 x 293 mm, with a height of 250 mm. 410 mm was the maximum dimension that could be used as the vibrating table that the scale model would be placed upon is 450 mm x 450 mm. The ratio of the scale model to the original dimension of the capesize bulk carrier hold was approximately 1:85, with a maximum volume of 29.7 L (29,700cm$^3$).

The scale model incorporated two drainage outlets, 20 mm in diameter, which were used to replicate the bilge areas in bulk carrier holds. The bilge areas on a bulk carrier are used to store excess water from the cargo hold before the bilge pumps evacuate it overboard (Plant Export Operations Branch, 2014). To replicate the mesh screening, used to stop the cargo obstructing the pipes and pumps in a bulk carrier hold bilge system (Transportation Safety Board of Canada, 2005), the drainage outlets on the scale model were covered with faucet aerators. On the scale model, the drainage outlets directed
excess water into the 25 mm diameter polytube through sealable valves and then into a moisture drainage container, where the weight of the moisture lost could be determined.

The scale model also incorporated five removable acrylic panels, 6 mm thick x 50 mm high, which were attached using wingnuts so that the sample could be extracted in layers. After each test, the five panels would be removed, from top to bottom, and another sharpened 6 mm acrylic panel would be used to extract the sample in horizontal layers.

The scale model was placed on a vibrating table that was typically used in soil mechanics to determine the minimum and maximum dry density of a cohesionless material (Standards Australia, 1998). The difference being that the table was operated at a frequency of 50-60 Hz, with an acceleration of 6±0.3 g RMS for 3600 seconds (1 hour) (~216k cycles per test). A typical bulk carrier transporting IOF from Brazil to China takes approximately 40 days and experiences a maximum acceleration of 1 g with an average frequency of 0.1 Hz (~345k cycles per voyage) (Iron Ore Technical Working Group, 2013b), therefore the SCT was performed with approximately 63% of the cycles and 600% the acceleration of a typical bulk carrier voyage transporting IOF.

The scale model was bolted securely at four points to the vibrating table in order to effectively transfer the vibration energy to the material inside the mould. The vibration was applied for 3600 seconds (1 hour), at the frequency and acceleration mentioned previously, as under these conditions the final

Figure 265 – Dimensions and features of the scale model developed during this study
density, void ratio and the degree of saturation were approximately equivalent to those produced by the Modified Proctor/Fagerberg Test (MPFT), as discussed previously.

14.3.4.2.2 Iron Ore Fines Plunger (IOFP) Test

A free-floating Iron Ore Fines Plunger (IOFP) with a weight of 845 g was developed to determine the apparent shear strength of Iron Ore Fines (IOF) under cyclic loading. The IOFP was based upon the apparatus that is used during the Penetration test, described in Appendix 2 of the IMSBC Code, which was designed to determine the Transportable Moisture Limit (TML) of coal and ore concentrates. A 15 mm diameter indicator bit is used during the IMSBC Code’s Penetration test with contact pressures of either 5 kPa or 10 kPa for coal and ore concentrates respectively. It is also recommended in the code that two penetration bits should be applied when the material has coarse particles to avoid misjudgement (International Maritime Organization, 2013b).

The dimensions of the IOFP, developed for this study, was greater along with the contact pressure because IOF contain larger particles compared to coal and ore concentrates. The IOFP developed during this study was manufactured with a diameter of 25.4 mm and contact pressure of 16.36 kPa, as seen in Figure 266 and Figure 267. It was assumed that by increasing the contact pressure and surface area of the IOFP, it reduced the chances of it being obstructed by the larger particles within IOF and therefore increased repeatability and reproducibility of the test.

The IOFP was used to determine the difference in penetration of the same IOF samples used during the Scaled Cyclic Testing (SCT). After the SCT was completed, the IOFP was placed on the sample for an additional 900 seconds (15 minutes) with the vibrating table operated at a frequency of 50-60Hz and an acceleration of 6±0.3g RMS, which was the same frequency and acceleration used during the SCT.
Based on the theory discussed previously, it could be assumed that if the IOFP penetrates into the sample without signs of bearing capacity failure, then the effective stress and shear strength surrounding the IOFP has reduced to zero and therefore the sample has potentially undergone liquefaction.

A conservative initial bearing capacity of the samples of IOF at the time the IOFP was applied was calculated to be greater than 20kPa. It was expected that by using this method the Critical Failure Curve (CFC) could be determined. The CFC is a term used in this study to refer to the boundary at which the apparent shear strength of the IOF was considered to be significantly reduced, under the applied magnitude and time of cyclic loading, possibly indication liquefaction.

### 14.3.4.3 Procedure

The following procedure was developed to achieve the objectives of this research using the previously described apparatus. The sample of Iron Ore Fines (IOF) was first riffled to produce five samples, each with a gross mass of approximately 35 to 40 kg. Calculations were then performed to determine the quantity of water to add to each of the five samples so that the final moisture contents would span an appropriate range.
The samples were then cured for at least 24 hours, similar to what would occur in stockpiles. The total mass of the sample to be tested was then placed into a container, weighed and mixed thoroughly before the initial moisture content of the sample was taken. Immediately afterwards, the sample was gently scooped into the scale model, which was securely attached to the vibrating table. The leftover sample was then weighed to determine the initial gross mass of the sample placed for testing. During the Scaled Cyclic Testing (SCT) and application of the Iron Ore Fines Plunger (IOFP), the drainage valves were set in the open position for the testing to be performed under drained conditions, which is similar to the drainage conditions in the hold of a bulk carrier.

The SCT then was initiated by starting the vibrating table, which was set to a frequency of 50-60Hz with an acceleration of 6±0.3g RMS. During the SCT, the vibrating table was briefly switched off to record height measurements and weigh the amount of moisture lost. These tasks were performed at the intervals seen in Table 84.

Table 84 – Vibration intervals when measurements were taken during the SCT and penetration of the IOFP

<table>
<thead>
<tr>
<th>Scaled Cyclic Testing (SCT) measurement intervals during vibration</th>
<th>Measurement intervals taken during the penetration of the Iron Ore Fines Plunger (IOFP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>Initial</td>
</tr>
<tr>
<td>5 seconds</td>
<td>1 second</td>
</tr>
<tr>
<td>30 seconds</td>
<td>5 seconds</td>
</tr>
<tr>
<td>60 seconds (1 minute)</td>
<td>10 seconds</td>
</tr>
<tr>
<td>120 seconds (2 minutes)</td>
<td>20 seconds</td>
</tr>
<tr>
<td>240 seconds (4 minutes)</td>
<td>40 seconds</td>
</tr>
<tr>
<td>480 seconds (8 minutes)</td>
<td>60 seconds (1 minute)</td>
</tr>
<tr>
<td>900 seconds (15 minutes)</td>
<td>120 seconds (2 minutes)</td>
</tr>
<tr>
<td>1800 seconds (30 minutes)</td>
<td>240 seconds (4 minutes)</td>
</tr>
<tr>
<td>3600 seconds (1 hour)</td>
<td>480 seconds (8 minutes)</td>
</tr>
<tr>
<td></td>
<td>900 seconds (15 minutes)</td>
</tr>
</tbody>
</table>
After 3600 seconds (1 hour) of vibration, the IOFP was placed in the centre of the sample and the vibrating table started again for an additional 900 seconds (15 minutes). Similar to the SCT, the vibrating table was briefly switched off to record the penetration made by the IOFP at the intervals also seen in Table 84.

For each sample, after vibration, each of the five front acrylic panels were removed from top to bottom and the sample was sequentially split horizontally. Each sample was only split into two layers to correspond with the height of the two bottom panels because the final height of the samples was lower than expected.

The total mass of each of the two layers, ‘Layer 1’ for the bottom layer and ‘Layer 2’ for the top layer, were then weighed to check the total mass of the overall sample. Samples from each of the two layers were also taken to determine their moisture content. This was carried out in accordance with AS 1289.2.1.1-2005 (Standards Australia, 2005).

14.3.5 Analysis of Results

14.3.5.1 Sample Identification

During the study, the sample of Iron Ore Fines (IOF) was split into five for the Scaled Cyclic Testing (SCT) and for the application of the Iron Ore Fines Plunger (IOFP). Table 60 shows the moisture contents of the samples and their identification that is used for description during the analysis of the results. As previously mentioned, after vibration, each sample was then split into two horizontal layers. The bottom layer was identified as ‘Layer 1’ and the top layer was identified as ‘Layer 2’.

<table>
<thead>
<tr>
<th>IOF sample Identification</th>
<th>Gross Water Content by Weight, GWC (%)</th>
<th>Net Water Content by Weight, NWC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TML-1.9%</td>
<td>10.88</td>
<td>12.20</td>
</tr>
<tr>
<td>TML-1.6%</td>
<td>11.25</td>
<td>12.68</td>
</tr>
<tr>
<td>TML%</td>
<td>12.82</td>
<td>14.71</td>
</tr>
<tr>
<td>TML+0.5%</td>
<td>13.37</td>
<td>15.44</td>
</tr>
<tr>
<td>TML+1.3%</td>
<td>14.09</td>
<td>16.40</td>
</tr>
</tbody>
</table>

14.3.5.2 Scaled Cyclic Testing (SCT)

The sample was split into five samples and subjected to, what has been termed for this study Scaled Cyclic Testing (SCT), to determine the variation in physical properties under cyclic loading and if moisture migration could be observed and recorded. The method involved vibrating the samples of Iron Ore Fines (IOF) in the scale model, at a frequency of 50-60Hz, with an acceleration of 6±0.3g RMS for 3600 seconds (1 hour). The initial placement of a sample prior to testing can be seen in Figure 268.
After the SCT had been completed, the sample was removed in two horizontal layers to determine changes in the moisture content and degree of saturation of the overall sample and against the height or depth of the sample. A description of the samples tested along with their identifications are given in Table 60.

To calculate the average variation of dry density, void ratio and degree of saturation, the height measurements that were taken during testing were used along with the sample volumes and moisture contents to create graphical representations of the data. Also measured during the test was the angle of repose. These results can be seen in Figure 269 to Figure 272 and the total variation in the physical properties during the SCT can be seen in Table 86.

<table>
<thead>
<tr>
<th>IOF sample Identification</th>
<th>Gross Water Content by Weight (%)</th>
<th>Variation of Dry Density after 1 hour of Vibration (t/m³)</th>
<th>Variation of Void Ratio after 1 hour of Vibration</th>
<th>Variation of Degree of Saturation after 1 hour of Vibration (%)</th>
<th>Variation of Angle of Repose after 1 hour of Vibration (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TML-1.9%</td>
<td>10.88</td>
<td>0.41</td>
<td>0.77</td>
<td>12.02</td>
<td>7.97</td>
</tr>
<tr>
<td>TML-1.6%</td>
<td>11.25</td>
<td>0.53</td>
<td>0.81</td>
<td>18.10</td>
<td>7.96</td>
</tr>
<tr>
<td>TML%</td>
<td>12.82</td>
<td>0.81</td>
<td>0.95</td>
<td>40.97</td>
<td>17.46</td>
</tr>
<tr>
<td>TML+0.5%</td>
<td>13.37</td>
<td>0.66</td>
<td>0.66</td>
<td>39.35</td>
<td>23.81</td>
</tr>
<tr>
<td>TML+1.3%</td>
<td>14.09</td>
<td>0.55</td>
<td>0.52</td>
<td>36.32</td>
<td>36.56</td>
</tr>
</tbody>
</table>
Figure 269 – The effect of moisture content on the variation of dry density produced during the SCT

Figure 270 – The effect of moisture content on the variation of void ratio produced during the SCT

Figure 271 – The effect of moisture content on the variation of degree of saturation produced during the SCT
Figure 272 – The effect of moisture content on the variation of angle of repose produced during the SCT

The results in Figure 269 to Figure 272 and Table 86 show that the average variation of physical properties of the samples of Iron Ore Fines (IOF) vary significantly. Figure 269 and Figure 270 show that the maximum dry density and minimum void ratio that the sample of IOF could reach under the magnitude and time of cyclic loading was 2.45 t/m³ and 0.78 respectively.

As shown in Eq. 30, the effective stress and therefore the shear strength is related to the degree of saturation of a soil. The variation in the degree of saturation seen in Figure 271 shows that by increasing the moisture content of the sample, the final degree of saturation increased consistently until the maximum value of 91% was reached.

Noting that the percentage of air voids is not the same as 100 – S, where S equals the degree of saturation, the minimum air voids recorded during testing (where the degree of saturation was equal to 91%) was calculated to be 4% of the sample’s volume (Head, 2006). This can be seen in Eq. 36 and Eq. 37 where the percentage of air voids ($V_a$) is a function the samples dry density ($\rho_d$), particle density ($\rho_{st}$) and net water content (NWC).

$$V_a = \left(1 - \rho_d \left(\frac{1}{\rho_{st}} + \frac{NWC}{100}\right)\right) \times 100 \quad (\text{Eq. 36})$$

$$V_a = \left(1 - 2.44 \left(\frac{1}{4.36} + \frac{16.40}{100}\right)\right) \times 100 = 4\% \quad (\text{Eq. 37})$$

While compacting soils using a compaction hammer, such as in AS1289.5.1.1 (Standards Australia, 2003b), the maximum degree of saturation of soils that can be reached occurs when the sample contains approximately 5% air voids. It was therefore considered safe to assume that at 91% saturation the sample was at the maximum density that could be achieved under the magnitude and time of cyclic loading.
Figure 273 – The surface profile of TML-1.9% recorded before and after 3600 seconds (1 hour) of vibration applied during the SCT

Figure 274 – The surface profile of TML-1.6% recorded before and after 3600 seconds (1 hour) of vibration applied during the SCT
Figure 275 – The surface profile of TML% recorded before and after 3600 seconds (1 hour) of vibration applied during the SCT

Figure 276 – The surface profile of TML+0.5% recorded before and after 3600 seconds (1 hour) of vibration applied during the SCT
In order to be able to visualize the changes in the physical properties of the samples of IOF, especially in terms of volume change and angle of repose, height measurements were used to produce the initial and final surface profiles of each sample. Along with Figure 272, the profiles given in Figure 273 to Figure 277 shows that after approximately 900 seconds (15 minutes) of vibration, the angle of repose for the sample at TML+1.3% reduced to zero. This indicated that during the test the shear strength of the sample was reduced to such a degree that the surface profile became level.

The void ratios recorded during the Scaled Cyclic Testing (SCT) were plotted against the moisture content and the degree of saturation. These curves along with the Modified Proctor/Fagerberg Test (MPFT) curve and resulting Transportable Moisture Limit (TML), as seen in Figure 260, are shown in Figure 278. The Restraining Moisture Content (RMC) shown in this figure is discussed ahead.
Figure 278 – The average variation in void ratio and the degree of saturation produced during the SCT, the MPFT compaction curve and the RMC
Figure 278 confirmed that the results produced a compaction curve similar to that produced by the MPFT after 3600 seconds (1 hour) of vibration. Studies have shown that the density produced by compacting IOF using the MPFT was similar to the density of IOF on board bulk carriers after transportation (Iron Ore Technical Working Group, 2013a). Figure 278 also shows that at TML+1.3%, the changes in the physical properties of the sample stabilized rapidly after 60 seconds (1 minute) of vibration.

The results are assumed to indicate that pore pressures within the samples with low moisture contents were minimal. As the moisture content increased, the air was expelled rapidly by the movement of moisture within the sample. This was indicated by an increase in density and the degree of saturation. The pore water pressure within the samples where the degree of saturation was initially high would likely increase steadily until fully saturated. When fully saturated and cyclic loading is applied, the changes in pore water pressure within the sample is maximised and therefore the liquefaction potential is assumed to be at its greatest.

The data shown in Figure 269 to Figure 278 as well as Table 86 on their own do not indicate that the sample was undergoing liquefaction, but indicated that the physical properties, which can influence the liquefaction potential of IOF, were undergoing significant changes.

A sample was retested at TML% to determine the time it would take for the average degree of saturation to reach 100%. However, instead of ending this test at 3600 seconds (1 hour), it was extended to run for 14400 seconds (4 hours). The results from a comparison between the 1 hour and 4 hour tests at TML% are seen in Table 87 and Figure 279.

Table 87 – The variation in physical properties of IOF produced during the SCT for the 4 hours and 1 hour tests at TML% 

<table>
<thead>
<tr>
<th>Sample = TML%</th>
<th>Variation of Dry Density from Beginning to End of Test (t/m³)</th>
<th>Variation of Void Ratio from Beginning to End of Test</th>
<th>Variation of Degree of Saturation from Beginning to End of Test (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TML% (1 hour)</td>
<td>0.81</td>
<td>0.95</td>
<td>40.97</td>
</tr>
<tr>
<td>TML% (4 hour)</td>
<td>0.96</td>
<td>1.18</td>
<td>47.13</td>
</tr>
<tr>
<td>Difference between 1 hour and 4 hour tests at TML%</td>
<td>0.04</td>
<td>-0.03</td>
<td>2.14</td>
</tr>
</tbody>
</table>
Figure 279 shows that it would take approximately 30 days of vibration for the sample to reach 100% saturation. Although this could be seen as the case for the overall sample, by looking at the changes in the degree of saturation of the layers, it could be seen that ‘Layer 1’ may reach 100% after approximately 8 hours of vibration. Based on the previously discussed theory, at 100% saturation, the potential for a soil to liquefy is increased, therefore partial liquefaction of the sample may occur if vibrated for 8 hours.

14.3.5.3 Restraining Moisture Content (RMC)
In order to determine the Restraining Moisture Content (RMC), it was necessary to determine when moisture migration within the sample began to occur. Similar to what is shown in Figure 279, all the other 1-hour test samples were extracted from the scale model in two horizontal layers, after the Scaled Cyclic Testing (SCT) testing, and the moisture content and the degree of saturation were determined on both these layers. Along with changes in pore pressures, these properties, have the greatest influence on the effective stress and consequently the liquefaction potential of soils.
The overall moisture content of each sample against the degree of saturation and moisture content of Layers 1 and 2 is shown in Figure 280 and Figure 281. Taking into account the reproducibility and variability of the tests when determining the moisture content and degree of saturation, it could be seen in Figure 281 that there was a clear change in the distribution of moisture within the sample between TML% and TML+0.5%. Between these samples, the moisture at the bottom of the sample was shown to migrate upwards to give the top layer (‘Layer 2’) a higher moisture content than the bottom layer (‘Layer 1’). Increasing the initial overall moisture content of the sample to TML+1.3% further increased the difference in moisture contained in the layers.

Analysing the results seen in Figure 280 shows that the greatest difference in the degree of saturation could be seen to be also between TML% and TML+0.5%. As expected, the degree of saturation for TML+1.3% began to converge due to the maximum degree of saturation possible being 100%. 

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**Figure 280 – The variation of the degree of saturation of each layer against the overall moisture content produced during the SCT after 3600 seconds (1 hour) of vibration**

**Figure 281 – The variation of the moisture content of each layer against the overall moisture content produced during the SCT after 3600 seconds (1 hour) of vibration**
Both figures show that moisture migration to the top layer (‘Layer 2’) began to occur between TML% and TML+0.5%. This point we have referred to as the RMC. This migration of moisture could be attributed to changes occurring in the pore pressures within the sample of Iron Ore Fines (IOF). TML+0.5% and TML+1.3%, the two wettest samples, showed a steady deviation away from normal indicating increasing changes in pore pressures. It was assumed that moisture migration, caused by changing pore pressures within the sample of IOF, indicated that the sample was potentially liquefiable.

To determine the degree of saturation where the RMC occurred, it was plotted on Figure 278 and Figure 280. It could be seen in these figures that the corresponding degree of saturation was approximately 80%. It was concluded that at the RMC (approximately 0.1% GWC above the TML) the sample of IOF was considered to be potentially liquefiable.

This method was based on the assumption that moisture migration within the sample was related to changes in pore pressures, which reduced the shear strength of the sample and increased its potential to liquefy. Further experimentation is required with additional data points and pore pressure measurements to confirm these results.

14.3.5.4 Iron Ore Fines Plunger (IOFP) Test
To determine the apparent shear strength of Iron Ore Fines (IOF) under cyclic loading and validate the Restraining Moisture Content (RMC) a free-floating Iron Ore Fines Plunger (IOFP) with a contact pressure of 16.36kPa was utilised to determine if the shear strength of the sample of Iron Ore Fines (IOF) decreased significantly under cyclic loading. The IOFP was placed on the sample of IOF for 15 minutes after the 3600 seconds (1 hour) of initial vibration. As discussed previously, the sample was allowed to vibrate initially for 3600 seconds (1 hour), during the SCT, to let it reach the same density, void ratio and degree of saturation produced by the Modified Proctor/Fagerberg Test (MPFT).

During the tests, the depth of penetration of the IOFP along with time was recorded. As discussed previously, it was noticed that after the initial placement there were no signs of bearing capacity failure. The graphical representations of the test results can be seen in Figure 174 and Figure 175. The apparent shear strength is also shown in Figure 174 and Figure 175. The apparent shear strength depicts the theoretical relationship of the shear strength to the penetration of the IOFP.
The percent penetration by the IOFP was assumed to be associated with the apparent loss of shear strength, which can be interpreted directly from Figure 175. This is assumed to be the case due to the...
relationship between shear strength and effective stress, which has been discussed previously. The boundary termed the Critical Failure Curve (CFC), can also be seen in Figure 175.

The results shown in Figure 174 and Figure 175 clearly indicated that the depth and rate of penetration by the IOFP increased as the moisture content increased. The samples tested at TML-1.9% and TML-1.6% were initially penetrated by the IOFP by 15% of the samples depth and then gradually increased to 20%. This was attributed to the IOFP penetrating only the surface layer of the sample, which was loosely compacted.

Figure 175 shows that the samples at TML-1.9% and TML-1.6% were unlikely to reach any critical conditions that would indicate a loss of shear strength or liquefaction under this magnitude and time of cyclic loading. The sample tested at TML% was penetrated by the IOFP near linearly. It was safe to assume that at this moisture content, the IOFP would reach the maximum penetration possible after a further 100 seconds of vibration. As the moisture content increased to TML+0.5% and TML+1.3%, the speed of penetration by the IOFP increased respectively and both reached the maximum penetration possible using this apparatus. Although further validation is required, it was assumed that these two samples had significantly reduced shear strength and may have undergone liquefaction under these conditions.

After 900 seconds (15 minutes) of vibration, the sample at TML% could be seen to behave similar to the sample at TML+0.5% after 300 seconds (5 minutes) of vibration. This demonstrated that by increasing the time of cyclic loading, the critical conditions could be met on a sample with a relatively low moisture content. Increasing the moisture content meant that the critical conditions were met sooner. Based on the tests performed at TML% and TML+0.5%, the apparent shear strength of the samples could be seen to be a function of the time of cyclic loading and initial moisture content.

Based on the results from this test, the sample showed a significant reduction in shear strength between TML-1.6% and TML% and liquefaction was assumed to have occurred there onwards (above the CFC). Additionally, the Restraining Moisture Content (RMC) determined during the SCT (approximately 0.1% GWC above the TML) intersected the CFC giving confirmation boundary.

14.3.6 Conclusion
The objective of this study was to develop a scale model of bulk carrier hold in order to investigate the variability of the physical properties of Iron Ore Fines (IOF), which govern the liquefaction potential under cyclic loading. These physical properties include the moisture content, void ratio, dry density, degree of saturation and angle of repose. Additionally, by associating the theory of liquefaction of partially saturated soils to the cyclic behaviour of the samples, the apparent shear strength of the samples was determined.

By monitoring changes in the physical properties of the samples of IOF during the Scaled Cyclic Testing (SCT), it was concluded that under the applied frequency and acceleration, the sample of IOF reached a similar density to that produced by the Modified Proctor/Fagerberg Test (MPFT). Analysing changes in the moisture content and degree of saturation of the sample of IOF against the height or depth of the sample indicated changing pore pressures within the sample. This was exhibited by changes in the distribution in moisture content and the degree of saturation as well as being accompanied by a shift in the layer that dominated these properties (i.e. moisture migration). This occurred between TML%
and TML+0.5%. This study referred to this point as RMC, which was the point at which the sample was considered potentially liquefiable.

Based on the results from the application of the IOFP, the apparent shear strength of the sample of IOF under cyclic loading reduced significantly between TML-1.6% and TML%. Above TML%, or the Critical Failure Curve (CFC), the samples were assumed to have undergone liquefaction. Additionally, the RMC determined during the SCT intersected the CFC giving confirmation of the boundary.

These results were based on the assumptions that moisture migration was related to changes in pore pressure and loss of shear strength within the sample and furthermore, the loss of shear strength observed while the IOFP was applied indicated that the sample of IOF had a significant reduction in shear strength possibly indicating liquefaction. It is purposed in the next stage of this study to attach pressure transducers to the scale model to determine the actual changes in pore air and pore water pressures within the sample to determine the effective stress and therefore liquefaction potential of the material.
14.4 SUPPLEMENTARY RESULTS AND FIGURES

The supplementary results for the manuscript presented in Chapter 14 are given in Appendix E.

14.5 SUMMARY AFTER THE FACT

The results from utilizing the scale model and application of the Iron Ore Fines (IOFP) showed that there was a significant loss of shear strength within specimens of iron ore fines at moisture contents lower than the Transportable Moisture Limit (TML) determined using the Modified Proctor/Fagerberg Test (MPFT).

The results from the preliminary scale model testing also indicated that the pore air and water pressure monitoring devices were indeed necessary in order to conclude the phenomena responsible for the loss of shear strength in the specimens. There were also other modifications that were needed that became apparent during testing in terms of both the apparatus and procedure used.

While the testing that was presented in this manuscript was underway, so was the installation and utilization of the new cyclic triaxial. The next stage of research involved utilizing the newly obtained cyclic triaxial in order to determine if liquefaction is possible under simulated seagoing conditions.
CHAPTER 15 SIMULATING MARINE TRANSPORTATION USING A CYCLIC TRIAXIAL TO DETERMINE THE LIQUEFACTION POTENTIAL OF IRON ORE FINES

15.1 INTRODUCTION

The following manuscript presented in this chapter introduces the newly obtained cyclic triaxial and results produced from its utilization. The cyclic triaxial is the most common apparatus used in geotechnical engineering and soil mechanics to determine the cyclic strength of soils. This triaxial apparatus differs from the previous apparatus used, presented in Chapter 12, due to the inclusion of pore pressure transducers, to monitor the pressure within the sample, and a volume change device, to monitor volume change and apply back pressure for saturation.

Exclusions made from this manuscript and not included in this chapter are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made continuous throughout this document.

15.2 CITATION

Chapter 15 - Simulating Marine Transportation using a Cyclic Triaxial to Determine the Liquefaction Potential of Iron Ore Fines

15.3 MANUSCRIPT CONTENTS

15.3.1 Abstract
It has been nearly seven years since the mandatory implementation of the International Maritime Solid Bulk Cargoes Code (IMSBC Code), which is the code of safe practice to be followed when transporting hazardous solid bulk cargoes. Over this time, the Modified Proctor/Fagerberg test (MPFT) was implemented to reduce the likelihood of liquefaction of iron ore fines during marine transportation. The objective of this study is to utilize a cyclic triaxial test to investigate the likelihood that liquefaction will occur in materials, such as iron ore fines, as suspected by some industry and research associations. To achieve this, comparisons of the strength parameters obtained by monotonic triaxial testing were made against the behaviour of the material under cyclic loading, which replicated the expected conditions during marine transportation. It was concluded during this study that liquefaction of the specimen of iron ore fines obtained and tested would be extremely unlikely to occur under the expected loading conditions that a cargo may experience during marine transportation. If the assumptions made during this study are representative of real life conditions, it is more likely that another type of failure is the cause of the incidents where liquefaction was suspected.

15.3.2 Introduction
Recently a group of industry and research associations, referred to as the Iron Ore Technical Working Group (TWG), developed a new test method under the directions of the International Maritime Organization (IMO). Known as the Modified Proctor/Fagerberg test (MPFT), this test method produces a parameter for iron ore fines known as the Transportable Moisture Limit (TML). The TML is the maximum allowable moisture content that iron ore fines may contain to prevent liquefaction of the cargo whilst undergoing marine transportation (Munro and Mohajerani, 2014, 2015, 2016c).

The MPFT is specified in the International Maritime Solid Bulk Cargoes Code (IMSBC Code), which is the code of safe practice to be followed when transporting hazardous solid bulk cargoes (International Maritime Organization, 2016). The method was introduced due to the mandatory implementation of the IMSBC Code in 2011 (Munro and Mohajerani, 2016b). At the time the IMSBC Code came into force, there was no individual schedule or TML test method specifically employed for use with iron ore fines that were considered liquefiable (Munro and Mohajerani, 2016b). Due to recent incidents during the marine transportation of iron ore fines and similar cargoes, where liquefaction was the suspected cause, (Munro and Mohajerani, 2016a, 2016b), a test method to determine the TML of iron ore fines was required by the IMO, and, hence, came about the TWG and the implementation of the MPFT.

Between 1988 and 2016, 23 incidents were reported where liquefaction of a solid bulk cargo was suspected. These incidents resulted in 138 casualties and the loss of 17 vessels. Even though liquefaction was suspected in these cases, the deep-rooted cause of the majority of the incidents was never agreeably established (Munro and Mohajerani, 2016a, 2017b). When referring to liquefaction in this study, the term will also encompass the phenomenon known as cyclic mobility. Both terms are more clearly defined in Section 15.3.4.1.

15.3.2.1 Objective
The objective of this study is to utilize a cyclic triaxial to investigate the liquefaction potential of iron ore fines under simulated conditions to represent those expected during marine transportation, and
establish if liquefaction in materials, such as iron ore fines, is conceivable as a failure mode, as suspected by some industry and research associations. To achieve this, comparisons of the strength parameters obtained by monotonic triaxial testing will be made against the behaviour of the material under cyclic loading that replicates the conditions expected during marine transportation.

### 15.3.3 Material

The specific variant of iron ore fines tested during this study was chosen due to its representative physical properties when compared to similar cargoes that typically undergo marine transportation on bulk carriers (Munro and Mohajerani, 2015). The physical properties of this specimen of iron ore fines can be seen in Table 88.

**Table 88 – Physical properties of the iron ore fines specimen used during this study**

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard/ Apparatus</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen Identification</td>
<td>N/A</td>
<td>MA004</td>
</tr>
<tr>
<td>abc Modified</td>
<td>MSC 95/22/Add.2 (International Maritime Organization, 2015e)</td>
<td>10.9% GWC or 12.2% NWC at 80% Saturation</td>
</tr>
<tr>
<td>Proctor/Fagerberg TML</td>
<td>(OMC occurring at 96% Saturation)</td>
<td></td>
</tr>
<tr>
<td>Maximum Dry Density</td>
<td>AS1289.5.5.1 (Standards Australia, 1998)</td>
<td>2.76 t/m³ (e = 0.50)</td>
</tr>
<tr>
<td>Minimum Dry Density</td>
<td>AS1289.5.5.1 (Standards Australia, 1998)</td>
<td>2.18 t/m³ (e = 0.90)</td>
</tr>
<tr>
<td>Atterberg Limits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Liquid Limit</td>
<td>AS1289.3.1.2 (Standards Australia, 2009a)</td>
<td>17% NWC</td>
</tr>
<tr>
<td>* Plastic Limit</td>
<td>AS1289.3.2.1 (Standards Australia, 2009b)</td>
<td>16% NWC</td>
</tr>
<tr>
<td>* Plasticity Index</td>
<td>AS1289.3.3.1 (Standards Australia, 2009c)</td>
<td>1% NWC</td>
</tr>
<tr>
<td>d Particle Size Distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel (&gt;2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>51%</td>
</tr>
<tr>
<td>Sand (75 μm – 2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>38%</td>
</tr>
<tr>
<td>Silt (2 μm – 75 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>9%</td>
</tr>
<tr>
<td>Clay (&lt;2 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>1%</td>
</tr>
<tr>
<td>Classification</td>
<td>AS1726 (Standards Australia, 1993)</td>
<td>Poorly graded gravel to silty gravel (GP-GM)</td>
</tr>
<tr>
<td>Particle Density, Gs</td>
<td>AS1289.3.5.1 (Standards Australia, 2006)</td>
<td>4.15 t/m³</td>
</tr>
<tr>
<td>Hydraulic Conductivity, K</td>
<td>AS1289.6.7.1 (Standards Australia, 2001b)</td>
<td>2.08 x10⁻⁵ m/s</td>
</tr>
<tr>
<td>Quantitative X-Ray Diffraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hematite (Fe₂O₃)</td>
<td>X’Pert Pro PW3040</td>
<td>36% Total Weight</td>
</tr>
<tr>
<td>b Goethite (FeOOH)</td>
<td>X’Pert Pro PW3040</td>
<td>62% Total Weight</td>
</tr>
</tbody>
</table>

*a* The percentage of moisture is reported according to the relevant standard first (i.e. NWC or GWC). In geotechnical engineering and soil mechanics, the Net Water Content (NWC) is commonly used, whereas, in most other cases, including metallurgy and marine transportation, the Gross Water Content (GWC) is favoured. NWC is referred to as the percentage of moisture to dry material, while GWC is the percentage of moisture to wet material; hence, net and gross.

*b* According to MSC 95/22/Add.2, if a cargo of iron ore fines has more than 35% goethite total weight, then the schedule for iron ore must be followed but the cargo does not need to undergo testing using the Modified Proctor/Fagerberg method, as it is considered unable to liquefy (International Maritime Organization, 2015e).

*c* The Modified Proctor/Fagerberg test compaction curve and TML for this specimen of iron ore fines can be seen in Figure 284.

*d* The particle size distribution for this specimen of iron ore fines can be seen in Figure 285.
Figure 284 – Modified Proctor/Fagerberg test compaction curve and TML of the specimen of iron ore fines used during this study
15.3.4 Method

15.3.4.1 Critical State Framework

Critical state soil mechanics describes the strength and compressibility response of soils and other materials used in engineering designs. The framework under which the critical state is defined is employed to understand the response of soils negotiating the specified stress paths that are expected during the lifetime of a project. Under this framework, the response of a material under compression tends towards an ultimate condition where plastic shearing could continue indefinitely without a change in the volume or effective stress. This condition of perfect plasticity is known as the critical state and is where soils undergo failure. The expression seen in Eq. 38 is true when the critical state has been reached (Wood, 1990).

\[
\frac{\partial p'}{\partial \varepsilon_q} = \frac{\partial q}{\partial \varepsilon_q} = \frac{\partial \nu}{\partial \varepsilon_q} = 0
\]

The critical state of a material is unique unto itself and does not depend on the initial state of the material or stress path the material negotiates. As seen in Figure 286, when soil is in its critical state there is a unique relationship between the difference in principal stresses (i.e. deviator stress), effective stress and the specific volume of the material. In this framework, the specific volume, \( \nu \), can also be represented by the void ratio, \( e \), or moisture content, \( w \). The results in this study present the results in relation to the void ratio, \( e \).

The locus of critical states is called the Critical State Line (CSL), and can be shown on the \( q:p' \) plane passing through the origin and the top of the yield loci, which are located at the failure points on the

Figure 285 – Particle size distribution of the specimen of iron ore fines used during this study
stress paths. The slope of the CSL in the $q:p'$ plane is the parameter $M$. The CSL can also be shown on the $\nu:p'$ plane, where $\Gamma$ is the location and $\lambda$ is the slope of the line.

In Figure 286, the Normal Consolidation Line (NCL) for a material that has undergone isotropic consolidation is shown on the $\nu:p'$ plane, where $N$ is the location and, like the CSL, $\lambda$ is the slope of the line. When isotropically-consolidated, the shear stress, hence, the deviator stress, $q$, is zero, and, therefore, is located only on the $\nu:p'$ plane.

For a material that has undergone anisotropic consolidation, the coefficient of lateral earth pressure must be taken into account. As depicted in Figure 287, the coefficient of lateral earth pressure, $K$, is defined as the ratio of the horizontal effective stress, $\sigma'_h$, to the vertical effective stress, $\sigma'_v$. The critical shear strength of the soil increases with increasing effective stress and with decreasing water content.
The effective stress ratio can be used to evaluate the conditions of yielding for a Normally-Consolidated (NC) and Over-Consolidated (OC) soil. The effective stress ratio, \( \eta \), is defined as the ratio of the deviator stress, \( q \), to the effective stress, \( p' \). Yielding commences for a normally-consolidated soil when \( \eta < M \) and for an over-consolidated soil when \( \eta > M \). The effective stress ratio at the critical state is given by Eq. 39 (Wood, 1990).

\[
q_{cs} / p'_{cs} = \eta_{cs} = M
\]  

\text{(Eq. 39)}

The stress paths that soils negotiate until failure on the Critical State Line (CSL) are dependent on both the loading conditions they experience and the initial state of the material. Four example stress paths are shown in Figure 288 and Figure 289. For an over-consolidated soil, under undrained conditions, the specific volume remains constant throughout loading with the deviator stress increasing to the yield locus, where, after this point is reached, pore suction develops within the soil, thereby increasing the effective stress until failure on the CSL (see Eq. 40).

The second example, also over-consolidated but under drained conditions, follows the overconsolidation line causing a reduction in the specific volume and an increase in the effective stress. This continues until a specific volume is reached that causes the material to dilate until failure occurs on the CSL.

The third example is for a normally-consolidated undrained soil. Similar to the over-consolidated soil, the specific volume remains the same, but positive pore water pressure develops reducing the effective stress until failure on the critical state line. Both these examples start at the same specific volume, and, due to compression occurring under undrained conditions, failure occurs at the same

\[\text{Figure 287} – \text{Effect of coefficient of lateral earth pressure, } K, \text{ on the } q:p' \text{ relationship (figure produced by authors)}\]
effective stress as the effective stress; increasing or reducing being dependent on the pore pressure that develops within the material.

The final stress path, shown in Figure 288, is for a soil that is normally-consolidated and under undrained conditions. For this example, the path begins at the same specific volume as the two previous example stress paths. Under drained conditions, the soils specific volume is reduced, and the effective stress increases. This contractive behaviour continues until failure on the critical state line. The effective stress paths of drained soils increases with a gradient $\delta q / \delta p' = 3$ (Wood, 1990). This unique relationship between the deviator stress, effective stress and specific volume can also be seen in three-dimensional form in Figure 289 where the approximate locations of the Hvorslev and Roscoe surfaces are also shown (Estabragh and Javadi, 2014). The critical state parameters, including $M, \lambda, \Gamma, N$, are necessary for finding the end states in terms of $q:v:p'$ for conventional drained and undrained compression tests.
Figure 288 – Example of the 2D relationship between drained and undrained stress paths for the critical state framework (figure produced by authors)
Figure 289 – Example of the 3D relationship between stress paths for the critical state framework (figure produced by authors)
Understanding that the critical state framework, as explained so far, is in terms of both monotonic and cyclic loading. Figure 290 shows typical phenomena that can also occur during cyclic loading under drained and undrained conditions (Holtz and Kovacs, 1981; Luong, 1979; Wood, 1990).

Liquefaction is described by Holtz and Kovacs, 1981, as a phenomenon whereby shock loading of short duration causes a loose saturated material, such as sand, to lose all bearing capacity and behave like a liquid (or flow). Shock loading can occur during earthquakes, pile driving, blasting and other dynamic events. Under loading, a saturated material attempts to densify and expel moisture from the pores. Under loading of short duration, the material congests the moisture trying to escape, causing the pore water pressure to increase (Holtz and Kovacs, 1981). This induced congestion is related to the permeability of the material.

Cyclic Mobility is similar to liquefaction and is often referred to as liquefaction, even though it occurs in a dense dilative material rather than a loose contractive material. It occurs under undrained conditions when cyclic loading causes an increase in the pore pressure within the material, rather than a decrease, which occurs during monotonic loading (see ‘OC Undrained Stress Path’ in Figure 288) (Holtz and Kovacs, 1981). Cyclic mobility results in limited soil deformation without the liquid-like flow that occurs during liquefaction. During cyclic mobility, the effective stress may reach zero, as shown in Figure 291, but is not always the case. The difference in the $\nu:p'$ plane between liquefaction and cyclic mobility can be seen in Figure 291.

Incremental Collapse occurs under drained conditions when the total permanent strain rate increases rapidly and the failure occurs after a low number of cycles (Werkmeister et al., 2005). Incremental collapse is seen to occur when the cyclic stresses applied are greater than the CSL.

Finally, Shakedown is a phenomenon whereby deformation will eventually cease to occur under cyclic loading, and the total permanent strain reaches equilibrium. Equilibrium is commonly observed relatively early on during loading and failure is unlikely to occur if this phenomenon is observed. All these phenomena are related to the critical state framework of the material.
Figure 290 – Typical phenomena that occur during drained and undrained cyclic loading (figure produced by authors)

Figure 291 – Difference between liquefaction and cyclic mobility in the $v:p'$ plane (figure produced by authors)
Eq. 40 shows that the effective stress, $\sigma'$, of a material is considered to be a function of the normal stress, $\sigma$, and pore water pressure, $u_w$. This equation is termed Terzaghi’s principal of effective stress and was developed during his research on soil consolidation (Terzaghi, 1925, 1943).

$$\sigma' = \sigma - u_w$$  \hspace{1cm} (Eq. 40)

Eq. 41 was also derived by Terzaghi (Terzaghi, 1942) from Coulomb’s equation (Coulomb, 1776), and, in soil mechanics, is commonly referred to as the Mohr-Coulomb failure criterion. It asserts that the shear strength, $\tau$, of a material is a function of its inherent effective stress, internal friction angle, $\phi$, and cohesion, $c$. This equation can also be expressed in terms of the effective stress, as shown in Eq. 42.

$$\tau = c + \sigma \tan \phi$$  \hspace{1cm} (Eq. 41)

$$\tau = c' + \sigma' \tan \phi'$$  \hspace{1cm} (Eq. 42)

During shock loading of short duration, and when the total stresses applied to the material are not directly increased, the pore water pressure increases resulting in the effective stress reducing towards zero (Eq. 40) (Holtz and Kovacs, 1981; Terzaghi, 1925, 1943). During liquefaction, when the stress path intersects the CSL, flow liquefaction occurs with an effective stress close to, but not at zero. On the other hand, cyclic mobility results in an effective stress much lower than commonly experienced during flow liquefaction. The Mohr-Coulomb failure criterion (Eq. 42) shows that, as the effective stress reduces towards zero, there is a similar reduction in the shear strength (Terzaghi, 1942).

Materials undergoing cyclic or monotonic loading can exhibit one of three forms of behaviour shown in Figure 292. These three behaviours are referred to as contractive (strain-softening, steady-state), intermediate (quasi-steady-state) and dilative (strain-hardening). Contractive materials are more likely to fail due to flow liquefaction under cyclic loading, and intermediate materials may show limited signs of liquefaction (G.E. Blight et al., 1999). Liquefaction can also occur under monotonic loading in a material with significantly low permeability; however, under monotonic conditions, the pore pressure needs to be much greater than under cyclic loading (Sladen et al., 1985).
The theory just discussed assumes that the material in question is fully saturated. The theory of liquefaction of unsaturated materials is discussed in a related publication (Munro and Mohajerani, 2017c). In the same publication, a similar sample of iron ore fines undergoing significant vibration exhibited significant moisture migration. Depending on the moisture content, the moisture migrated either towards the top of the sample or towards the base. For the purpose of this study, it has been assumed that due to moisture migration specific layers within the cargo may become saturated. Although not yet proven to be the case, the process of moisture migration, which may cause parts of a cargo of iron ore fines to become saturated, has been tested with the results indicating that there is a potential for this to occur. The analysis will soon be available regarding the outcome of these related tests (Munro and Mohajerani, 2017d).

Other than the critical state approach for the assessment and analysis of liquefaction, others include the traditional approach (Seed and Idriss, 1971), the semi-empirical approach (Byrne, 1991; Martin et al., 1975) and the constitutive modelling approach (Seid-Karbasi and Byrne, 2006).

15.3.4.2 Apparatus
Cyclic triaxial testing was employed during this study to investigate the liquefaction potential of iron ore fines under the simulated conditions that are expected during marine transportation, and to establish if liquefaction as a suspected failure mode is conceivable. Monotonic testing was also performed using the same triaxial apparatus to determine the critical state parameters of the specimen.

The triaxial test is arguably the most flexible geotechnical laboratory test currently available, and, ultimately, allows the stiffness and the strength of soils to be determined under varying stress states.
Triaxial systems apply pressure around three axes while taking advantage of the ability to measure the pore pressure and control drainage simultaneously. Due to the design of the triaxial test, two of the applied principal stresses, $\sigma_2$ and $\sigma_3$, are equal. The principal stresses applied to a specimen during triaxial testing can be seen in Figure 293, and the apparatus used to perform the triaxial tests, IPC Global’s Universal Cyclic Triaxial System (UCTS), can be seen in Figure 294.

$$\text{Major Principal Stress} = \sigma_1 = \sigma_3 + \sigma_q$$

$$\text{Minor Principal Stress (Confining)} = \sigma_2 = \sigma_3$$

*Figure 293 – Stresses applied to the specimen during triaxial testing (this figure was produced by the author for this publication)*

*Figure 294 – IPC Global’s Universal Cyclic Triaxial System (UCTS) employed to perform the monotonic and cyclic triaxial testing*
The main aspects of the UCTS are shown in Figure 295. The apparatus consists of a cylindrical chamber that encloses a specimen and can be filled with a fluid, commonly water. As seen as $\sigma_2$ and $\sigma_3$ in Figure 293, the fluid can be pneumatically pressurized to apply a confining pressure to the specimen. The deviator stress, $\sigma_d$, is applied to the specimen by means of a pneumatic piston rod and the force applied by the piston rod is measured using a submersible load cell located within the chamber. Connected via tubing to the top of the specimen is a volume control device that can monitor the volume change as well as apply a back pressure to the specimen during testing. Additionally, the pore pressure within the specimen is monitored using a transducer connected to the base of the sample.

![Diagram of UCTS apparatus](image)

* Figure 295 – Main aspects of the UCTS used to perform the monotonic and cyclic tests

All the tests performed during this study were done so under saturated drained conditions. The samples were tested while saturated because it has been speculated that during marine transportation, with sufficient cyclic loading, a cargo of iron ore fines may experience moisture migration causing portions to become saturated, specifically, the top Section of the cargo (Munro and Mohajerani, 2017c). The conditions under which moisture migration may occur will be presented in detail in a related publication (Munro and Mohajerani, 2017d).

After directly measuring the permeability of the specimen tested during this study, it was shown that, under the expected range of densities expected on board a bulk carrier, the average hydraulic conductivity was measured to be $2.08 \times 10^{-5}$ m/s. According to Casagrande, a soil with a hydraulic conductivity of $2 \times 10^{-5}$ m/s, or $2 \times 10^{-3}$ cm/s has good drainage (see (Holtz and Kovacs, 1981)). Due to this property of iron ore fines along with the low frequency of loading, as explained later, it seemed appropriate to consider that the material was under drained conditions. If conditions change during
cyclic loading, the sample may become partially undrained, and, therefore, may exhibit the associated behaviours described in Section 15.3.4.1.

The preparation procedure involved calculating the range of relative densities that could be expected in the hold of a bulk carrier and preparing the iron ore fines to these conditions. The samples were compacted in layers into a split mould upon the triaxial pedestal, as seen in Figure 296a. Once sealed within the membrane, the chamber was placed around the sample and filled with water. The sample was then initially manually saturated using the vacuum method (British Standard, 1990). After all possible voids were saturated using this method, the back pressure and confining pressure were increased to 300 kPa and 320 kPa, respectively, over five hours. A constant effective stress of 20 kPa was maintained throughout the saturation stage. After saturation was confirmed using Skempton’s B-Check (British Standard, 1990), testing either monotonically or cyclically could commence.

In this stage, to determine the critical state parameters, monotonic testing was performed after consolidation under varying effective stresses. The results of the monotonic tests can be seen in Section 15.3.5.1. Afterwards, the strengths of the samples under the same range of densities were also determined under cyclic loading to compare the cyclic behaviours with the critical state of the material. The results of the cyclic tests can be seen in Section 15.3.5.2.
The samples that were to undergo cyclic loading were first consolidated at 27 kPa to replicate the conditions within the top 2 m of the cargo. As previously mentioned, it was assumed that moisture migration towards the surface occurs during cyclic loading (Munro and Mohajerani, 2017c). It was therefore assumed for the calculation of the equivalent deviator stress that the saturated layer would extend approximately 2 m from the surface with an approximate bulk density of 2.7 t/m$^3$ (Munro and Mohajerani, 2017c). Following the idea of replicating worst-case conditions, this material, with a low relative density, would have an increased likelihood of liquefying.

The loading that was chosen to be applied to the samples during the cyclic testing was based upon wave data from a significant storm event. Wave data from the Draupner platform in the North Sea on 1 January 1995 was obtained from Sverre Haver and used for the analysis (Haver, 2003). Shown in Figure 297, the raw wave data were converted to the equivalent initial deviator stress based on the maximum vertical acceleration of 6.0 m/s that was estimated by the Iron Ore Technical Working Group (TWG) (Iron Ore Technical Working Group, 2013b). As previously mentioned, the TWG was responsible for the design and implementation of the Modified Proctor/Fagerberg Test (MPFT) (Iron Ore Technical Working Group, 2013a).

![Figure 297 – a) Time-domain chart of wave data (Haver, 2003) and b) calculated equivalent initial deviator stress (depth: 2.0 m, bulk density: 2.7 t/m$^3$)](image-url)

Figure 297 – a) Time-domain chart of wave data (Haver, 2003) and b) calculated equivalent initial deviator stress (depth: 2.0 m, bulk density: 2.7 t/m$^3$)
To simplify the analysis, the raw wave data shown in Figure 297 was not directly used to apply the cyclic loading to the sample. It was decided to initially use the maximum calculated deviator stress of 50 kPa and a frequency of 0.1 Hz for 24 hours (8,640 cycles).

Based on the frequency-domain chart of the wave data presented in Figure 298, it was shown that the majority of waves occur within 0.05 and 0.10 Hz. As the time of loading increases the likelihood that the pore pressure within the sample can dissipate decreases. Based on the theory described in Section 15.3.4.1, the increase in the pore pressure reduces the effective stress, and, therefore, increases the likelihood of liquefaction. Attempting to replicate the worst-case conditions, a frequency of 0.1 Hz was chosen. Additionally, the duration chosen was considered greater than the length of a typical storm event, and, hence, the effect the storm event would have on a vessel. These conditions can also be representative of areas of the cargo undergoing transverse accelerations of the same magnitude.

To observe additional portions of the stress paths of the samples under cyclic loading, if the sample did not meet the failure criteria, the deviator stress was increased by another 50 kPa, and the same frequency and duration of loading was again applied. These increases in deviator stress continued until failure of the sample occurred. As is common in cyclic testing, the sample was considered to have undergone failure once 5% double amplitude permanent axial strain (± 2.5% axial strain) had been reached (American Society for Testing and Materials, 2013; Ishihara, 1993).

15.3.5 Experimental Results
15.3.5.1 Monotonic Loading
Before cyclic testing was performed, three samples underwent monotonic loading until failure under consolidated drained conditions. The results from these three tests enabled the identification of the critical state line (CSL), as described in Section 15.3.4.1. The results from the monotonic tests and graphical representation of the CSL can be seen in Figure 299 and Figure 300. Note, in Figure 300, the sample with the lowest relative density contracts until failure and the two samples with higher relative densities dilate until failure.
Figure 299 – The CSL and stress paths in the q:p’ plane determined from the initial three monotonic drained tests

Figure 300 – The CSL and stress paths in the e:ln(p’) plane determined from the initial three monotonic drained tests

Table 89 – Critical state line parameters of the specimen of iron ore fines used during this study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>2.030</td>
<td>Slope of CSL in the q:p’ plane.</td>
</tr>
<tr>
<td>aλ</td>
<td>0.103</td>
<td>Slope of the CSL in the v:ln(p’) plane.</td>
</tr>
</tbody>
</table>
Chapter 15 - Simulating Marine Transportation using a Cyclic Triaxial to Determine the Liquefaction Potential of Iron Ore Fines

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma$</td>
<td>1.217</td>
<td>Location of the CSL in the $\ln(p')$ plane.</td>
</tr>
<tr>
<td>$\phi'$</td>
<td>49°</td>
<td>Critical state angle of shearing resistance.</td>
</tr>
<tr>
<td>$k$</td>
<td>0.004</td>
<td>Slope of OCL in the $\ln(p')$ plane.</td>
</tr>
</tbody>
</table>

* Unlikely to be the slope of the NCL due to the granular nature of the material; therefore, NCL unobtainable with the current results.

The critical state parameters determined from the monotonic tests and used to create the CSL shown in Figure 299 and Figure 300 are given in Table 89. As discussed, the CSL depicts the ultimate conditions that occur for the failure of the cargo within the hold of a bulk carrier based on the initial state of the cargo, loading conditions and stress path. By comparing these results to those from the cyclic triaxial testing, the most likely mode of failure that would occur during cyclic loading can be determined.

15.3.5.2 Cyclic Loading

Cyclic triaxial tests were performed on samples of iron ore fines to verify their final relationship to the critical state framework. These cyclic tests simulated the loading conditions expected in the hold of a bulk carrier during marine transportation. To identify the samples of iron ore fines that were tested, each was given a unique identifier. The identification of each of the samples and the properties before, during and after cyclic testing are given in Table 90. The results from sample B can be seen in Section 15.3.8. All the samples exhibited a similar behaviour.

| Table 90 – Identification of the samples tested along with their respective stress paths |
|-----------------|-----------------|--------|--------|--------|--------|
| Stage           | Sample Identification | A  | B  | C  | D  | E  |
|-----------------|-----------------|--------|--------|--------|--------|
| Initial         | Void Ratio, $e_0$ | 0.560 | 0.655 | 0.714 | 0.764 | 0.807 |
| Consolidation   | Void Ratio ($p'_c = 27$ kPa), $e_c$ | 0.559 | 0.649 | 0.699 | 0.756 | 0.798 |
| 1               | Deviator Stress, $q_{1s}$ (kPa) | 55  | 57  | 55  | 57  | 27   |
|                 | Mean Effective Stress, $p'_{1s}$ (kPa) | 48  | 45  | 48  | 49  | 33   |
|                 | Void Ratio, $e_{1s}$ | 0.557 | 0.642 | 0.691 | 0.731 | 0.795 |
|                 | Mean Effective Stress, $p'_{1s}$ (kPa) | 106 | 102 | 102 | 106 | -    |
| 2               | Deviator Stress, $q_{2s}$ (kPa) | 66  | 62  | 63  | 66  | -    |
|                 | Mean Effective Stress, $p'_{2s}$ (kPa) | 66  | 62  | 63  | 66  | -    |
|                 | Void Ratio, $e_{2s}$ | 0.555 | 0.639 | 0.686 | 0.731 | -    |
|                 | Mean Effective Stress, $p'_{2s}$ (kPa) | 156 | 157 | 153 | -    | -    |
| 3               | Deviator Stress, $q_{3s}$ (kPa) | 156 | 157 | 153 | -    | -    |
|                 | Mean Effective Stress, $p'_{3s}$ (kPa) | 82  | 80  | 82  | -    | -    |
|                 | Void Ratio, $e_{3s}$ | 0.555 | 0.631 | 0.693 | -    | -    |
|                 | Mean Effective Stress, $p'_{3s}$ (kPa) | 208 | 209 | -   | -    | -    |
| 4               | Deviator Stress, $q_{4s}$ (kPa) | 208 | 209 | -   | -    | -    |
|                 | Mean Effective Stress, $p'_{4s}$ (kPa) | 100 | 101 | -   | -    | -    |
|                 | Void Ratio, $e_{4s}$ | 0.556 | 0.639 | -   | -    | -    |
|                 | Mean Effective Stress, $p'_{4s}$ (kPa) | 261 | -   | -   | -    | -    |
| 5               | Deviator Stress, $q_{5s}$ (kPa) | 261 | -   | -   | -    | -    |
|                 | Mean Effective Stress, $p'_{5s}$ (kPa) | 119 | -   | -   | -    | -    |
|                 | Void Ratio, $e_{5s}$ | 0.559 | -   | -   | -    | -    |
|                 | Mean Effective Stress, $p'_{5s}$ (kPa) | 321 | -   | -   | -    | -    |
| 6               | Deviator Stress, $q_{6s}$ (kPa) | 321 | -   | -   | -    | -    |
|                 | Mean Effective Stress, $p'_{6s}$ (kPa) | 141 | -   | -   | -    | -    |
|                 | Void Ratio, $e_{6s}$ | 0.566 | -   | -   | -    | -    |

It is first to be noted that there were no signs of liquefaction or cyclic mobility, as described in Section 15.3.4.1 and depicted in Figure 290. This was not unexpected due to the high permeability of iron ore fines coupled with the low frequency and amplitude of loading. This combination was predicted to cause near immediate dissipation of any pore pressure.

Figure 301 and Figure 302 show graphical representations of the stress paths the samples navigated during the drained cyclic triaxial tests. In Figure 302, the maximum deviator stresses experienced during each stage of loading, along with the respective mean effective stress, are plotted against the
CSL determined during the drained monotonic triaxial tests. A line of best fit has been plotted through these points to depict the average drained cyclic stress path.

By referring to the theory discussed in Section 15.3.4.1, we can break down the behaviours exhibited by the samples. As shown in Figure 301, all the samples were first isotropically-consolidated at 27 kPa. After this point, cyclic loading began. Each point after consolidation represents the void ratio after the respective stage of cyclic loading. As specified in Section 15.3.4.2, each cyclic stage continued for 24 hours (8,640 cycles) with 50 kPa increments in deviator stress until the failure criteria were met. The CSL determined during the drained monotonic triaxial testing is also shown in this figure.

The sample tested during this study with the lowest relative density, sample E, did not survive any stages of cyclic loading. This sample reached the failure criteria immediately after the cyclic testing began. The sample’s behaviour is similar to that of the ‘OC Drained Stress Path’ in Figure 288, which initially follows the over consolidation line in the e:p’ plane, while the effective stress is increasing at a ratio of approximately 3 to 1 in the q:p’ plane, then experiences dilation until failure once the yield locus is met. The initial stages of this behaviour can also be seen in Figure 302.

Figure 301 – CSL and cyclic stress paths of the samples in the e:ln(p’) plane
Sample D shows a change in behaviour when compared to sample E. Sample D exhibits the largest reduction in void ratio during testing. Since the sample was able to survive the first stage of cyclic loading at 50 kPa, it had a chance to densify due to what is assumed to be particle rearrangement. When the deviator stress was increased to 100 kPa the magnitude and extent of the suction within the sample increased enough to cause the sample to dilate until the failure criteria were met.

Sample C and B both show similar behaviour to sample D with dilation occurring just before the failure criteria were met. An example of the relationship between the void ratio and deviator stress during cyclic loading can be seen in Figure 303 along with the respective pore pressure that developed within the sample seen in Figure 304. Figure 303 shows that a steady state would likely have been reached during the 50 kPa stage if cyclic loading was continued due to the continuous dissipation of negative pore pressure, as seen in Figure 304. A similar state, although over a much longer period of time, may have been reached during the 100 kPa stage.

Figure 302 – CSL and average drained cyclic stress path in the q:ln(p') plane (the maximum deviator stress reached before failure criteria was met is marked for each sample)
Sample A, which has the highest relative density, exhibits steady state behaviour during each stage of cyclic loading until 250 kPa deviator stress is applied. This is due to its high initial density; a steady
state has been reached, or shakedown can be said to be occurring during the stages where no change in void ratio is recorded. After the deviator stress is increased to 250 kPa, the sample exhibits an increasingly dilative behaviour similar to samples B, C and D.

Based on the results, it is assumed that until dilation is observed, the sample would continue towards a steady state, or shakedown, under the applied deviator stress. During these stages, failure would never occur, and the CSL would never be reached if cyclic loading was continued indefinitely. Failure ultimately begins when dilative behaviour is observed. The dilative behaviour causes the stress path to navigate towards the CSL due to the increase in the void ratio where failure would occur. As described in Section 15.3.4.1 and shown in Figure 290, this behaviour can be more accurately described as incremental collapse.

Since liquefaction or cyclic mobility was not observed, comparison of the conditions under which incremental collapse occurs can be compared to the conditions expected during marine transportation. Figure 305 shows the Cyclic Stress Ratio (CSR) based on the deviator stress and mean effective stress that caused dilation of the samples, which is assumed to cause failure.

As part of the development of the Modified Proctor/Fagerberg Test (MPFT), as described in the introduction, the TWG performed numerical analysis to determine the induced CSR within a cargo of iron ore fines. It was concluded that, during a 14-day voyage, the sub-surface of a cargo or iron ore fines would not experience a CSR of greater than 0.4 over 10 wave cycles in the worst conditions. It was also shown by the TWG that the relative density of a cargo of iron ore fines was comparatively low during the initial stages of the voyage, being approximately 20 – 40 % at 12 m depth (Iron Ore Technical Working Group, 2013c).

With this in mind, it is considered likely that partial dilation of the cargo may occur during the initial stages of transportation under rough sea states. This may possibly lead to incremental collapse of the cargo if the cycles are great enough but is unlikely to result in liquefaction.
15.3.6 Discussion
The assumption made during this research is that the top portion of a cargo, which is considered drained due to the physical properties of iron ore fines, becomes saturated during marine transportation due to moisture migration. This assumption has been investigated with results indicating that this is indeed a possibility, as seen in Figure 306 (Munro and Mohajerani, 2017d).

![Figure 306 – Before and after cyclic loading during scale model testing showing moisture migration (Munro and Mohajerani, 2017d)](image)

The commonly recognised definition of liquefaction states that, under cyclic loading, liquefaction may occur during shock loading of short duration (Holtz and Kovacs, 1981). It has been shown in this study, as well as by the TWG, that during a significant storm event, the maximum frequency of loading is approximately 0.1 Hz (Iron Ore Technical Working Group, 2013b, 2013c). Comparing this to the typical seismic frequency during earthquakes (0.2 Hz to 20 Hz), during which liquefaction commonly occurs, this, to us, is not comparable to shock loading.

With this said, liquefaction may not be the correct definition of the failure mode of the cargo that is causing bulk carriers to founder (Munro and Mohajerani, 2016a). Described in Section 15.3.4.1, there are three main failure modes to consider under cyclic loading. Liquefaction, cyclic mobility or incremental collapse. All of which, if they occur, may cause instability in a bulk carrier.

Liquefaction and cyclic mobility are phenomena that occur commonly under undrained conditions. Since the cyclic tests that were performed under drained conditions, it was unlikely, but not improbable, that these failure modes would occur. If the loading frequency and amplitude were sufficient enough to cause undrained behaviour, these phenomena might have been seen. In this case, there were no signs of liquefaction or cyclic mobility of any of the samples tested. Increased loading may have caused liquefaction under undrained conditions, but this action simply resulted in incremental collapse of the samples as they dilated towards the critical state line.

Taking into account that the testing performed during this study was considered under worst-case conditions, if typical conditions were encountered on board a bulk carrier, the likely result is shakedown of the cargo, meaning no permanent deformation would occur.
The main questions resulting from this study concern whether this (or any) cargo of iron ore fines can be considered undrained under cyclic loading representative of real life conditions. The cyclic stress ratio at failure will significantly reduce under undrained conditions resulting in a material much more likely to dilate and develop excess pore pressures, which could result in either liquefaction or cyclic mobility.

One way for undrained conditions to occur is for the cargo to have a reduced permeability, thus allowing the build-up of pressure within the cargo. It may be possible that significant segregation may occur during transportation, thereby leading to areas of highly liquefiable material. Segregation may come hand in hand with moisture migration, which was assumed during this study to lead to saturated portions of the cargo. The results shown in Figure 302 indicate no build-up of pore pressures within the sample, as a whole, as all the stress paths taken is typical of that of a sample that is drained, that is having a slope of approximately 3:1.

Finally, it is considered that the relationship between the Modified Proctor/Fagerberg Test (MPFT) Transportable Moisture Limit (TML) is more or less incomparable to the liquefaction potential of iron ore fines. As shown in Section 15.3.4.1, the strength of a material under cyclic loading is complicated. It cannot be defined by one parameter, such as the TML. Specifying a maximum moisture content for a cargo will limit the overall moisture content to a point, other variables that influence liquefaction of materials are more likely to dominate the potential for it to occur. This may include permeability, particle size, particle shape, density, and other physical and system variables.

15.3.7 Conclusion
The objective of this study was to utilize a cyclic triaxial to investigate if liquefaction is the probable cause, as suspected by some industry and research associations, for the foundering of bulk carriers while transporting iron ore fines. To achieve this, the strength parameters of a specimen of iron ore fines were compared against the behaviour of the material under cyclic loading, which was representative of the conditions during marine transportation.

Under the conditions tested during this study, there were no signs of liquefaction. It has been concluded from this study that liquefaction of the specimen of iron ore fines obtained and tested is highly unlikely to occur under the expected loading conditions that a cargo may experience during marine transportation. If the assumptions made during this study are representative of real life conditions, it is much more likely that another type of failure is the cause of the suspected liquefaction incidents.

Further research is required to determine the likelihood that moisture migration may cause segregation of finer particles within the cargo. This process may lower permeability in areas, thereby causing them to have a higher potential to liquefy.
15.3.8 Appendix A – Typical Cyclic Triaxial Results

Results for sample B from the cyclic triaxial testing.

Figure 307 – Stress path of sample B in the q:p’ plane during final stage of cyclic loading
Figure 308 – $q$ vs $\varepsilon$ plot of sample B during final stage of cyclic loading

Figure 309 – Excess pore pressure against strain for sample B during final stage of cyclic loading
Figure 310 – ΔV-ε plot of sample B during final stage of cyclic loading
15.4 SUPPLEMENTARY RESULTS AND FIGURES

The supplementary results for the manuscript presented in Chapter 15 are given in Appendix F.

15.5 SUMMARY AFTER THE FACT

The manuscript presented in this chapter analysed the behaviour of iron ore fines under simulated conditions representing those expected during marine transportation. The results from this study indicated that although there were signs of failure of the samples, there were no signs of liquefaction even at stresses well exceeding those expected during marine transportation.

In order to define the conditions under which iron ore fines may liquefy, research was continued using the now completed scale model apparatus. This apparatus does not use the calculated frequency and magnitude of cyclic loading expected during marine transportation, but a frequency and magnitude likely to result in liquefaction of the specimens, if at all possible.
CHAPTER 16 SCALE ANALYSIS OF THE BEHAVIOUR OF IRON ORE FINES UNDER CYCLIC LOADING FOR THE PREVENTION OF LIQUEFACTION DURING MARINE TRANSPORTATION

16.1 INTRODUCTION

The following manuscript includes results from the now completed scale model. Additional to the previous aspects incorporated into the apparatus, were pore pressure transducers and resistivity probes. The pore pressure transducers were included to measure both the pore air and water pressure during the cyclic loading. This new addition would allow the determination of the effective stress within the samples to indicate if liquefaction was occurring.

The resistivity probes, on the other hand, were used to determine if there was a relationship between the measured pore pressure from the transducers to the resistivity measured through the sample. This aspect of research is anticipated to continue into the future.

Exclusions made from this manuscript and not included in this chapter are the list of references, abbreviations, and acknowledgments. The references, abbreviations, and acknowledgments are combined on page 465, xxxvi and iv with all the other references, abbreviations, and acknowledgments included within this document to prevent duplication.

It is noted that only minor changes have been made to this manuscript for its inclusion in this document. The differences are that with the referencing and caption style, whereby modifications may have been made to create uniformity within the current document. Additionally, the figure, table and equation numbering may differ due to them being made continuous throughout this document.

16.2 CITATION

16.3 MANUSCRIPT CONTENTS

16.3.1 Abstract
With the marine transportation of solid bulk cargoes on bulk carriers comes specific hazards related to the task. One unexpected hazard is the liquefaction of the cargo. Liquefaction is a phenomenon whereby a shock loading of short duration causes a commonly loose saturated material to flow like a liquid. Over the past 30 years, there have been 23 incidents in which liquefaction of the solid bulk cargo was the suspected cause of a bulk carrier foundering. The Modified Proctor/Fagerberg Test (MPFT), which is specifically designed for iron ore fines, produces what is referred to as the Transportable Moisture Limit (TML). The TML is a safe moisture content under which a cargo is considered unable to liquefy while undergoing marine transportation. The objective of this study is to design and construct a scale model to test the conditions under which iron ore fines may liquefy, and to monitor the changes that occur within the material that may adversely affect the stability of the cargo during marine transportation. The parameters that are believed to influence the liquefaction potential of iron ore fines, including pore air and water pressure, moisture migration, segregation as well as other changes in physical properties, are monitored and compared to the TML from the MPFT. This study concludes that moisture migration caused by an increase in the pore pressure within the material causes segregation of the material to occur. This process creates portions of the sample that are much more likely to liquefy than the sample as a whole. The moisture content where this begins takes place is 1.5% less than the MPFT TML. Overall, it is considered that the TML as a parameter to indicate liquefaction is inadequate, as liquefaction is much more complicated and cannot be predicted one factor.

16.3.2 Introduction
With the marine transportation of solid bulk cargoes on bulk carriers comes specific hazards related to the task. One unexpected hazard is the liquefaction of the cargo. Described in more detail in related publications (Munro and Mohajerani, 2017c, 2017e) this is a phenomenon whereby shock loading of short duration causes a commonly loose saturated material, such as sand, to lose all bearing capacity and flow like a liquid (Holtz and Kovacs, 1981). During marine transportation, it is said that shock loading can be transferred through the structure of the bulk carrier to the cargo from ocean waves under varying sea states (Iron Ore Technical Working Group, 2013b).

Over the past 30 years, there have been 23 incidents in which liquefaction of the solid bulk cargo was the suspected cause of foundering of a bulk carrier. Of these 23 incidents, 17 vessels were lost and 138 people perished (Munro and Mohajerani, 2016a, 2017b). Although these incidents involved a number of different types of cargo, including nickel ore, bauxite and manganese, the cargo focussed on in this study, which was being transported in 30% of the aforementioned incidents, is iron ore fines.

In 2011, a code of safe practice which is to be followed when transporting hazardous solid bulk cargoes became mandatory (International Maritime Organization MSC85/26/Add.2, 2008). This code, known as the International Maritime Solid Bulk Cargoes Code (IMSBC Code), is amended and re-published by the International Maritime Organisation (IMO) on a regular basis (International Maritime Organization, 2016).

In Appendix 2 of the IMSBC Code, the Modified Proctor/Fagerberg Test (MPFT) is specified, which is a test that must be performed on a cargo of iron ore fines that is to be shipped via bulk carrier. The
MPFT, which is specifically designed for iron ore fines, produces what is referred to as the Transportable Moisture Limit (TML). The TML is inferred by the code as being the maximum moisture content that the cargo may contain at which it is considered unable to liquefy while undergoing marine transportation. More information on the introduction and history of the MPFT, related test methods and IMSBC Code can be seen in related publications (Munro and Mohajerani, 2014, 2015, 2016b, 2016c).

This publication has been created to standalone, but the preliminary concept, creation and implementation of the scale model that is presented herein, can be seen in two related publications (Munro and Mohajerani, 2016d, 2017c).

The objective of this study is to design and construct a scale model to test the conditions under which iron ore fines may liquefy and to monitor changes that occur within the material that may adversely affect the stability of the cargo during marine transportation. The parameters that are monitored include the pore air and water pressure, moisture migration, and segregation, as well as the changes in physical properties, such as density, degree of saturation and resistivity. All the parameters that are monitored are believed to influence the liquefaction potential of iron ore fines and are compared to the TML produced by the MPFT.

16.3.3 Material and Method

16.3.3.1 Material

The specimen of iron ore fines tested during this study was chosen due to it being representative of typical cargoes of iron ore fines that commonly undergo marine transportation on bulk carriers (Munro and Mohajerani, 2015). The physical properties of iron ore fines can be seen in Table 91.

Table 91 – Physical properties of the iron ore fines specimen used during this study

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard/ Apparatus</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen Identification</td>
<td>N/A</td>
<td>MA004</td>
</tr>
<tr>
<td>Modified Proctor/Fagerberg TML</td>
<td>MSC 95/22/Add.2 (International Maritime Organization, 2015e)</td>
<td>10.9% GWC or 12.2% NWC at 80% Saturation (OMC occurring at 96% Saturation)</td>
</tr>
<tr>
<td>Maximum Dry Density</td>
<td>AS1289.5.5.1 (Standards Australia, 1998)</td>
<td>2.76 t/m³ (e = 0.50)</td>
</tr>
<tr>
<td>Minimum Dry Density</td>
<td>AS1289.5.5.1 (Standards Australia, 1998)</td>
<td>2.18 t/m³ (e = 0.90)</td>
</tr>
<tr>
<td>Atterberg Limits</td>
<td></td>
<td></td>
</tr>
<tr>
<td>* Liquid Limit</td>
<td>AS1289.3.1.2 (Standards Australia, 2009a)</td>
<td>17% NWC</td>
</tr>
<tr>
<td>* Plastic Limit</td>
<td>AS1289.3.2.1 (Standards Australia, 2009b)</td>
<td>16% NWC</td>
</tr>
<tr>
<td>* Plasticity Index</td>
<td>AS1289.3.3.1 (Standards Australia, 2009c)</td>
<td>1% NWC</td>
</tr>
<tr>
<td>d Particle Size Distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravel (&gt;2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>51%</td>
</tr>
<tr>
<td>Sand (75 μm – 2.36 mm)</td>
<td>AS1289.3.6.1 (Standards Australia, 2009d)</td>
<td>38%</td>
</tr>
<tr>
<td>Silt (2 μm – 75 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>9%</td>
</tr>
<tr>
<td>Clay (&lt;2 μm)</td>
<td>Mastersizer Aero 3000 (International Standards Organization, 2009)</td>
<td>1%</td>
</tr>
<tr>
<td>Classification</td>
<td>AS1726 (Standards Australia, 1993)</td>
<td>Poorly graded gravel to silty gravel (GP-GM)</td>
</tr>
<tr>
<td>Particle Density, Gs</td>
<td>AS1289.3.5.1 (Standards Australia, 2006)</td>
<td>4.15 t/m³</td>
</tr>
<tr>
<td>Hydraulic Conductivity, K</td>
<td>AS1289.6.7.1 (Standards Australia, 2001b)</td>
<td>2.08 x10⁻⁵ m/s</td>
</tr>
<tr>
<td>Quantitative X-Ray Diffraction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Haematite (Fe₂O₃)</td>
<td>X’Pert Pro PW3040</td>
<td>36% Total Weight</td>
</tr>
<tr>
<td>Goethite (FeOOH)</td>
<td>X’Pert Pro PW3040</td>
<td>62% Total Weight</td>
</tr>
</tbody>
</table>
The percentage of moisture is reported according to the relevant standard first (i.e. NWC or GWC). In geotechnical engineering and soil mechanics, the Net Water Content (NWC) is commonly used, whereas, in most other cases, including metallurgy and marine transportation, the Gross Water Content (GWC) is favoured. NWC is referred to as the percentage of moisture to dry material, while GWC is the percentage of moisture to wet material; hence, net and gross. Throughout the rest of this publication GWC is used.

According to MSC 95/22/Add.2, if a cargo of iron ore fines has more than 35% goethite total weight, then the schedule for iron ore is to be followed, and, therefore, the cargo does not need to undergo testing using the Modified Proctor/Fagerberg method, as it is considered unable to liquefy (International Maritime Organization, 2015e).

The Modified Proctor/Fagerberg test compaction curve and TML for this specimen of iron ore fines can be seen in Figure 284.

The particle size distribution for this specimen of iron ore fines can be seen in Figure 285.

![Figure 311 – Modified Proctor/Fagerberg test compaction curve and TML of the specimen of iron ore fines used during this study](image_url)
16.3.3.2 Method
16.3.3.2.1 Theory
Liquefaction is a phenomenon that frequently occurs during earthquakes of significant magnitude. Seismic activity causes pressure within certain types of soil to increase resulting in a flow like behaviour of the material. This is the same behaviour that may be experienced by a cargo undergoing marine transportation, where the sea states being traversed, rather than seismic activity, are responsible for the cyclic loading.

Liquefaction is more commonly seen in less permeable saturated materials. A more direct transfer of pressure is experienced from particles through fluid, such as water, whereas air acts as a buffer that allows pressure to dissipate over the time taken for the transfer of pressure through the entrained air. With this said, unsaturated materials are also liable to liquefy under certain circumstances.

Discussed in more detail in the preliminary paper related to this topic (Munro and Mohajerani, 2017c), the shear strength of a soil is directly influenced by the effective stress of the material, and, therefore, pore pressure within the particles. In soil mechanics, and as seen in Eq. 43, the Mohr-Coulomb failure criterion (Coulomb, 1776; Terzaghi, 1942) expresses that the shear stress, $\tau$, of a soil is a function of the effective stress, $\sigma'$, friction angle, $\phi'$, and the cohesion factor, $c'$:

$$\tau = \sigma' \tan \phi' + c'$$  \hspace{1cm} ( Eq. 43 )

This expression illustrates that, in a cohesionless material, where $c' = 0$, there is a direct relationship between the effective stress and the shear strength of a soil. A reduction in the effective stress will result in reduced shear strength. The expression to determine the effective stress of an unsaturated
material is shown in Eq. 44. This equation, suggested by Bishop (Bishop, 1959), shows the relationship between the pore air, \( u_a \), and water, \( u_w \), pressure, and the effective stress.

\[
\sigma' = \sigma - u_a + \chi (u_a - u_w)
\]

(Eq. 44)

The expression relates the effect that the pore pressure has on the effective stress related to the current saturation of the material. The parameter, \( \chi \), is a value between 0 and 1 that relates to the degree of saturation. When fully saturated, \( \chi = 1 \), and Eq. 44 can be rewritten as Eq. 45. This shows, as previously stated, the increased effect that pore pressure can have on the effective stress of a saturated material.

\[
\sigma' = \sigma - u_w
\]

(Eq. 45)

Table 82 provides a summarized version of the classification system by Robertson and Fear to define soil liquefaction (Rauch, 1997; Robertson and Fear, 1996). There are two main types of liquefaction to be acknowledged based upon the reduction of the effective stress caused by the changing pore pressure within the soil. Flow liquefaction can occur under the conditions of reduced effective stress that is caused by cyclic loading increasing the pore water pressure, which exceeds the normal stress, \( \sigma \), experienced by the soil. This condition of perfect plastic flow is commonly referred to as liquefaction. Also, referred to as liquefaction but occurring under slightly different conditions is cyclic liquefaction. In this case, under cyclic loading, the effective stress is reduced to zero causing large deformations.

<table>
<thead>
<tr>
<th>Flow Liquefaction</th>
<th>Cyclic Softening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Used to describe the undrained flow of a saturated, contractive soil when the static shear stress exceeds the residual strength of the soil. Failure may be triggered by cyclic or monotonic shear loading.</td>
<td>Used to describe large deformations occurring during cyclic shear due to pore pressure build-up in soils that would tend to dilate in undrained, monotonic shear. Cyclic softening, where deformations do not continue after cyclic loading, can be further classified as:</td>
</tr>
<tr>
<td>Cyclic Liquefaction</td>
<td>Cyclic Mobility</td>
</tr>
<tr>
<td>Occurs when cyclic shear stresses exceed the initial, static shear stress to produce a stress reversal. A condition of zero effective stress may be achieved during which large deformations may occur.</td>
<td>Occurs when cyclic loads do not yield a shear stress reversal and a condition of zero effective stress does not develop. Deformations accumulate in each cycle of shear stress.</td>
</tr>
</tbody>
</table>

One parameter of a soil that heavily affects the rate of dissipation of pore pressure under cyclic loading, and, therefore, the liquefaction potential, is the hydraulic conductivity or permeability. The permeability is the ease with which water can flow through the pores of a soil. Direct measurements of the permeability of the sample used during this study was shown to be \( 2 \times 10^{-5} \) m/s, or \( 2 \times 10^{-3} \) cm/s. This value is indicative of a soil that has good drainage (Holtz and Kovacs, 1981). The less drainage, the more likely that pore pressure can build within the soil.

A major influence on the permeability of a soil is the particle size distribution. A comparison is shown in Figure 313 between the boundaries of varying types of liquefiable material (Ishihara, 1985; National Research Council, 1985) along with the particle size distribution of the sample of iron ore fines tested during this study.
According to the boundaries for liquefiable soils, it can be seen that only approximately 10% of the mass of this sample of iron ore fines is considered to fall within the range of most liquefiable soils, and that approximately 35% fall within the range of potentially liquefiable. It was assumed that this percentage of liquefiable particles may not be particularly significant.

The assumption made, resulting in the direction this study has progressed, is that due to the permeability, which is considered to have good drainage, moisture migration occurs leading to segregation by means of fine particles being transported to the areas of the cargo along with the moisture. These areas with a higher moisture content and finer particles were assumed to have a permeability that is reduced, and, along with the reduction in air voids, an increased likelihood of being potentially liquefiable.

16.3.3.2.2 Apparatus

The scale model described in this Section was designed and constructed specifically for this study for the testing of iron ore fines. The model consisted of a base constructed from 10 mm thick steel along with 20 mm acrylic making up the scale cargo hold, or mould. The dimensions used for the mould, which can be seen in Figure 314, were 410 mm wide, 293 mm deep and 250 mm high. These proportions were based upon the hold of a typical Capesize bulk carrier, as this subclass of bulk carrier was found to transport approximately 92% of iron ore by tonnage in 2012 (Iron Ore Technical Working Group, 2013b, 2013c). The final ratio of the mould to the chosen cargo hold was approximately 1:85.
The main features incorporated into the mould are the tensiometers. The tensiometers, which are placed at three different heights, are used to record the pore air and water pressures within the sample of iron ore fines during vibration. The tensiometers were modified so that either the pore air or pore water pressure was measured by the transducers. This was achieved by using different types of filter medium, as seen in Figure 315. Since, in an unsaturated soil, the pore air pressure is commonly greater than the pore water pressure (Fell et al., 2014), high air entry ceramic tips were attached to the end of the tensiometers that were to measure pore water pressure. Once saturated with air free water, the ceramic tip prohibits the entry of air into the tensiometer, thus only measuring pore water pressure. The width of the pores in the ceramic (w in Figure 315) effects the air pressure required to enter the tensiometer. The strength of the meniscus of the fluid is increased or decreased based on the width of these pores. The air entry value of the ceramic tips used was 100 kPa. This is much higher than the pressure expected during the tests.
To measure the pore air pressure, low air entry porous bronze discs were used instead of the high air entry ceramic tips. The porous bronze discs allowed the entry of air into the tensiometer. Pressure ($P$ in Figure 315) in the fluid is transmitted to the air within the tensiometer, consequently, the pore pressure of the fluid is not measured by the transducer but the pore air pressure. Eq. 46 shows the relationship of pore air and water pressure to the total pressure within the pores of the material. This is part of the equation to determine the effective stress of an unsaturated material (Eq. 44). In most static situations, the pore air pressure is zero (atmospheric); therefore, matric suction, ($u_a - u_w$), can be measured directly using only a tensiometer with a high air entry ceramic tip.

\[ u = u_a + \chi (u_a - u_w) \]  

\text{(Eq. 46)}

The tensiometers that were used were 2100F soil column tensiometers. Three of the tensiometers were left unmodified with the ceramic tips that were supplied left attached, with the other three being modified with the previously explained bronze porous plates. These were filled with de-aired water and the tips left to saturate before use. GT3-15 transducers were used to measure the water within the tensiometers. Figure 316 shows the tensiometers to the right of the bench with the transducers attached. Voltage sensor loggers were used to log the data from the transducers, which could be accessed by a laptop. All the aforementioned equipment was obtained from ICT International.

Also obtained from ICT International was what we refer to as resistivity probes, but with this said, the MP306 probes are supplied as moisture probes, which are used to determine the change in moisture...
content of a static soil over a range of moisture contents. These four probes, which were evenly spaced from top to bottom on the rear of the mould, were also connected to voltage sensor loggers. The purpose of the probes was to determine if there was a relationship between the resistivity output by the probes and the pore pressure monitored by the transducers.

Additional features include the drainage system, which was included to replicate the cargo hold bilge areas that are used to store excess water from the cargo hold before being evacuated overboard (Plant Export Operations Branch, 2014). Also, five 6 mm thick x 50 mm high front panels, which could be removed individually, were used to sample the iron ore fines at varying heights after completion of the test.

The scale model, seen in Figure 314, was placed on a vibrating table, which is typically used in soil mechanics to determine the minimum and maximum dry density of a cohesionless material (Standards Australia, 1998). The vibrating table was able to be operated at a nominal frequency of 50 Hz and a vertical double amplitude (peak to peak) setting of 0.5 ± 0.05 mm. It is to be noted that although the apparatus was designed to replicate the actual drainage and constraints of a bulk carrier cargo hold, the vibrations applied to the mould simply induce conditions under which liquefaction is most likely to occur (i.e. worst-case scenario). The complete installation of equipment used to perform the scale model tests can be seen in Figure 316 and Figure 317.
16.3.3.2.3 Procedure

The procedure used to conduct the scale model tests included preparation, placement, monitoring, and sampling of the test specimen. Approximately 70 kg of the sample was needed per test in order to completely fill the mould. During each test, a total of approximately 6 kg was taken in order to obtain the physical properties of the sample as a whole and per layer. Therefore, approximately 130 kg of material was needed for this study.

The samples were prepared and tested in order from those containing the least moisture to the those containing the most. The day prior to testing, the sample was adjusted to the specified moisture content and left to cure overnight. When ready to test, the sample was carefully scooped into the mould making sure to envelop the tensiometers, which, at this stage, were deaired and fully saturated. Once filled, the sample was levelled to entirely fill the volume of the mould. A typical sample prior to testing can be seen in Figure 318.
After placement, the drainage valves were opened, photos were taken and scale rulers were placed on the surface to monitor the change in height. The data logging devices were then started along with the vibrating table. Vibration, at a nominal frequency of 50 Hz and a vertical double amplitude (peak to peak) setting of $0.5 \pm 0.05\text{ mm}$, was continued without interruption for exactly 7200 seconds (2 hours). It was chosen to end the test after 2 hours of vibration as preliminary testing showed that the volume of the sample would show no significant changes after this amount of time (Munro and Mohajerani, 2017c).

Once vibration ceased, in sequence from top to bottom, the front panels of the mould were removed, along with the sample equivalent to the height of the panel. From each of these layers, a sample for the determination of moisture content and particle size distribution was taken. This procedure was repeated for nine separate samples at varying moisture contents.

### 16.3.4 Experimental Results

To identify the samples tested, each was given a unique identifier. This identifier, along with the initial and final properties of the samples, are given in Table 90. The samples were labelled in order based on the final gross water content measured. Approximate logarithmic interpolation was performed to estimate the rate of change of total moisture within the sample during the tests based on the initial and final measured moisture contents.

#### Table 93 – Identification of the samples tested along with their overall physical properties during the tests

<table>
<thead>
<tr>
<th>Stage</th>
<th>Sample Identification</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>Gross Water Content, $w_{G(i)}$ (%)</td>
<td>5.8</td>
<td>7.1</td>
<td>8.4</td>
<td>8.9</td>
<td>11.3</td>
<td>10.8</td>
<td>11.0</td>
<td>11.4</td>
<td>11.8</td>
</tr>
<tr>
<td></td>
<td>Void Ratio, $e_{(i)}$</td>
<td>1.24</td>
<td>1.28</td>
<td>1.19</td>
<td>1.13</td>
<td>1.06</td>
<td>1.01</td>
<td>0.92</td>
<td>0.83</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>Dry Density, $\rho_{(i)}$ (t/m$^3$)</td>
<td>1.86</td>
<td>1.82</td>
<td>1.89</td>
<td>1.95</td>
<td>2.01</td>
<td>2.07</td>
<td>2.16</td>
<td>2.27</td>
<td>2.17</td>
</tr>
<tr>
<td></td>
<td>Degree of Saturation, $S_{(i)}$ (%)</td>
<td>21</td>
<td>25</td>
<td>32</td>
<td>36</td>
<td>50</td>
<td>50</td>
<td>56</td>
<td>65</td>
<td>61</td>
</tr>
<tr>
<td>Final</td>
<td>Gross Water Content, $w_{G(f)}$ (%)</td>
<td>5.8</td>
<td>7.1</td>
<td>8.4</td>
<td>8.9</td>
<td>9.4</td>
<td>9.5</td>
<td>10.3</td>
<td>10.9</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>Void Ratio, $e_{(f)}$</td>
<td>1.04</td>
<td>0.97</td>
<td>0.75</td>
<td>0.72</td>
<td>0.59</td>
<td>0.57</td>
<td>0.52</td>
<td>0.54</td>
<td>0.55</td>
</tr>
<tr>
<td></td>
<td>Dry Density, $\rho_{(f)}$ (t/m$^3$)</td>
<td>2.03</td>
<td>2.11</td>
<td>2.37</td>
<td>2.42</td>
<td>2.61</td>
<td>2.64</td>
<td>2.74</td>
<td>2.70</td>
<td>2.67</td>
</tr>
<tr>
<td></td>
<td>Degree of Saturation, $S_{(f)}$ (%)</td>
<td>25</td>
<td>33</td>
<td>51</td>
<td>56</td>
<td>73</td>
<td>76</td>
<td>92</td>
<td>95</td>
<td>92</td>
</tr>
</tbody>
</table>
The change in the void ratio during vibration for each sample can be seen in Figure 319 along with the change in the degree of saturation in Figure 320. As expected, the time taken for the samples to reach near equilibrium occurred rapidly. Due to the moisture content of Samples, G, H and I, they were more likely to take the longest for equilibrium to be met. It seems that after approximately 3600 seconds (1 hour) equilibrium was reached.

Also, as expected, Figure 319 shows that fewer voids were likely after vibration as the moisture content was increased. This is due to lubrication of the particle surfaces allowing increased particle rearrangement to occur. With this said, this was not the case for Samples H and I as they exceeded the Optimum Moisture Content (OMC), and, therefore, the maximum density for this frequency and magnitude of vibration. Above the OMC, which occurred at approximately 95% saturation, voids increased with increasing moisture content due to the positive pore pressure forcing the particles apart. The OMC can be clearly seen in Figure 321.
Figure 320 – Change in degree of saturation for each sample during vibration

Figure 321 also shows the changes that occurred to each sample throughout the duration of the scale model tests alongside the Modified Proctor/Fagerberg Test (MPFT) compaction curve. As previously mentioned, the samples were lightly placed in the mould so that the sample would densify throughout the entire range of densities that would be produced under this frequency and amplitude of cyclic loading until the changes were perceived to be insignificant. This was achieved throughout the 2-hour duration of vibration. The moisture contents tested could not be increased greater than sample I due to not being able to handle the samples at the high moisture content without significant segregation of the fine and coarse particles occurring.

As shown in Figure 321, the samples of iron ore experienced densities less than, equivalent to and greater than the compaction curve produced by the MPFT (Figure 284). This shows that, under varying degrees of vibration, it is possible that a cargo may experience this range of densities. Also shown is the Transportable Moisture Limit (TML) where the equivalent degree of saturation, equal to 80%, intersects the MPFT curve. More information on how the TML is determined using the MPFT can be seen in related publications (Munro and Mohajerani, 2014, 2015, 2016b, 2016c) or in Appendix 2 of the IMSBC Code (International Maritime Organization, 2016).
Figure 321 – Changes that occurred to the samples throughout the duration of the scale model tests ($S$ = degree of saturation)
The TML determined by the MPFT is coincidentally equivalent to the final moisture content measured after vibration of the two wettest Samples, H and I. The scale tests of Samples G and F, which both began approximately equal to the MPFT TML, each ended with a moisture content that was further reduced. It can be seen that the final moisture content of the sample significantly relies on the initial void ratio. This can be clearly seen by looking at the path for sample E where the initial moisture content was approximate to sample H, but the final moisture content had a significant difference of 1.5% gross water content. From this relatively simple relationship it can be seen that the ability for a cargo to drain excess moisture under significant vibrations is increased with a decrease in the initial placed density.

Figure 322 shows the relationship between the overall change in moisture content against the initial and final moisture content. Assuming that a cargo will experience drainage if loaded within the range of moisture contents experienced by Samples E and F, we can safely say that, if initially placed above 9.5% gross water content, moisture is likely to migrate downwards through the cargo. This migration of moisture may create saturated areas within the base of the cargo that may be well above the TML determined using the MPFT, and, therefore, may be potentially liquefiable.

During the development of the MPFT it was speculated that moisture migration to the base may occur during transportation and was taken into account during the development of the test (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e). But, with this said, we believe that moisture migration is not only occurring towards the base, but also towards the surface. Moisture migrating upwards would transport finer particles towards the surface and create areas that due to the high moisture content and finer particles are potentially more liquefiable.

If this phenomenon was to occur it would likely only produce liquefaction of the material on the surface. This may have been seen before where it was assumed that liquefaction of the entire cargo occurred rather than just the surface layer. Photographs after suspected liquefaction incidents are rare, but one example of this can be seen in Figure 323, where a cargo of nickel ore underwent what was assumed to be total liquefaction during a voyage from New Caledonia to Australia. Also, shown in Figure 324, is a cargo of iron ore fines in India showing fines and free water pooling on the surface.
To be able to observe moisture migration to the surface of the cargo and possible segregation after the 2-hours of vibration in the scale model the sample was split into layers. For each layer the moisture content, void ratio and particle size distribution was determined.
Figure 325 shows the moisture content of each sample against the moisture content for the top, middle and bottom layers after the completion of the test. Similar to Figure 322, it can be seen that at approximately 9.5% gross water content, the moisture slightly increased in Layer A, which is the bottom layer, indicating moisture draining down towards the base. The moisture content at the base was unable to increase further due to moisture draining out of the drainage system as expected. With a slight increase in moisture content above 9.5%, the direction of moisture migration was reversed and the difference in moisture within the top and bottom layers was more significant. When the sample in the scale model was at the moisture content equivalent to the MPFT TML the top layer had a moisture content of approximately 7% greater than that of the base. It is shown here that even if a cargo is loaded at the TML, areas within may far exceed this safe moisture limit. This is similar to the results produced during preliminary testing and published in a related publication (Munro and Mohajerani, 2017c). Images of sample I before and after testing can be seen in Figure 326.
Figure 327 – Surface water on sample I forming during vibration

Figure 327 shows surface water on sample I during vibration. After vibration ceased, the moisture that had migrated to the surface was measured separately before being reconstituted back into the rest of the mass of the top layer. This was in order to compare the moisture that drained to the top with what drained out of the base. Figure 328 shows this comparison. It can be seen that, compared to Figure 325, the trend was the same. Moisture was seen to begin to migrate throughout the sample at a gross water content of approximately 9.5%.

![Figure 328](image)

Figure 328 – Difference between the drainage to the surface and base of each sample during vibration

As described in Section 16.3.3.2.1, segregation brought about by moisture migration may lead to areas of the cargo having a much higher potential to liquefy due to the changes in the distribution of particles in certain areas. As shown in Figure 313, the particle size distribution of materials is related to their potential to liquefy. These areas would most likely be those that moisture migrates towards, such as the base or the surface.

The samples that were taken at varying heights to determine the changes in the physical properties of the iron ore fines also underwent particle size distribution testing to determine the degree of
segregation. Particle size distribution testing was carried out in accordance with AS1289.3.6.1 (Standards Australia, 2009d).

Figure 329 to Figure 331 show the particle size distribution after testing of the bottom, middle and top layers, respectively. Although it can be seen that there was no significant variation in the particle size distribution for the bottom and middle layers, this was not the case for the top layer.
Figure 331 shows that there was a significant change in the distribution of fine particles within the sample where they were shown to be migrating towards the top layer. The range of particle sizes that migrated towards the surface was shown to be between 75 μm and 2 mm. By referring back to Figure 313 shown in Section 16.3.3.2.1, we can see that this range was within the highly liquefiable boundaries determined by Ishihara (Ishihara, 1993). The change seen in Figure 331 is said to be significant as the samples taken were approximately 50 mm thick, and, with the fine layer being approximately 20-25 mm thick, dilution of the fine portion observed at the surface occurred.

By sampling the top 20 mm of sample I, the particle size distribution shown in Figure 332 was obtained. This confirms the magnitude of fine particle migration that was observed during testing and pooled on the surface of the sample. According to the boundaries for liquefiable soils, it can now be seen that approximately 60% of the particles in the top 20 mm of sample I fall within the range of being potentially liquefiable rather than 35% of the sample as a whole. This change in particle size distribution is considered significant.
To show the change in particle size in terms of moisture content, Figure 333 and Figure 334 were created based on the data presented in Figure 331. For comparison between the initial stages of moisture migration and segregation, 9.5% gross water content is shown in this graph. It can be seen that significant segregation occurred alongside moisture migration. The same trend can be seen in Figure 333 and Figure 334 as is seen in Figure 322.
The mechanism forcing moisture to migrate to the surface was assumed to be the increase in density in the base layers and the increase in pore pressure within. The increase in density decreases the permeability of the material reducing the drainage ability in those areas. As explained in Section 16.3.3.2.1, a reduction in permeability within the material increases the likelihood of pore pressure building and causing a reduction in the effective stress.

Figure 335 shows the change in void ratio of each of the layers for each sample during vibration. Since the bottom layer had the most pressure being applied to it from the layers on top it was initially assumed that this would be the densest, however, this was not the case. The likely explanation being that during initial vibration, the pore pressure increased in the central layer causing an increase in density and moisture to migrate from this area. This is similar to consolidation of soils with two-way drainage.

This central layer was now less permeable than the layers above and below. The moisture continued to migrate both to the base and to the surface, ultimately, leaving the central layer as the densest. The base layer did not become as dense as there was still moisture inducing pore pressure in the area due to the drainage not being as adequate when compared to the drainage to the surface.
Figure 335 – Change in void ratio for each layer against the total final gross water content

Figure 336 shows the change in the degree of saturation of each of the layers for each sample during vibration. This indicates what was previously speculated, that the middle layer was the first to saturate with increasing moisture content followed by the bottom and then the top layer. As stated previously in terms of the particle size distribution, the samples taken were an average of the entire layer. The top half of the top layer was significantly different to the bottom half of the top layer. Total saturation of the top half of the top layer was observed above samples with moisture contents above 10%.

Figure 336 – Change in degree of saturation for each layer against the total final gross water content

Since the samples were under significant vibration during the scale model tests, it was required to determine if the samples as a whole underwent liquefaction during the tests. As described in Section 16.3.3.2.2, tensiometers were used to measure the pore air and water pressure at varying depths. As described in Section 16.3.3.2.1, the effective stress of a soil is an indication of liquefaction. As the effective stress reduces, perfect plasticity (or flow) may be exhibited by a soil, which is referred to as flow liquefaction. If the effective stress is reduced to zero, cyclic liquefaction occurs whereby the soil does not flow, but undergoes large deformations during load cycles (Robertson and Fear, 1996).
Figure 337 shows the typical trend for the pore pressure measured for Samples A through D. It was shown that, during these tests, the pore pressure was consistently stable. There was no significant increase in pore pressure for these samples with the maximum recorded pressure being 1 kPa and the minimum being -0.6 kPa.

The averaged pore air and water pressure data recorded for Samples G, H and I are shown in Section 16.3.7. The data indicate that increasing total pore pressure was experienced towards the centre of the sample. The trend seen in the data shows that the pore air pressure increased towards the centre of the sample and decreased towards the surface and base. This is unlike the pore water pressure, which continued to increase, instead of decrease, from the centre to the base. It is speculated that the drainage system allows the dissipation or pore air pressure to occur so that the air within the sample is at atmospheric pressure like at the surface. This may not be the case on bulk carriers. If the bilge system is sealed and pumps are used to evacuate water overboard (Plant Export Operations Branch, 2014), the pressure may increase further than in a system open to atmospheric pressure.

The time taken for peak pore pressure or minimal effective stress to be reached during testing is related to the density, moisture content and resulting permeability of the material under the time and magnitude of cyclic loading. The maximum time taken under the frequency and magnitude of loading used during this study was 30 mins. A summary of the peak and residual pressures shown in Section 16.3.7 is given in Figure 338 to Figure 341. Figure 338 and Figure 339 show the combined total pore pressure within each layer while Figure 340 and Figure 341 represent the approximate effective stress calculated using Equation 2.
Figure 338 – Peak total pore pressure measured within each layer during vibration

Figure 339 – Residual total pore pressure measured within each layer during vibration
The peak total pore pressure, therefore, the minimum effective stress, was most predominant in the middle layer of the samples with the moisture content exceeding 9.5%. In contrast, the bottom layer showed an increase in the effective stress due to increased matric suction, \( u_a - u_w \). Matric suction was likely increased by the area attempting to equalize itself due to the increase in capillary forces created under the unsaturated conditions. As the top layer had no applied stress, the effective stress was initially small and experienced no significant change. The total pore pressure, on the hand, indicated suction within the layer similar to the bottom layer. It is noted that at the MPFT TML the sample experienced zero effective stress in the middle layer under this frequency and magnitude of cyclic loading.

Due to the nature of the test, it was not possible to determine definitively if liquefaction occurred within the sample, however, it can be said that a loss of strength did occurred due to the reduction in the effective stress. This was only for a short time before the sample strengthened and finally reached...
a residual effective stress after excess moisture was expelled and particle to particle interaction, therefore, cohesion, was at its maximum.

Increased density and moisture content creates a less permeable material, which does not allow the dissipation of pore pressure; therefore, this is able to build, causing separation and lubrication of the particles and thereby allowing moisture migration to occur. Due to the nature of this phenomenon and the conductivity of iron ore, it was speculated that measuring the resistivity through the sample may be another way to visualise the particle to particle interaction.

As described in Section 16.3.3.2.2, resistivity probes were also attached to the mould at varying heights to determine the relationship between the change in resistivity and the pore water pressure of each layer. The resistivity probes in the samples where no pore pressure changes were recorded, as seen in Figure 337, also showed no unexpected change in resistivity. As seen in Figure 342, the only noticeable change that occurred was that, as the samples densified, there was a decrease in resistivity due to there being increased particle to particle contact. This behaviour was expected.

![Graph](image1)

*Figure 342 – Change in resistivity in layer A (bottom) for Samples F and B showing the expected decreasing trend*

Figure 343 to Figure 345 show comparisons of the decrease in resistivity to the pore water pressure for the first hour of vibration for Samples G, H and I. By comparing the resistivity and the pore water pressure in layers A and B (bottom and middle), it is noticeable that there is a trend whereby an increase in pore water pressure is accompanied by a rapid decrease in resistivity.
Figure 343 – Comparison of the decrease in resistivity to the pore water pressure in layer A (bottom) for Samples G, H and I

Figure 344 – Comparison of the decrease in resistivity to the pore water pressure in layer B (middle) for Samples G, H and I
This is also seen to be the case for layer C (top) for samples H and I, but not sample G. As shown in Section 16.3.7, the pore water pressure measured in sample G for layer C (top) was the lowest recorded. This low value, along with the differing locations between the resistivity probes and tensiometers may have caused the times for the recorded pore water pressure increase and decrease in resistivity to be 1400 seconds apart.

As shown in Figure 343 to Figure 345, there may be an important relationship between the change in the resistivity and pore water pressure within iron ore fines. This was assumed to be due to the conductivity or iron ore being significantly different to that of other materials. Although it may not be the case for other materials, this may be an alternative and cheaper option for monitoring changes in pore pressure within a material such as iron ore fines.

16.3.5 Discussion
It is to be noted that although the apparatus was designed to replicate the actual drainage and constraints of a bulk carrier cargo hold, the vibrations applied to the mould were simply to induce conditions under which liquefaction was most likely to occur (i.e. worst-case scenario). The conditions replicate a cargo that has been trimmed flat or a cargo that has become flat due to initial loading on the vessel during transportation. A cargo stockpiled in the hold of the bulk carrier is not assumed to experience moisture migration to the surface.

It has been shown in this study that densification of a cargo under cyclic loading causes moisture migration to occur. Where moisture migration was recorded, segregation was also shown to have occurred. The combination of both segregation and moisture migration caused portions of the sample to have a moisture content exceeding that of the Transportable Moisture Limit (TML) even though the initial conditions of the sample as a whole were below or equal to the TML.
When compared to the TML of the material, 10.9%, moisture migration was shown to occur between 9.5% and 10.3% gross water content. This moisture migration was shown to occur due to the increase in pore pressure within the material due to a decrease in the permeability from the centre outwards. The peak total pore pressure, therefore minimum effective stress, is most predominant in the middle layer of the samples with the moisture content exceeding 9.5%. In contrast, the bottom layer showed an increase in the effective stress due to increased matric suction.

The segregation of the cargo also allowed for areas of the cargo to contain particles that were considered more liable to liquefy. The particle size distribution of the material that migrated to the surface was the same as the widely accepted range for potentially liquefiable materials. It was shown that 60% of the particles of the top portion of the sample were considered potentially liquefiable rather than 35% of the sample as a whole. It is likely that if liquefaction was to occur in the top portion of the cargo, it would be more susceptible due to the higher moisture content and increased potential to liquefy due to segregation of the particles.

Another aspect of densification showed that if two samples were loaded into the scale model at the same moisture content, the one that was initially at a lower density when loaded experienced more drainage of moisture to the base than the other. Drainage of moisture to the base of the cargo would allow the moisture to enter the bilge system and be evacuated overboard. Drainage was seen to occur towards the base at approximately 9.5% gross water content. The samples where drainage to the base occurred, due to initially loose conditions, did not experience any pore pressure increase within the material.

Due to the nature of the test it was not possible to determine definitively if liquefaction occurred within the sample, however, it can be said that a loss of strength did occur due to the reduction in effective stress. This was only for a short time before the sample strengthened and finally reached a residual effective stress after excess moisture was expelled and particle to particle interaction, therefore cohesion, is at its maximum.

16.3.6 Conclusion
The objective of this study was to design and construct a scale model to test the conditions under which iron ore fines may liquefy, and to monitor the changes that occur within the material that may adversely affect the stability of the cargo during marine transportation. The parameters monitored included both the pore air and water pressure, moisture migration, segregation as well as the changes in physical properties, such as density, degree of saturation and resistivity. All the parameters monitored are believed to influence the liquefaction potential of iron ore fines and were compared to the TML produced by the MPFT.

It is concluded that due to the permeability of iron ore fines, which are considered to have good drainage, moisture migration occurs leading to segregation by means of the fine particles being transported to the areas of the cargo, specifically the surface, along with the moisture. These areas with a higher moisture content and finer particles are assumed to have a reduced permeability, and, along with the reduction in air voids, there is an increased likelihood of the pore pressure increasing and liquefaction occurring in these areas.

This study does not conclude if liquefaction occurred within the samples but does show the potential for it to occur, specifically in portions of the cargo, and not the cargo as a whole. From the results from
this study, it has been shown that at 9.5% gross water content, which is 1.5% less than the TML produced from the MPFT, segregation, moisture migration, and increased pore pressure began to occur within the samples.

The MPFT TML may be safe for a cargo as a whole, but does not take into account moisture migration and/or segregation of a cargo. Minimising the moisture migration will reduce the likelihood of areas forming with a higher liquefaction potential. A single parameter, the TML, indicating the potential for a cargo to liquefy, may not be the best solution to this problem. There is a reason why it is not common practice in geotechnical engineering and soil mechanics to use a method like the MPFT to determine the liquefaction potential of soils for engineering purposes. Using the TML as a parameter to indicate liquefaction is inadequate, as liquefaction is much more complicated and cannot be predicted by one factor. That is said assuming that liquefaction is indeed the most likely mode of failure to occur to this type of cargo.

Due to the wide range of properties that iron ore fines can exhibit, further research is required to determine the behaviour of other types of iron ore fines during marine transportation. Additionally, further research into the relationship between the change in resistivity and pore pressure is recommended as it may be a simpler and cheaper solution to monitor the conditions of a cargo of iron ore fines or even a method for testing purposes.
16.3.7 Appendix A – Pore Air and Water Pressures during Scale Model Testing
The following are the averaged pore air and water pressures measured for Samples G, H and I during the scale model test.

![Figure 346 – Averaged pore water pressure recorded at layer C (top) during the scale model test](image-url)
Figure 347 – Averaged pore water pressure recorded at layer B (middle) during the scale model test

Figure 348 – Averaged pore water pressure recorded at layer A (bottom) during the scale model test
Figure 349 – Averaged pore air pressure recorded at layer C (top) during the scale model test

Figure 350 – Averaged pore air pressure recorded at layer B (middle) during the scale model test
Figure 351 – Averaged pore air pressure recorded at layer A (bottom) during the scale model test
16.4 SUPPLEMENTARY RESULTS AND FIGURES

The supplementary results for the manuscript presented in Chapter 16 are given in Appendix G.

16.5 SUMMARY AFTER THE FACT

The results from the scale testing that are presented in this chapter proved specific behaviour that iron ore fines exhibit during cyclic loading. This behaviour had been suspected by some, but not proven to occur. The relationship that the scale testing performed during this research has in regards to the marine transportation of iron ore fines, cannot be proven at this stage. The frequency and loading used to perform this research is considered to be the worst-case scenario.

In order to determine the most probable phenomena occurring during the marine transportation of iron ore fines, and, therefore, provide recommendations and conclusions regarding this research, a final summary of the experimental results was made. The summary evaluates, validates and compares the test results obtained and presented throughout this research.
CHAPTER 17 SUMMARY DISCUSSION OF EXPERIMENTAL RESULTS

17.1 INTRODUCTION

Provided in this chapter is a combined discussion of the results presented in Chapter 12, Chapter 13, Chapter 15 and Chapter 16. These results relate to the testing of sample MA004, where the properties are given in Chapter 3. This discussion is to go alongside the discussions already presented for each individual manuscript. The aspects of this combined discussion include:

- [Chapter 12] unsaturated repeated load triaxial testing,
- [Chapter 13] slope stability evaluation,
- [Chapter 15] saturated cyclic triaxial testing, and
- [Chapter 16] scale model testing.

The results presented in Chapter 14 are also discussed, which relates to the preliminary scale model and Iron Ore Fines Plunger (IOFP) testing of sample MA003. Furthermore, discussions are made on the comparisons between the Modified Proctor/Fagerberg Test (MPFT) Transportable Moisture Limit (TML) value and the aforementioned test results in order to confirm or otherwise their relationship.

17.2 REFERENCED FIGURES

This section provides a summary of the significant figures that are referenced during the discussion.

17.2.1 Sample MA004

17.2.1.1 [Chapter 12] Preliminary Repeated Load Triaxial Testing
During this research, sample MA004 was tested using the unsaturated repeated load triaxial apparatus. The following shows one of the figures produced from this test, which is discussed herein. The results shown here are presented in detail in Chapter 12 Section 12.3.5.
17.2.1.2 [Chapter 13] Slope Stability Evaluation

During this research, sample MA004 was tested using the unsaturated repeated load triaxial apparatus. The following is a summary of the figures produced from this test, which are discussed herein. The results shown here are presented in detail in Chapter 13 Section 13.3.4.2.
Chapter 17 - Summary Discussion of Experimental Results

Michael Colin Munro – July 2017

Figure 353 – The average rotational analysis factors of safety and boundaries for a trimmed and untrimmed cargo of sample MA004 at varying angles of heel (method of slices) (Munro and Mohajerani, 2017f)
17.2.1.3 [Chapter 15] Advanced Cyclic Triaxial

During this research, sample MA004 was tested using an advanced cyclic triaxial apparatus. The following is a summary of the figures produced from this test, which are discussed herein. The results shown here are presented in detail in Chapter 15 Section 15.3.5.2.
Figure 356 – CSL and cyclic stress paths of the samples in the e:ln(p') plane

Figure 357 – CSL and average drained cyclic stress path in the q:ln(p') plane (the maximum deviator stress reached before failure criteria was met is marked for each sample)
17.2.1.4  [Chapter 16] Advanced Scale Model Testing
During this research, sample MA004 was tested using the unsaturated repeated load triaxial apparatus. The following is a summary of the figures produced from this test, which are discussed herein. The results shown here are presented in detail in Chapter 16 Section 16.3.4.
Figure 358 – Changes that occurred to the samples throughout the duration of the advanced scale model tests on sample MA004 (S = degree of saturation) (Munro and Mohajerani, 2017d)
Figure 359 – Overall change in gross water content against the initial and final gross water content for each sub-sample of sample MA004 (Munro and Mohajerani, 2017d)

Figure 360 – Change in gross water content for each sub-sample of sample MA004 comparing the top and bottom layers (Munro and Mohajerani, 2017d)
Figure 361 – Percent particles passing 0.075 mm for Layer C (Top) for all sub-samples of sample MA004 (Munro and Mohajerani, 2017d)

Figure 362 – Percent particles passing 0.425 mm for Layer C (Top) for all sub-samples of sample MA004 (Munro and Mohajerani, 2017d)
17.2.2 Sample MA003

17.2.2.1 [Chapter 14] Preliminary Scale Model and Iron Ore Fines Plunger Testing
During this research, sample MA003 was tested using the preliminary scale model apparatus and Iron Ore Fines Plunger (IOFP). The following is a summary of the figures produced from these tests which are discussed herein. The results shown here are presented in detail in Chapter 14 Section 14.3.5.
**Figure 365** – The variation of the degree of saturation of each layer against the overall moisture content produced during the preliminary scale model tests on sample MA003 after 3600 seconds (1 hour) of vibration (Munro and Mohajerani, 2017c).

**Figure 366** – The variation of the moisture content of each layer against the overall moisture content produced during the preliminary scale model tests on sample MA003 after 3600 seconds (1 hour) of vibration (Munro and Mohajerani, 2017c).
17.3 DISCUSSION

Of the two samples discussed in this chapter, the particle size of sample MA003 was considerably finer when compared to sample MA004. According to AS1726, sample MA003 is a silty sand (SM) whereas sample MA004 is a Poorly graded gravel to silty gravel (GP-GM) (Standards Australia, 1993). The major differences between the two samples seem to end there. They both have similar Atterberg Limits, particle density (specific gravity) and goethite contents as is shown in Chapter 3.

It is to be noted that the two samples discussed in this chapter both contain above 35% goethite by weight. In this case, according to the newly implemented schedule for iron ore fines given in the IMSBC Code, these samples would not have to undergo TML testing and the schedule for iron ore, not iron or fines, could be followed. This means these cargoes would be treated as a Group C or non-liquefiable material. During previous research by the Iron Ore Technical Working Group (TWG), it was shown that the increased surface area, of particles of goethite, were shown to increase the moisture-holding ability of iron ore fines and increase the moisture required to reach certain degrees of saturation.

This research assumes that the liquefaction potential cargoes of iron ore fines with goethite content above 35% remains the same as iron ore fines with goethite content below 35%. It is assumed that increased particle surface area simply means the cargo will require more moisture to become saturated to a point similar to that of a material with particles with lesser surface areas. Furthermore, materials, such as these, tend to hold more moisture, therefore, initially contain more moisture during extraction, transportation and loading. This is similar to having a material with smaller particle sizes.
As is common knowledge in geotechnical engineering and soil mechanics, a soil with finer particle sizes tend to require more moisture to reach their maximum densities or specific degrees of saturation due to the increased surface area created by the finer particles. This is considered the major contributor to the increased TML values for sample MA003 given in Chapter 3 Section Table 9. Furthermore, with increased finer particles and moisture also comes a reduction in the maximum density at specific degrees of saturation. This can be seen in Chapter 3 Figure 32 and Figure 33 where the equivalent densities for both the Proctor/Fagerberg test compaction curves vary depending on these factors.

Discussion will commence by reviewing the slope stability analysis provided in Chapter 13 Section 13.3.4.2. These results provided this research with conditions under which a cargo of sample MA004 may shift if under static conditions. It is obvious that during marine transportation a solid bulk cargo experiences dynamic as well as static forces, therefore, a cargo shift will likely occur prior to these conditions being met. With this said, it is acceptable to assume that the conditions shown during this analysis are the worst-case conditions and if met, the cargo will shift.

By looking at the reference figures given in Section 17.2.1.2 of this chapter, in regards to slope stability, the likely angle of heel that would cause the cargo to shift is given where the factor of safety is equal to 1. Figure 353 and Figure 354 shows the rotational and translational analysis angles of heels to be significantly different. The cause of difference is the conservative nature of translational analysis. Due to this, the discussions will focus on the results from the rotational analysis.

The rotational analysis, shown in Figure 353, indicates that the likely angle of heel a bulk carrier will need to reach to cause failure of a cargo of MA004, under static conditions, is 30-degrees. This angle of heel is at the upper angles that bulk carriers would realistically be expected to experience without suffering unrelated issues. The angle of heel needed to reach failure increases significantly, to above 60-degrees, if the cargo has been trimmed.

It can be therefore said that under the range of conditions expected in the hold of a bulk carrier it is unlikely a cargo of iron ore fines, similar to sample MA004, will fail during marine transportation due to shearing alone. With the addition of dynamic loading, another mode of failure is likely to occur before the vessel experiences the significant sea state required to result in these pronounced angles of heel.

Due to the nature of slope stability analysis, a safety factor of 1.5 was used rather than 1. By looking at Figure 355, this can be seen to reduce the angle of heel required under both trimmed and untrimmed conditions but, even untrimmed, the calculated angle of heel at failure is considered conservative as the profile of a cargo is not typically uniform, as assumed during analysis. Cargoes are commonly loaded into a cargo hold in multiple stacks, as seen in Figure 368. This configuration will increase the angle of heel needed to cause the cargo to shear.
The most common apparatus used in civil engineering and soil mechanics to determine the cyclic strength of soils is the triaxial apparatus. By looking at the reference figure given in Section 17.2.1.1 of this chapter, in regards to the preliminary repeated load triaxial testing, it can be seen that samples with increased moisture content and density tended to survive the repeated loading. It is well known that with increased moisture should come a decrease in strength. The opposite can be seen as when the moisture content was increased, the initial density also increased. This increase in density, along with a minor increase in moisture content, allowed the material to survive an increased number of cycles.

Using the advanced cyclic triaxial, which included additional capabilities over the preliminary repeated load triaxial, allowed the additional monitoring of pore pressures and volume change. Figure 356 and Figure 357 show the behaviour of the samples during these tests. Rather than shearing along a single plane of failure, as theorized during the slope stability analysis, the triaxial results indicated another mode of failure. This mode of failure, referred to as incremental collapse, occurs when there is a progressive loss of strength within the cargo during each successive load cycle. This mode of failure occurs progressively, unlike liquefaction or shear failure, but may result in an instant cargo shift if it becomes significant enough to cause weakening.

It is likely that multiple phenomena are responsible for cargoes of iron ore fines shifting. Looking back at the preliminary repeated load triaxial results, some samples showed immediate failure after a relatively low number of cycles and others showed incremental collapse. If the cargo is initially weak it may collapse and cause an immediate shift within the hold, as may have occurred to cargoes resulting in the incidents described in Chapter 11. Progressive weakening or incremental collapse of a cargo may increase the time for a cargo to shift, but may result in an instant shear plane developing if it collapses and weakens to a certain point. The angle of heel needed to cause a shear plane to develop, after incremental collapse has occurred, is likely much less than if no incremental collapse occurred.

The main phenomena referenced during this research, but not observed was liquefaction. The advanced cyclic triaxial testing, designed to test for this under simulated seagoing conditions, showed no signs of liquefaction occurring or indications of the potential for it to occur. In order to determine
if liquefaction of sample MA004 was even possible, the scale model tests were performed simulating
worst-case scenario conditions.

Referencing Figure 358 in Section 17.2.1.4 of this chapter, the changes in moisture content and void
ratio that occurred during the advanced scale model testing are shown. Under these worst-case test
conditions, it can be clearly seen that there is a point where changes within the samples begin to occur
being dependant on both the initial moisture content and void ratio. The point at which changes occur
can be related to the moisture-holding ability of the cargo. Increasing the moisture content above the
materials moisture-holding ability results in drainage to the base or moisture migration to the surface.

Referencing Figure 359, the moisture-holding ability of sample MA004 is considered to be
approximately 9.5% gross water content, 1.4% less than the Transportable Moisture Limit (TML)
produced by the Modified/Proctor Fagerberg Test (MPFT). At this moisture content, under the applied
cyclic loading, the material beings to exhibit moisture migration. This aspect is important as during
moisture migration, fine particles can be transported throughout the cargo creating areas with an
increased potential to liquefy. Figure 360 through Figure 362 show the particle migration occurring
along with the moisture migration below the TML.

One difference between the advanced scale model testing of sample MA004 and the preliminary scale
model testing of sample MA003 was the addition of pressure transducers. Figure 363 and Figure 364
show the approximate peak and residual effective stresses within the sample layers during loading.
Although not definitive, the peak pressures calculated within the central layer of the samples indicates
that liquefaction may have occurred in this area for a brief amount of time until the moisture was
expelled. Considering that the applied loading is worst-case scenario, it is likely that this would not
occur. Under a more realistic loading conditions, fine particles and moisture would likely migrate to
the surface. This would destabilize the transporting vessel if the sea state being traversed induced the
momentum of the surface mass.

The same moisture migration trend can be seen when looking at the preliminary scale model testing
of sample MA003. Figure 365 and Figure 366 show the Restraining Moisture Content (RMC). The RMC
is the term used during this research to refer to the point at which migration began to occur. In Figure
367, the RMC is compared against the results from the IOFP. This comparison indicates that there is a
relationship between the RMC and the Critical Failure Curve (CFC). By looking at the TML from the
MPFT plotted on Figure 360 and Figure 365, there can be seen that there is no relationship between
the TML value and the point at which moisture migration begins.

Referring back to the slope stability analysis, it was shown that trimming reduces the likelihood of
slope failure occurring. On the other hand, common sense indicates that moisture and fine particles
would be unable to form on the surface of an untrimmed cargo. It is therefore noted that there are
definite advantages and disadvantages when considering to trim cargo of iron ore fines.
CHAPTER 18 CONCLUSIONS AND RECOMMENDATIONS

18.1 CONCLUSIONS

The main objective of this research was to examine and recognise, at a fundamental level, the possible phenomena that may be responsible for cargoes of iron ore fines shifting in the holds of bulk carriers during marine transportation. A comprehensive literature review was performed in regards to iron ore fines, as a commodity and cargo, as well as the policies and procedures currently implemented to prevent the cargo from shifting during marine transportation.

Research began with a thorough examination of the conditions under which iron ore fines are transported in the holds of bulk carriers along with a comprehensive investigation into incidents where cargoes of iron ore fines have shifted. Identified from this initial research was the possible types of phenomena that may be the cause of the cargo shifting. Many standard test methods were used, in combination with several novel physical, numerical and theoretical methods, to reproduce and analyse the identified phenomena.

It has been concluded that there are multiple phenomena that can result in a cargo of iron ore fines shifting in the hold of a bulk carrier during marine transportation. The phenomena likely to occur depends on the initial conditions of the cargo after placement into the cargo hold and the loading conditions experienced during transportation. Although liquefaction was the major suspect at the commencement of this research, it has been concluded that liquefaction of the cargo, as a whole, is unlikely to occur before the other identified phenomena.

There are two likely phenomena that both masquerade as full cargo liquefaction due to the similarities when described and sometimes observed. The first phenomenon is identified as liquefaction, although not liquefaction of the cargo as a whole as speculated. Due to increased pressures within the cargo during transportation, moisture migrates to the surface and transports finer particles along with it to the surface. This material, now separated from the majority of the cargo mass, can liquefy under calmer conditions than the cargo mass as a whole.

Although it has been shown that iron ore fines with high moisture contents may partially liquefy, under contrasting initial conditions of the loaded cargo, the phenomenon may differ. As moisture migration to the surface of a cargo is only likely if the cargo is initially trimmed or profile becomes increasingly horizontal, due to dynamic loading, an untrimmed cargo is likely to shift due to another phenomenon. This research identified incremental collapse as the other phenomena likely to occur. Unlike partial liquefaction, as described above, incremental collapse is likely to weaken an untrimmed cargo, resulting in a shear plane developing and slope failure occurring. These phenomena can be linked to the documented behaviour of the cargo and vessels during the suspected liquefaction incidents investigated during this research.

The principal theory used to design and develop the test method currently listed in the International Maritime Solid Bulk Cargoes Code (IMSBC Code), used to determine the Transportable Moisture Limit (TML) of iron ore fines, is not one that is widely accepted in geotechnical engineering and soil mechanics. The introduction of the test in 1971 by metallurgist Bengt Fagerberg, assumed the cargo was a refined concentrate with particle uniformity. These properties created the inability for the materials to reach high degrees of saturation. The differences between the cargoes of then and today...
is significant. Notwithstanding the conditions of transport (i.e. height of cargo, loading techniques, etc.), the physical properties of iron ore fines can vary significantly simply due to the surrounding strata from where it was extracted. This is due to the unrefined nature of the cargo and significant variation of the locations of the ore within natural deposits.

The question therefore arises; what is the relationship between the stability of iron ore fines in the hold of a bulk carrier and the TML determined by the Modified Proctor/Fagerberg Test (MPFT)? Liquefaction of iron ore fines was not observed during this research, therefore, there is no objective comment that can be made in regards to the relationship of the TML, determined by the MPFT, and the liquefaction potential of iron ore fines. With this said, there is some subjective points to be made in regards to the relationship of this parameter and the other observed phenomena. It is concluded from this research that the moisture-holding ability of iron ore fines is a major influence in the likelihood of partial liquefaction occurring. Preventing moisture migration will prevent the possibility of partial liquefaction.

The TML, as determined using the MPFT, was consistently equal to or higher than the moisture contents measured where migration of moisture and fine particles were recorded. This indicates that if a cargo of iron ore fines is loaded onto a bulk carrier, at the TML, moisture migration may occur resulting in areas within the cargo with a high potential to liquefy. With this said, the ability for a material to liquefy is not considered to be simply dependent on the moisture content as is inferred by the preventative parameter, the TML.

Ignoring the effect physical properties can have on the strength of a material, such as particle size, shape, porosity, permeability, plasticity, etc., a material with the exact same physical properties and moisture content can either experience liquefaction or not depending on the magnitude and duration of dynamic loading that is applied. In reality, any material can undergo liquefaction if the conditions are favourable. There are obvious limitations to the conditions that can be experienced (i.e. during an earthquake or during marine transportation), therefore, there are also limitations to the liquefaction potentials of materials, as described during this research.

The range of densities that can be produced from the varying types of cargoes, loading techniques, transportation conditions and applied dynamic loading, creates a wider range of scenarios where liquefaction, or another phenomenon causing a cargo shift, may occur. This is not a simple problem and cannot be solved using such a simple, basic and unrecognised testing technique.

Currently, in the field of geotechnical engineering and soil mechanics, the most common test used to determine the liquefiability of soils is the cyclic triaxial test. This test utilizes the ability to dynamically load a specimen while measuring parameters, such as pore pressures and volume change, to determine the strength of the material and likelihood of failure.

The conclusions from this study are based on the results from the testing of limited specimens of iron ore fines. The comments made within relate to the assumption that iron ore fines, as a cargo, have a constantly changing and significantly wide range of physical properties, from location to location. This conclusion notes that the testing of iron ore fines and other cargoes, with again, significantly different properties to iron ore fines, use a similar, yet only slightly modified method, such as is the case for coal (Australian Coal Association Research Program, 2014; Australian Coal Association Research Program (ACARP), 2014b).
18.2 KEY FINDINGS

Based on the results from the samples of iron ore fines tested, described in Chapter 3, the following are the key findings made during the duration of this research:

- the properties of a cargo of iron ore fines vary significantly due to both the unrefined nature of the material and varying strata the ore is extracted from,
- depending on the facilities of the port and transporting vessel, the initial conditions of a cargo of iron ore fines can vary significantly,
- the likelihood of a cargo shifting has a sensitive dependence to the physical properties and initial conditions,
- the likely phenomenon to occur, resulting in a cargo shifting, also has a sensitive dependence to the physical properties and initial conditions,
- not one physical or system variable controls the likelihood of a specific phenomenon occurring or type of phenomenon that may occur,
- while traversing typical sea states, it is unlikely a cargo of iron ore fines will undergo; liquefaction, as a whole, or instant slope failure, without initial weakening,
- instability of bulk carriers during marine transportation may have been caused by; slope failure occurring after weakening by incremental collapse of the cargo caused by limited yet successive dynamic loading,
- partial liquefaction of a highly liquefiable portion of a segregated cargo,
- the phenomenon that has occurred during incidents is likely not only dependant on the physical properties and initial conditions, which are under limited control at the time of loading, but also initial conditions which can be controlled, such as trimming,
- a trimmed cargo that shifts, would have likely initially undergone incremental collapse, while a trimmed cargo, or untrimmed cargo that’s profile becomes horizontal due to the dynamic loading, is more likely to have experienced moisture migration, segregation and partial liquefaction,
- under dynamic loading, with a greater frequency and amplitude, a cargo would likely experience partial liquefaction rather than incremental collapse, which is likely at high angles of heel with lesser frequency and amplitude of dynamic loading,
- to control segregation and moisture migration the moisture-holding ability of the cargo seems to be a limiting parameter, and
- the initial amount of water to drain from the base of a cargo, which has been loaded above its moisture-holding ability, is dependent on the initial density. The less dense the initial cargo, the more moisture can drain out of the base before increasing density, caused by dynamic loading, reduces the permeability of the material, restricting moisture flow from the surface to the base.
18.3 DETAILED RECOMMENDATIONS

The following are detailed recommendations made in regards to the conclusions drawn from this research. The recommendations made herein relate to three different aspects of research or areas of interest. They are as follows:

- the International Maritime Solids Bulk Cargoes Code,
- the testing, loading and transportation of iron ore fines, and
- the occurrence of a cargo shift.

Irrespective of the applicability and validity of the methods, the following recommendations are made in regards to the test procedures given in Appendix 2 of the 2016 Edition of the International Maritime Solids Bulk Cargoes Code (IMSBC Code) (International Maritime Organization, 2016):

- Supplying the operator with specific curing times for specimens, after the moisture content of a sample is adjusted, is necessary in order for the sample to be at conditions similar to those in the field. Experience has shown that samples not cured sufficiently or cured excessively will give significantly varying results. This is particularly noticeable when testing manganese using the flow table apparatus. It is assumed that once moisture is added to the sample, free water will be present on the particle surfaces, reducing the resulting Transportable Moisture Limit (TML). After curing, similar to field conditions, the free moisture would have time to enter the pores and reduce surface moisture. Similar recommendations for curing times should be given as is done so for the widely used Proctor Compaction Tests (American Society for Testing and Materials, 2012; Head, 2006; Japanese Standards Association, 2009; Proctor, 1933; Standards Australia, 2003b, 2003c). Currently, the TML test methods give the following curing times;
  - mixed thoroughly then immediately tested (Flow Table Test (FTT), Penetration Test (PT) and Proctor/Fagerberg Test (PFT)), and
  - operator discretion, “the sample material is gently mixed before being allowed to rest and equilibrate” (International Maritime Organization, 2016) (Modified Proctor/Fagerberg Test (MPFT)).

- The PFT procedure begins by drying out the specimen, at approximately 100°C. It is recommended that this step is removed and replaced with air drying if necessary. Oven drying of a specimen can damage the structure of the particles altering the redistribution characteristics of the material when rewetting, which is required, especially if there is not enough time to allow the sample to cure before testing of the sample.

- Also, in order to assist with curing, without prolonging test time, it is recommended to add increments of water to the main test samples, which should be prepared in polythene bags, then left to cure. This will eliminate the need to change the moisture content of the specimen multiple times, during a test, and will also eliminate the need for constant mixing, which may result in segregation at lower moisture contents. This procedure is currently being implemented by some laboratories and is also similar to the procedure used for Proctor Compaction Tests (American Society for Testing and Materials, 2012; Head, 2006; Japanese Standards Association, 2009; Proctor, 1933; Standards Australia, 2003b, 2003c).

- There are numerous examples of instances when the procedures, given in Appendix 2 of the IMSBC Code, use uncommon techniques to perform tasks that have widely accepted and utilized procedures. It is recommended that a review of these procedures is undertaken so
that the methods conform with other widely accepted and utilized procedures. The procedures may me specific to soil mechanics and geotechnical engineering, as it is assumed that the technicians performing these tests will already be familiar with the related methods and techniques.

- The terminology and nomenclature used in the IMSBC Code is sometimes conflicting, therefore, confusing. Depending on the background of the technician performing the test can determine its interpretation. Specifically, emphasis must be made that the TML is reported in gross water content rather than net water content. In geotechnical engineering and soil mechanics, the moisture content of materials is given in net water content, whereas in other fields, including metallurgy and the handling of solid bulk cargoes, gross water content is favoured.

- In regards to the FTT, the main disadvantage is that the operator must be well trained to identify when the material has reached the Flow Moisture Point (FMP). The description of plastic deformation, in the IMSBC Code, is vague and does not give the technician any in-depth detail of what to be monitoring to detect plastic deformation. This is especially the case for materials that don’t display a typical behaviour, such as those with significant amounts of coarser particles.

- To determine the pressure used for compaction during the FTT and PT, either an equation or table in the IMSBC Code is used, see section 5.3.4.2.6. This method assumes a uniform density from the top to the bottom of a cargo, which is assumed not to be the case. Determining the bulk density, for use in the tamping pressure equation, does not seem to represent the actual density in the hold of a bulk carrier. It is recommended than an improved method, for estimating the bulk density of specific cargoes, is implemented if it cannot be directly measured. It is noted here that the method used to determine the bulk density is ASTM D-698 (American Society for Testing and Materials, 2012), which is also known as the “Proctor C Method”. It is recommended to clarify that it is not to be confused with the Proctor/Fagerberg test, also called “Method C” by researchers.

- It is recommended that, as has been done for iron ore fines, each material should have its respective test procedure giving in the individual schedule for the cargo. It has been shown, during this research, that the TML can vary depending on the test that has been chosen.

- The final recommendation, in regards to the IMSBC Code, is in respect to the goethite content limitation that classifies a cargo as either iron ore or iron ore fines. This classification, as either iron ore or iron ore fines, regulates whether the cargo should undergo mandatory TML testing. It was shown by the Iron Ore Technical Working Group (TWG), who developed the MPFT, that iron ore fines with a goethite content exceeding 35% by weight is unlikely to undergo liquefaction due to its increased moisture holding ability (Iron Ore Technical Working Group, 2013a, 2013b, 2013c, 2013d, 2013e). It is recommended that a full review be completed on this aspect of research as it is assumed that a material containing particles with increased surface areas only increases moisture holding ability of the material, therefore, only requires additional moisture to become potentially liquefiable.

It is noted that the following recommendations, made in regards to the testing, loading and transportation of iron ore fines, consider a cargo shift phenomenon’s likelihood of occurring to increase along with any increase in moisture content of the cargo. The following are those recommendations:
It is recommended that the importance of the sampling is made clear in all related procedures. The importance of sampling is commonly overlooked, but is the most imperative aspect of any test procedure. If the sample does not represent the cargo being tested then the results will not represent the cargo being transported. Section 4.6 of the IMSBC Code outlines sampling procedures that are to be followed when sampling stockpiles consigned to vessels (International Maritime Organization, 2013b). It is recommended that following these techniques is imperative when sampling cargoes.

It is clear that the ingress of water into the cargo is a major problem prior to a vessels departure from port. Ingress of water can occur during, extraction, transportation to port, storage and loading. Cargoes can contain a significant amount of fine particles, which can increase the inherit hygroscopic properties. Protective equipment should be easily accessible and readily available for use when rain is forecast. Masters should insist on checking if this protective equipment is available, as if this equipment is unavailable it can be an indication of poor practices at the site and therefore the Master should be extra vigilant.

Section 4.5 of the IMSBC Code states that the interval between moisture content sampling should not be more than seven days prior to loading (International Maritime Organization, 2016). If rainfall has occurred, or the humidity in the area is high, the moisture content of a stockpiled cargo can change significantly within seven days. Since determining the moisture content is relatively cheap and simple, it is recommended that the moisture content of any Group A cargo be determined the day prior to loading, as well as during loading. The sampling of the centre of stockpiles is imperative as this is where the moisture content is commonly at its highest as moisture migrates to this area and is protected from evaporation.

Irrespective of the applicability and validity of the TML test methods given in the IMSBC Code, as it is the only currently implemented preventative measure, it is recommended that the TML of all liquefiable cargoes be determined seven days prior to loading. If sampling was done correctly, the TML should not change unless a significant change occurs to the physical properties of the cargo.

It is recommended that an accredited independent testing laboratory is available to perform the required moisture content and transportable moisture limit testing. These laboratories may be located at the mine or port and be under the supervision of the International Maritime Organization.

Some mines where bauxite and nickel ore are being extracted only have basic amenities and are situated in remote locations. This makes it hard for surveyors and experts to attend them. Hence, it is not easy to arrange for cargo samples to be tested independently due to the lack of reliable laboratories in these areas. Due to this, the responsibly falls onto the mine operators, port authority and Master of the vessel to make sure the test results are valid and are representative of the cargo and that all necessary precautions are taken to reduce the potential for the cargo to shift during transportation.

If the Master suspects that a cargo may have a moisture content that exceeds the TML, it is recommended that a ‘Can Test’ be performed on the cargo. Although primitive, the ‘Can Test’ provides an estimate on whether the cargo may exceed the TML. The master should use it to check if his suspicions are correct. The ‘Can Test’ should not be used to confirm that a cargo is below the TML, only above. Although, passing the ‘Can Test’ test indicates the cargo may be safe to transport, a more reliable test should be performed to confirm the results.
Once a cargo is loaded onto a bulk carrier, it is still susceptible to the ingress of moisture. During loading, it is highly recommended that when rain is forecast all cargo holds be closed and the cargo that has not been loaded be protected from the elements. The ingress of water into the holds can sometimes be removed by bilge pumps, but due to some cargoes ability to retain moisture it can be preserved within and migrate out during transportation. Furthermore, sampling a cargo once loaded is not recommended as securing a representative sample is near impossible one it is in the cargo hold.

To control moisture migration within a cargo and increase stability during transportation it is recommended to only partially trim cargoes of iron ore fines. Trimming a cargo so that the surface is horizontal will allow the water to migrate to the surface, along with fine particles and create areas with an increased potential to liquefy. Not performing any trimming will result in a cargo with an increased surface angle, which makes it susceptible to the development of a shear plane, which may result in slope failure, after some weakening.

It is recommended that limited compaction is allowed to occur during trimming of a cargo of iron ore fines. An uncompacted cargo of iron ore fines, has been shown to have an increased ability to drain free moisture, throughout the cargo, whereby it can reach the bilge system at the base of the cargo hold and be evacuated overboard.

In Appendix 1 of the IMSBC Code, it is recommended that cargoes be checked regularly to make sure that there are no changes in the state of the material. The IMSBC Code states, “The appearance of the surface of the cargo shall be checked regularly during a voyage. If free water above the cargo or fluid state of the cargo is observed during a voyage, the Master shall take appropriate actions to prevent cargo shifting and potential capsize of the ship, and give consideration to seeking emergency entry into a place of refuge” (International Maritime Organization, 2013b). It is recommended that additional observations be made. It is recommended to monitor for excess pore pressures within the cargo by observing the behaviour of the surface of the cargo. Not only should monitoring of free water be taking place, but it is also recommended to monitor for localised bubbling or ‘volcanoes’ forming on the surface of the cargo. These phenomena indicate changing pressures within the cargo and possible subsurface liquefaction occurring. An example of localised bubbling or ‘volcanoes’ occurring during cyclic loading can be seen in Figure 369a and the formation of surface water after the fact can be seen in Figure 369b. It is recommended at the same time that the profile of the cargo is monitored. Changes in the profile may indicate incremental collapse is occurring that may result in a rapid cargo shift. Additionally, it is recommended that the water that is contained within, or has been expelled from, the bilge system be monitored. Variations in this data may indicate moisture migration throughout the sample, indicating free water and that the sample has a moisture content exceeding its moisture holding ability.
Due to both poor documentation and the nature of cargo shift incidents, there are limited reports available detailing specific aspects. This hinders investigations trying to identify the specific cause. The following recommendations are made in regards to the occurrence of a cargo shift during marine transportation:

- If there has been a case where a solid bulk cargo has shifted in the hold of a bulk carrier, it is recommended that significant time and resources are given to identify the mode of failure that caused the cargo to shift.
- It is recommended that a plan to investigate and report a cargo shift incident be implemented by the International Maritime Organisation (IMO). The plan of investigation, along with resulting incident reports, should be made publicly available to industries and researchers.
- It is recommended to include in this plan:
  - documentation of the condition of the cargo that has shifted if the vessel did not founder (written as well as photographic),
  - the witness questioning and handling procedure (questions specific to observations of the cargo and behaviour of the vessel, from both port employees and maritime personnel, during both loading and transportation),
  - specific documentation to be gathered relating to:
    - the navigated path of the vessel, including route and speed,
    - weather conditions during transportation,
    - sea state during transportation,
the presumed/measured physical properties of the cargo prior to the incident,
the testing techniques used to determine the parameters, such as particle size, goethite content, particle density (specific gravity), transportable moisture limit and moisture content, and qualifications of laboratory and/or individual performing each test,
sampling of the cargo, both as a whole and at varying heights, for testing after the incident may include;
for comparisons with the original documented results, the;
particle size distribution,
goethite content,
particle density (specific gravity), and transportable moisture limit.
determination of the variation with height of the;
moisture content,
density, and
particle size distribution.
disturbed samples for permeability and direct shear testing, and
undisturbed sample also for permeability as well as cyclic and monotonic triaxial testing.
planning for in-situ testing, which may include ground penetrating radar or Cone Penetration Testing (CPT), to determine the internal state of the shifted cargo.
planning for similar in-situ testing of the cargo in holds that have not shifted.

Noting that there are many other aspects to be documented after a cargo shift incident, including the above in a detailed plan of investigation to be actioned, will allow the identification of the likely phenomenon that occurred that resulted in the shift. Without detailed documentation, as has been the case up to now, confident analysis of the incidents, after the fact, is near impossible. Identifying the phenomenon will allow research to be concentrated in order to prevent it from occurring in the future.

Although further research is recommended, as described in Chapter 19, these recommendations will help reduce the potential for solid bulk cargoes to shift in the cargo hold during marine transportation. This will further protect the safety of maritime personnel, the environment, and prevent the needless loss of resources and assets.
CHAPTER 19 - FURTHER RESEARCH

This research merely scrapes the surface of the possible work still to be performed regarding this topic. It is to be noted that the ‘scale effect’ was not investigated during this research due to the resources required to do so. Further research is recommended to analyse the influence the ‘scale effect’ has on the tests performed during this research, specifically regarding the cyclic triaxial and scale model tests.

The cyclic triaxial is the most common apparatus used in geotechnical engineering and soil mechanics to determine the cyclic strength of soils. Further research is required to create a procedure whereby the cyclic strength of a cargo can be analysed with greater certainly. This may involve analysis of the behaviour of bulk carriers under varying sea states to determine the expected loading on a cargo being transported. This loading can then be used in conjunction with the triaxial apparatus create an improved an accepted test procedure that can be used to test solid bulk cargoes.

Further research using the cyclic triaxial apparatus can verify the relationship between the simpler methods given in the IMSBC Code as well as the methods presented during this research. If confirmation of the relationship between the Restraining Moisture Content (RMC), the Critical Failure Curve (CFC) or Transportable Moisture Limit (TML) can be made, possible implementation of the method, with or without modification, may be deemed acceptable.

Future research should not purely focus on methods already implemented in the IMSBC Code. These methods were designed for materials unlike iron ore fines, bauxite and nickel ore and, furthermore, are not acceptable tests used in geotechnical engineering and soil mechanics, to determine the cyclic strength of soils.

Further research into a simpler method to determine a safe moisture content at which a cargo can be shipped may include determining the point at which moisture migration commences. It has been shown during this research that moisture migration is related to pore pressure changes within the cargo as well as resulting in a reduction in the shear strength of the material. The point at which moisture migration begins to occur may indicate a moisture content at which phenomena, discussed during this research, may occur, resulting in a cargo shift.

Finally, touched upon during this research was resistivity testing. Further research may include analysis of the relationship between the measured changes in resistivity and the likelihood of a cargo shift occurring. This research may focus on development of a laboratory test method or a monitoring device that can determine the degree to which the structure of a cargo has changed during loading.
CHAPTER 20 REFERENCES

The references existing herein are presented in alphabetical order.


References

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References


Figure 370 – Major Australian iron ore deposits (Geoscience Australia, 2016)

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APPENDIX B – SUPPLEMENTARY RESULTS FOR MANUSCRIPT PRESENTED IN CHAPTER 5

The following supplementary results and figures were produced along with the manuscript presented in Chapter 5. Discussions and conclusions related to this information are considered to have been provided in the manuscript therefore only relevant descriptions of the supplementary results and figures have been provided herein. This information is provided to expand on or support information provided in Chapter 5.

Given in Figure 80 are the Particle Size Distribution (PSD) boundaries for 45 samples of iron ore fines tested. The PSD data that was used to create these boundaries are shown in Figure 371. Also included is a PSD for a typical sample of iron ore concentrate. Note the uniform nature of the iron ore concentrate compared to iron ore fines. Also, shown in Figure 372 are split samples, ordered by particles size, provided to give a visual of the typical particle sizes of iron ore fines.
Figure 371 – Particle size distributions of the 45 samples of iron ore fines used to create the boundaries of iron ore fines seen in Figure 371 and a single particle size distribution for a typical sample of iron ore concentrate.
Given in Section 5.3.12, Table 22, are the TML results obtained by performing the standard Proctor/Fagerberg Test (PFT). In order to visualise the results, Figure 373 has been supplied showing the normal distribution of this data. It can be seen that the TML range for iron ore fines, based on the PFT, is rather limited.
As stated in the manuscript, the three test methods given in the IMSBC Code are mainly for the testing of coal and ore concentrates. When testing iron ore fines, the difference between the TML produced by the flow table and penetration tests, seen in Figure 85, is significant. Provided in Figure 374 and Table 94 is a comparison between the Flow Table Test (FTT) and Penetration Test (PT) TML values for ore concentrates (T Ura, 1992). This data shows that there is a significant difference in the results when testing iron ore fines but not when testing materials for which they were designed.

Figure 373 – Normal distribution for the TML from the standard Proctor/Fagerberg test
Another comparison that shows this trend, excluding sample 6, is given in Figure 375 and Table 95. This data compares the Proctor/Fagerberg TML and Flow Table FMP. These values are compared, rather than both the TML values, as the Flow Table test TML has a 10% safety factor applied, as shown in Section 5.3.11.2. This is also the case for the Penetration test TML, hence they are directly compared in Figure 374.
Table 95 – Comparison between Proctor/Fagerberg TML and Flow Table FMP values for ore concentrates (Fagerberg and Stavang, 1971)

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Concentrate Type</th>
<th>Proctor/Fagerberg TML (%)</th>
<th>Flow Table FMP (%)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coarse Magnetite 1</td>
<td>7.0</td>
<td>7.7</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>Coarse Magnetite 2</td>
<td>7.9</td>
<td>7.6</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>Medium Magnetite 1</td>
<td>8.5</td>
<td>8.7</td>
<td>0.2</td>
</tr>
<tr>
<td>4</td>
<td>Medium Magnetite 2</td>
<td>9.3</td>
<td>9.3</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>Fine Magnetite</td>
<td>8.8</td>
<td>8.7</td>
<td>0.1</td>
</tr>
<tr>
<td>6</td>
<td>Copper</td>
<td>11.0</td>
<td>9.4</td>
<td>1.6</td>
</tr>
<tr>
<td>7</td>
<td>Zinc 1</td>
<td>11.3</td>
<td>11.7</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
<td>Zinc 2</td>
<td>10.6</td>
<td>11.2</td>
<td>0.6</td>
</tr>
<tr>
<td>9</td>
<td>Lead</td>
<td>8.2</td>
<td>8.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>
APPENDIX C – SUPPLEMENTARY RESULTS FOR MANUSCRIPT PRESENTED IN CHAPTER 7

The following supplementary results and figures were produced along with the manuscript presented in Chapter 7. While performing the Modified Proctor/Fagerberg Test (MPFT) and standard Proctor/Fagerberg Test (PFT) there were some issues that arose when testing certain samples of iron ore fines with distinct properties.

These issues were considered to be influencing factors resulting in the provisions outlined by the Iron Ore Technical Working Group (TWG), which are explained in Section 7.3.4. These provisions included the particle size and goethite content limitations resulting in a cargo being considered either iron ore fines, Group A and able to liquefy, or iron ore, Group C and not able to liquefy (International Maritime Organization, 2013a).

Explained herein are some contributing issues that were assumed to be related to the inclusion of these provisions in the amendment (International Maritime Organization, 2013a). When testing iron ore fines, which contained coarse particles (>75 μm) and had little or no fines (<75 μm), it was extremely difficult, if not impossible, to achieve saturation to the desired degree of saturation of 70 or 80 percent. It was common to only achieve saturation of up to 50 or 60 percent, where moisture began to seep from the base of the mould, as seen in Figure 376. This moisture content, at which seepage began, has been referred to as the materials moisture-holding ability.

![Figure 376 – sample of iron ore fines undergoing compaction exhibiting moisture flowing from the base reducing the ability to achieve the required degree of saturation as outline in the PFT or MPFT procedures](image)

This seepage is assumed to be similar to what would occur in the hold of a bulk carrier, also limiting the degree of saturation possible during marine transportation, as water seeping from the base would be evacuated overboard using the bilge system on-board. This would ultimately reduce the likelihood...
of liquefaction occurring in such a cargo, but not necessarily eliminate it. Blockages of the drainage system along with high moisture contents and dynamic loading may still result in liquefaction.

Figure 377 shows another sample that instead of draining occurring, significant dilation occurred. As the moisture content of the samples were increased, fine material was increasingly lost from the surface as the sample was levelled. The loss of fine material reduced the samples overall moisture content and increased the density, from the normal, producing a compaction curve that is not typical of those commonly produced and not representative of the sample tested.

![Figure 377 – sample of iron ore fines during the MPFT, after levelling, exhibiting dilation](image)

Other issues included; the reduced ability to homogenise some samples at lower moisture contents due to the minimal energy produced during compaction using the MPFT and fine sand and silt migration at higher moisture contents for samples that had gap-graded particle size distributions.
APPENDIX D—SUPPLEMENTARY RESULTS FOR MANUSCRIPT PRESENTED IN CHAPTER 13

The following supplementary results and figures were produced along with the manuscript presented in Chapter 13. Figure 378 to Figure 386 show Mohr’s circles for each of the samples tested and presented in the manuscript given in Chapter 13. The total failure envelopes shown were determined to estimate the total internal friction angles and total cohesion factors for analysis.

![Figure 378 – Mohr’s circles and the resulting total failure envelope for sample 1](image1)

![Figure 379 – Mohr’s circles and the resulting total failure envelope for sample 2](image2)
Figure 380 – Mohr’s circles and the resulting total failure envelope for sample 3

Figure 381 – Mohr’s circles and the resulting total failure envelope for sample 4
Figure 382 – Mohr’s circles and the resulting total failure envelope for sample 5

Figure 383 – Mohr’s circles and the resulting total failure envelope for sample 6
References

Figure 384 – Mohr’s circles and the resulting total failure envelope for sample 7

Figure 385 – Mohr’s circles and the resulting total failure envelope for sample 8
Figure 386 – Mohr’s circles and the resulting total failure envelope for sample 9
APPENDIX E – SUPPLEMENTARY RESULTS FOR MANUSCRIPT PRESENTED IN CHAPTER 14

The following supplementary results and figures were produced along with the manuscript presented in Chapter 14. Figure 387 to Figure 395 show different stages of the procedure for some of the samples tested during the preliminary scale model testing. Additionally, Table 96 shows photos of the samples during cyclic loading at specific time intervals during the preliminary scale model testing.

Figure 387 – Sample TML% during the preliminary scale model testing after 480 and 1800 seconds of vibration

Figure 388 – Penetration of sample TML% by Iron Ore Fines Plunger (IOFP)
Figure 389 – Void left in sample TML% by Iron Ore Fines Plunger (IOFP)

Figure 390 – After preliminary scale model testing of TML% had been completed and layer B (top layer) had been removed
Figure 391 – Pooling of moisture and fine particles shown after preliminary scale model testing was complete for sample TML + 0.5%

Figure 392 – Pooling of moisture and fine particles shown after preliminary scale model testing was complete for sample TML + 0.5%
Figure 393 – Penetration of sample TML + 0.5% by Iron Ore Fines Plunger (IOFP)

Figure 394 – Void left in sample TML + 0.5% by Iron Ore Fines Plunger (IOFP)
Figure 395 – Penetration of sample TML + 1.3% by Iron Ore Fines Plunger (IOFP)
Table 96 – Photos of the samples during cyclic loading at specific time intervals during the preliminary scale model testing (Note: Photos for TML – 1.6% were corrupted so are unavailable)

<table>
<thead>
<tr>
<th>Time (Secs)</th>
<th>TML – 1.9% (10.88% GWC)</th>
<th>TML% (12.82% GWC)</th>
<th>TML + 0.5% (13.37% GWC)</th>
<th>TML + 1.3% (14.09% GWC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
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<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
<td><img src="image7" alt="Image" /></td>
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<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX F – SUPPLEMENTARY RESULTS FOR MANUSCRIPT PRESENTED IN CHAPTER 15

The following supplementary results and figures were produced along with the manuscript presented in Chapter 15. As discussed in Chapter 4 Section 4.2.2, prior to applying pressures to saturate the samples using the advanced cyclic triaxial apparatus, the hydraulic conductivity of each sample was determined. In order to achieve this, once the sample was sealed within the triaxial, manual saturation was performed until a constant outflow rate was observed.

After manual saturation, a graduated cylinder was attached to the outflow, as seen in Figure 396, to accurately measure the outflow from the sample. The inflow from the sample was applied using a constant head apparatus seen in Figure 397 so the permeability could be determined.

Figure 396 – Sealed sample within triaxial and attached graduated cylinder for the determination of hydraulic conductivity prior to cyclic loading.
Figure 397 – Constant head apparatus used to apply a constant pressure to a sample during the determination of hydraulic conductivity.
The results in Figure 398 show that the hydraulic conductivity through this range of void ratios are fairly high. Although being able to accurately determine the average hydraulic conductivity as being $2.08 \times 10^{-5}$ m/s, after considering the possible margin of error, the relationship between the hydraulic conductivity and the range of void ratios tested was considered to be insignificant. With this said, the consistently high hydraulic conductivity exhibited by the samples at the range of void ratios tested showed the increased ability to dissipate pore pressures that cargoes of iron ore fines are likely to exhibit.

Figure 399 to Figure 409 show additional photos taken during the preparation procedure performed prior to the cyclic loading being applied to the sample in the triaxial. For more information on the preparation procedure used, please refer to Chapter 15 section 15.3.4.2.
Figure 399 – Compaction of sample A during preparation for the advanced cyclic triaxial testing
Figure 400 – After levelling of sample A during preparation for the advanced cyclic triaxial testing

Figure 401 – After levelling of sample D during preparation for the advanced cyclic triaxial testing
Figure 402 – After placement of top cap during preparation for the advanced cyclic triaxial testing
Figure 403 – After removal of split mould from sample A during preparation for the advanced cyclic triaxial testing
Figure 404 – After placement of second membrane and O-rings during preparation for the advanced cyclic triaxial testing
Figure 405 – After attaching back pressure tubes and applying initial vacuum to sample during preparation for the advanced cyclic triaxial testing
Figure 406 – During filling of cell with confining medium after placement around the sample during preparation for the advanced cyclic triaxial testing.
Figure 407 – Vacuum flask used to apply suction to sample during preparation and manual saturation for the advanced cyclic triaxial testing.
Figure 408 – Measuring temperature of water that passed through the sample to correct permeability readings made prior the advanced cyclic triaxial testing.
Figure 409 – Set-up prior to loading using the advanced cyclic triaxial apparatus
APPENDIX G – SUPPLEMENTARY RESULTS FOR MANUSCRIPT PRESENTED IN CHAPTER 16

The following supplementary results and figures were produced along with the manuscript presented in Chapter 16. As the preliminary and advanced scale model tests were presented in separate manuscripts, one aspect that was different between the two procedures was not clearly identified. During the preliminary scale model testing the sample was placed in a stockpile and during the advanced scale model testing the sample filled the entire mould and was levelled at the brim.

There was a concern that levelling would reduce the amount of segregation that would occur during testing due to the way the sample was initially placed. In order to visualise the amount of segregation that would occur tests were carried out where iron ore fines at varying moisture contents were stockpiled, in scale, to visualise the degree of segregation.

Figure 410 and Figure 411 show two of these tests where the samples were placed using a scoop no more than 2 cm from the surface of the peak of the pile. It was assumed that coarse particles would segregate when testing samples at the lower moisture contents, but the opposite can be seen to occur. Due to the increase in the angle of repose caused by the increase in moisture content, the samples with higher moisture content showed significantly more segregation of coarse particles around the base.

If the sample seen in Figure 411 was to be loaded cyclically and levelling occurred due to this loading, it would be assumed that the initial segregation would contribute to an increase in the overall segregation caused by moisture migration. This only further confirms the likelihood of partially liquefiable areas of cargoes being able to form on the surface of the cargo as discussed in Chapter 16.

Figure 410 – Air dried sample of iron ore fines (MA004) stockpiled with scoop using placements of less than 2 cm
Figure 411 – Sample of iron ore fines (MA004) at 10% gross water content stockpiled with scoop using placements of less than 2 cm

Figure 412 to Figure 415 show additional photos taken during the preparation procedure performed prior to the cyclic loading being applied to the sample in the scale model. Additionally, Table 97 shows the sample profiles before and after the cyclic loading was applied. For more information on the preparation procedure used, please refer to Chapter 16 section 16.3.3.2.3.

Figure 412 – Initial set-up of apparatus prior to filling the scale model with the specimen to be tested
Figure 413 – During placement of sample A into the scale model prior to cyclic loading being applied (1)

Figure 414 – During placement of sample A into the scale model prior to cyclic loading being applied (2)
Figure 415 – After placement and levelling of sample A into the scale model prior to cyclic loading being applied
Table 97 – Sample profiles before and after the cyclic loading was applied during the advanced scale model testing

<table>
<thead>
<tr>
<th>Sample</th>
<th>Before cyclic loading (front)</th>
<th>Before cyclic loading (side)</th>
<th>After cyclic loading (front)</th>
<th>After cyclic loading (side)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>N/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>