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Cyclic direct simple shear test on soft clay at low normal stress – As applicable to offshore pipeline axial walking problems

Yang Ao¹, Jayantha Kodikara¹*, D.J. Robert²

¹ Department of Civil Engineering, Monash University, Victoria 3800, Australia
² School of Civil, Environmental and Chemical Engineering, RMIT University, Victoria 3001, Australia

* Corresponding author. Email: jayantha.kodikara@monash.edu

Abstract: Offshore pipelines play a significant role in transporting energy resources such as crude oil and natural gas from offshore platforms to processing facilities. The on-bottom stability of offshore pipelines is influenced significantly by the geotechnical conditions at the seabed. Pipeline would undergo a number of thermal cycles during its operational life. At the end of each thermal cycle, some part of the expansion would recover, whereas the irrecoverable expansion would accumulate at the free ends and cause the pipe to move axially in one direction, known as Axial Walking. The test results from the Monash Advanced Pipe testing System (MAPS) imply that pipe axial walking would induce relative movements of the soil below the pipe. Since the pipe-soil interaction is extensively influenced by the soil response, the portion of the soil below the pipe which undergoes shearing, characterised as the Shear Zone, is significant for pipe axial walking assessment and thus needs to be investigated thoroughly. This paper presents an investigation into the behaviour of soil within the shear zone in pipe axial walking problems. Cyclic direct simple shear tests on soft clay at low normal stress are performed as applicable to axial walking problems. The soil response in the shear zone is characterised as undrained, partially drained, or drained based on cyclic shearing rates and the relationship between residual peak shear resistance and shearing rate is investigated. Finite element analyses are also conducted to capture the behaviour of soil within the shear zone, utilising advanced constitutive soil model. Based on the results from both experimental work and numerical analysis, a set of data is established which can be applied in the calibration of large-scale pipe axial walking modelling, and provide guidance on the design practice of offshore pipelines when considering on-bottom stability in axial direction.

Keywords: axial walking, cyclic, finite element analysis, offshore pipeline, simple shear, soft clay.

1 Introduction

Offshore pipelines play a significant role in transporting energy resources such as crude oil and natural gas from offshore platforms to processing facilities. Due to the increasing demand for fossil fuels in recent years, and the development of technology which makes access to deep-sea energy resources possible, the offshore energy industry has been growing fast. Longer pipelines are laid and such pipes are required to operate at more extreme conditions. For instance to prevent petroleum from solidification, high temperature and pressure need to be applied within some offshore pipelines. These new technical challenges mean that a better understanding of the behaviour of offshore pipelines is required and the design code for offshore pipelines needs to be upgraded accordingly.

The on-bottom stability of offshore pipelines is influenced significantly by the geotechnical conditions at the seabed. Pipeline instability could be caused by the thermal expansion and contraction corresponding to the production and shutdown cycles of offshore platforms [1]. Pipeline would undergo a number of such thermal cycles during its operational life. At the end of each thermal cycle, some part of the expansion would recover, whereas the irrecoverable expansion would accumulate at the free ends and cause the pipe to move axially in one direction, known as Axial Walking.
Consequently, the soil in contact with the pipe will also be subjected to both static and dynamic loading which could affect the long-term mechanical stability of pipelines. The pipe-soil interaction is analogous to structure-soil interaction in foundation problems involving cohesive soils. However, unlike foundation structures where flexibility is usually not allowed, offshore pipelines can retain certain flexibility without exceeding the limit state at the centre [2]. Similar to foundation problems, the pipe-soil interaction can be divided into vertical, axial and lateral directions. The pipe-soil interaction in both vertical and lateral directions has been investigated extensively [3, 4], whereas the axial pipe-soil interaction, which is regarded as the primary cause of pipe instability, is yet to be clearly established. Some work has been done for example, by Bruton et al.[5], White et al.[6] and Randolph et al.[7]. Most recently, a specialised 2D electric actuator system, the Monash Advanced Pipe Testing System (MAPS), has been developed in Monash University, Australia, and results from scaled axial soil-pipe interaction testing using MAPS have been made available [8].

The MAPS results imply that pipe axial walking would induce relative movements of the soil below the pipe [8]. Since the pipe-soil interaction is extensively influenced by the soil response, the portion of the soil below the pipe which undergoes shearing, characterised as the Shear Zone, is significant for pipe axial walking assessment thus needs to be investigated thoroughly.

This paper presents an investigation into the behaviour of soil within the shear zone in pipe axial walking problems. Cyclic direct simple shear tests on soft clay at low normal stress are performed as applicable to offshore pipelines. The results obtained from the experimental work are used to complement and improve the results obtained from MAPS testing. Finite element analyses are also conducted to capture the behaviour of soil within the shear zone, utilising advanced constitutive soil model. Based on the results from both experimental work and numerical analysis, a set of data is established which can be applied in the calibration of large-scale pipe axial walking modelling.

2 Backgrounds

2.1 Shear zone in offshore pipeline axial walking

Pipe axial walking would induce relative movement of the soil underneath the pipe. Since the pipe-soil interaction is extensively influenced by the soil response, the portion of the soil below the pipe which undergoes shearing, characterised as the Shear Zone, is significant for pipe axial walking assessment. To characterise the shear zone, Senthilkumar [8] applied image correlation analysis in MAPS testing. Based on the observations and results of all the experiments conducted, the zone of shear influence can be illustrated as in Figure 1 (a).

![Figure 1](a) Shear zone underneath axially walking pipe and (b) Loading pattern of direct simple shear test

The shear zone consists of two parts. The first part, zone h is the soil block from the depth immediately below the pipe to a depth of h. When pipe axial walking takes place, the soil within zone h moves together with the pipe at the same displacement rate. This zone can be considered as the
direct failure zone. The second part, zone H-h, is the soil block from the depth of h to the depth of H, where H is the limit depth of the shear zone. The soil in this zone would be mobilised when axial walking occur, but the soil does not move together with the pipe at the same displacement rate. Instead the displacement decreases as the depth increases.

The experimental data [8] suggests that higher axial displacement rate would lead to deeper shear zone, i.e. a larger value of H. It was found that the depth of zone h increases with both pipe axial displacement rate and pipe embedment. In contrast, the depth of zone H-h increases with increasing axial displacement rate but it is largely independent from pipe embedment. The axial displacement rate depend primarily on soil axial resistance as well as the expansion/contraction rate of pipe wall, which in turn depends on heating/cooling rate and the properties of pipe and soil.

The soil within the shear zone is subjected to axial loading while under the vertical pipe loading due to pipe weight. This loading pattern can be closely resembled by direct simple shear test, as shown in Figure 1 (b) above, in particular for zone H-h.

2.2 Utilising direct simple shear test in pipeline axial walking problems

In offshore pipeline axial walking scenarios, the seabed soil underneath the pipe undergoes slow cyclic shearing with low normal stress imposed. In order to further investigate the behaviour of soil within the zone of shear influence, in particular the load-displacement relationship, cyclic direct simple shear test was proposed as a preferred testing method. Direct simple shear test has been used extensively in offshore geotechnical engineering applications. The increasing popularity of direct simple shear test is mainly due the relatively small sample size required, and the shearing pattern which closely resembles the loading condition in offshore geotechnical engineering problems. In particular for pipe axial walking scenarios, the soil within the zone of shear influence is subject to horizontal shearing while under a vertical loading, which is similar to the loading conditions in direct simple shear test. Furthermore, cyclic shearing can be applied in direct simple shear test, which can simulate the operation and shutdown cycles of offshore pipelines. The direct simple shear test also has merits compared with other testing method. For instance in direct shear test the shear failure plane is fixed as the horizontal plane, while the failure plane in direct simple shear is not pre-defined.

When utilising direct simple shear test in investigating pipeline axial walking problems, it is important to have a sound knowledge of the relevant parameters involved. The primary variables are normal stress, shearing rate and shearing amplitude. Some literature has given guidance on the magnitude of these variables.

Normally the magnitude of effective normal stress imposed on soil is relatively low in pipe axial walking problems. The effective normal stress ($\sigma_{\text{eff}}$) equals the total normal stress ($\sigma_n$) minus the pore water pressure (u). In drained cases, total normal stress ($\sigma_n$) may not equal to effective normal stress ($\sigma_{\text{eff}}$) since pore water pressure can be very high due to the depth of seabed, which can be in the magnitude of kilometers. Bruton et al.[5] suggests that the effective normal stress generated by typical pipeline weights is at the levels of 2kPa to 10kPa. The first stage of the Furgo SMARTPIPE project [6] saw an effective normal stress between 1kPa to 3kPa. In a pipe interface shearing example given by White and Cathie [9], an effective normal stress of 5kPa was applied.

Regarding the shearing rate in pipe axial walking problems, the magnitude ranges from 0.5mm/s to 0.001mm/s, and could be even lower for fully drained conditions. Bruton et al.[5] advised that the available field data on pipeline velocities were limited, an example problem provided in the literature showed that pipeline velocities only exceed 0.2mm/s near pipe ends and the durations are very short, and an average velocity of 0.005mm/s was given. In the first stage of the Furgo SMARTPIPE project [6], 0.04mm/s was applied for sweeps 1-4 and 0.15mm/s for sweeps 5 and 6. In the SAFEBUCK JIP project [10] where test was performed on a soft marine clay, 0.5mm/s was used but for sweep no.22, 0.001mm/s was applied. In a direct shear test [9] where normally consolidated kaolin clay was sheared on a steel interface, 0.003mm/s was applied. In the Monash Advanced Pipe Testing System
(MAPS), the maximum shearing rate was 0.5mm/s and the minimum was 0.01mm/s. The selection of shearing rate aims at covering the undrained, partially drained and drained condition in pipe axial walking.

No clear guidance is provided on how to transfer the pipe axial walking displacements into the shearing amplitude of direct simple shear test. The ‘Standard Test Method for Consolidated Undrained Direct Simple Shear Testing of Cohesive Soils’ [11] suggests at least a 20% shear strain for shear strength determination purpose.

3 Experimental program

3.1 Soil selection

Initially, the investigation was intended to simulate the environment of the petroleum pipelines which were to be laid on the seabed of the North Western Shelf, Australia. However the use of actual soil material from the field was found not feasible due to both accessibility as well as quantity issues. Alternatively, as suggested by the researchers at University of Australia (UWA Centre for Offshore Foundation Systems), a kaolinite soil known as Prestige NY of Granville (NSW) was selected as the soil to be tested in cyclic direct simple shear tests. The Prestige NY kaolinite is commercially available and it was concluded that it exhibits similar characteristic to that of the seabed soil [8]. A summary of the average geotechnical data of the seabed silt as well as the Prestige NY kaolinite is given in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Soil properties of Seabed silt and Prestige NY kaolinite [8]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Seabed silt</strong></td>
</tr>
<tr>
<td>Specific Gravity</td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
</tr>
<tr>
<td>Average Compression Index, c&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>Compressibility Parameter, λ</td>
</tr>
<tr>
<td>Average Swelling Index, c&lt;sub&gt;s&lt;/sub&gt;</td>
</tr>
<tr>
<td>Unload/Reload Parameter, κ</td>
</tr>
<tr>
<td>Average Coefficient of Consolidation, c&lt;sub&gt;v&lt;/sub&gt; (m&lt;sup&gt;2&lt;/sup&gt;/sec)</td>
</tr>
<tr>
<td>Average Permeability (m/s)</td>
</tr>
<tr>
<td>Secondary Compression, c&lt;sub&gt;a&lt;/sub&gt;</td>
</tr>
<tr>
<td>Drained/Undrained Friction Angle, φ' (°)</td>
</tr>
<tr>
<td>Critical State Line, M</td>
</tr>
</tbody>
</table>

3.2 Experimental Setup

Cyclic direct simple shear tests would be performed on Prestige NY kaolinite clay at low normal stress, using the GDS Standard Simple Shear System (GDS-STDSS). The GDS simple shear system is an electro-mechanical shear testing device which is designed to conform to the requirement of ASTM-D6528 (2007), ‘Standard Test Method for Consolidated Undrained Direct Simple Shear Testing of Cohesive Soils’.

The specimens tested in GDS simple shear system are cylindrical specimens with 50mm diameter. The specimen is laterally confined by Teflon coated low friction retaining rings as shown in Figure 2 (a), ensuring a constant cross-sectional area during shearing. The initial height of the specimen can vary by adjusting the number of rings. During soil specimen preparation and insertion, the friction rings are first constrained by supporting forms and the reconstituted soil is inserted into the sample preparation apparatus, as shown in Figure 2 (b). The assembly is then set up in the system as shown in Figure 2.
(c) and the supporting forms are removed. The top cap makes contact with the specimen and the hold-down assemblies are secured into place as shown in Figure 2 (d).

3.3 Pore Pressure Measurement

It is hard to achieve truly undrained condition in direct simple shear test, unless a pressurised chamber is used to host the sample. The GDS simple shear system is not originally designed to be capable of doing truly undrained test and to be equipped with pore pressure measurement capacity. In the current experimental setup, the drainage is kept open during consolidation as well as shearing. However, when the shearing rate is not slow enough, some amount of excess pore pressure would build up, since dissipation of pore pressure is not fast enough. As such pore pressure transducer is added to the system to estimate the level of excess pore pressure during shearing. The base pedestal of the sample setup, where the bottom porous stone is attached to, is connected to pore pressure transducer through the bottom drainage port as shown in Figure 3 above. If the base pedestal is saturated and the bottom drainage valve is closed, the reading from the pore pressure transducer would give an estimation of the pore pressure level at the bottom of the specimen.

3.4 Test approach and plan

The effective normal stresses imposed on soil in pipeline axial walking problems are relatively low, in the range of 2kPa to 10kPa. In the current testing system, a 10kPa normal stress equals an applied vertical load of 19N, and the corresponding shear load is even smaller. After several trial tests, it is concluded that the current testing system cannot produce satisfactory results under such low normal stress, due to friction of the horizontal actuator rail and the accuracy of the data taking components. Therefore a higher normal stress of 60kPa was applied in the tests conducted. Offshore pipelines may experience such higher normal stress in situations like pipe laying or pipe burying that aims at preventing upheaval buckling.
Table 2 Summary of test parameters

<table>
<thead>
<tr>
<th>Initial moisture content</th>
<th>Consolidation Stress</th>
<th>Total normal stress during shearing</th>
<th>Shearing amplitude</th>
<th>Shearing Rates</th>
<th>No. of Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>70%</td>
<td>60kPa</td>
<td>60kPa</td>
<td>10% of specimen height</td>
<td>0.3mm/s</td>
<td>10-30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.03mm/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.005mm/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0005mm/s</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 summarises the parameters of the tests reported in this paper. The Prestige NY kaolinite was first mixed from powder state to slurry using a soil mixer to 70% initial moisture content. All soil specimens were first normally consolidated to an effective normal stress of 60kPa in the testing system before shearing took place. Cyclic direct simple shear tests were performed on the normally consolidated specimens under a constant total normal stress of 60kPa. The cyclic shearing followed a sinusoidal horizontal displacement function. The shearing amplitude was 10% of sample height and various shearing rates were applied to cover the undrained, partially drained and the drained scenarios.

4 Test results

4.1 Pore pressure development during cyclic shearing

Shearing rates significantly affect the level of excess pore pressure that builds up during cyclic shearing, thus dominate whether the soil response in the shear zone is undrained, partially drained, or drained during pipeline axial walking. The readings of the pore pressure transducer, which was connected to the bottom drainage port, were recorded during cyclic shearing. Figure 4 shows the pore pressure readings versus time plots for four shearing rates. The shearing rates, from fastest to slowest, are (a) 0.3mm/s, (b) 0.03mm/s, (c) 0.005mm/s, and (d) 0.0005mm/s.

Figure 3 Pore pressure transducer readings during cyclic shearing
The shear strain versus time curves are also plotted on the same graph for each shearing rate. The plots show that for fast shearing rates, excess pore pressure is continuously built up as cyclic shearing progresses and it induces higher level of excess pore pressure. The fast shearing cases can be characterised as undrained shearing. For medium shearing rates cases, excess pore pressure is generated and plateaus, and as cyclic shearing continues, excess pore pressure dissipates. The medium shearing cases can be characterised as partially drained shearing. For slow shearing cases, the level of excess pore pressure is negligible compared with other cases and hence the slow shearing cases can be characterised as drained shearing.

4.3 Peak residual shear stress in cyclic shearing

The peak residual shear stress in cyclic shearing indicates the level of axial soil resistance in the shear zone when offshore pipeline axial walking occurs. Figure 5 (a) shows the peak residual stress against shearing rate plot in absolute values. Figure 5 (b) presents $\tau_{\text{peak}}/\sigma_n$ versus shear strain rate curve, where $\tau_{\text{peak}}$ is the peak residual shear stress, $\sigma_n$ is the total normal stress and shear strain rate is the shear displacement as a percentage of specimen height per hour. The curves imply that slower the shearing rate, the higher the peak residual shear stress. This is consistent with the excess pore pressure development in cyclic shearing. Slower shearing rate generates lower level of excess pore pressure that induce higher effective normal stress to result in higher shear stresses.

![Peak Shear Stress Vs Shearing Rate](image)

![\(\tau_{\text{peak}}/\sigma_n\) Vs Shear Strain Rate](image)

Figure 5 Peak residual shear stress versus Shear rate

5 Finite element analysis

5.1 Two-dimensional model of cyclic direct simple shear test

A two-dimensional finite element model has been developed using ABAQUS to investigate the modelling capabilities of direct simple shear test (Figure 6). The soil was represented by 4-node bilinear displacement and pore pressure elements (CPE4P) and the behaviour was simulated using modified Cam-clay model (Table 3 provides the model properties). A constant normal stress is applied uniformly on the top during consolidation and cyclic shearing. Pore water is free to drain from the top, and the bottom drainage is closed, same as in the experimental setup. Cyclic shearing is implemented by defining the horizontal displacement of the nodes along the vertical edges. The distribution of horizontal displacement along the vertical edges is linear and the two nodes at the same height level have the same horizontal displacement, as demonstrated in Figure 7 (a). The implementation is consistent with the mechanism of horizontal displacement in the experimental setup, where the specimen is constrained by stack of retaining rings as shown in Figure 7 (b). Same as in the experimental program, the cyclic horizontal displacement also follows a sinusoidal function.
5.2 Preliminary results

The results of the FE model prediction is compared with the experimental data in Figure 8 and Figure 9 for the case of shearing rate 0.03mm/s. Figure 8 shows the shear stress-strain curves obtained from the finite element analysis and the experimental result. There is some difference between the initial stiffness (i.e. elastic response) of the soils modelled in FE in contrast with the actual experimental data. However, the peak shear stress prediction of the FE model matches closely with the experimental data. Further calibration is needed to obtain similar elastic response between the data.

**Table 3** Inputs to Cam-clay model

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic bulk modulus, $\kappa$</td>
<td>0.040</td>
</tr>
<tr>
<td>Shear modulus, $G$</td>
<td>Instantaneously Calculated</td>
</tr>
<tr>
<td>Intercept, $N$</td>
<td>1.903</td>
</tr>
<tr>
<td>Plastic bulk modulus, $\lambda$</td>
<td>0.174</td>
</tr>
<tr>
<td>Stress ratio at critical state, $M$</td>
<td>0.890</td>
</tr>
</tbody>
</table>

*Figure 6* Two-dimensional finite element model

*Figure 7* Implementation of cyclic shearing in FEA model

*Figure 8* Shear stress-strain curves of FE analysis and experimental results

*Figure 9* Excess pore pressure generation
In Figure 9 the time history of the pore pressure generation from the FE model is compared with the test data. In the experimental setup, where the pore pressure transducer was connected to the bottom drainage port, can only give an approximation of the excess pore pressure development in the specimen during cyclic shearing. In contrast, the excess pore pressure generation of the single element of the FE model is recorded instantly, demonstrating the corresponding excess pore pressure evolution during shearing. However, in general, the predictions of the excess pore pressure from the FE model agrees well with the experimental data as shown in Figure 9.

6 Conclusions

Cyclic direct simple shear tests on soft clay at low normal stress were performed as applicable to offshore pipeline axial walking problems. Shearing rates significantly affect the level of excess pore pressure that builds up during cyclic shearing, thus dominate whether the soil response in the shear zone is undrained, partially drained, or drained during pipeline axial walking. Various shearing rates were applied to characterise undrained, partially drained and drained cyclic shearing. The experimental results imply that slower the shearing rate, the higher the peak residual shear stress. This is consistent with the excess pore pressure development in cyclic shearing. Such results can be applied in the calibration of large-scale pipe axial walking modelling, and provide guidance on the design practice of offshore pipelines when taking into account on-bottom stability in axial direction.

A two-dimensional finite element analysis model of the cyclic direct simple shear test has been developed to capture the behaviour of soil within the shear zone, using modified Cam-clay model with the parameters calibrated using triaxial test data. The model predicts the realistic pore pressure generation and shearing response when compares to the experimental data. Having properly calibrated, such FE models can predict the realistic response of simple shear behaviour which replicate the underlying response of axial walking pipelines.

7 References

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