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Axial interaction behaviour of offshore pipelines

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ABSTRACT

Offshore pipelines are increasingly being required to operate at high temperature and pressure, and the associated axial expansion is a major concern for design. It is essential to have an in-depth understanding of pipe-soil interaction phenomenon to control the creeping and buckling failures. In this regard the paper presents laboratory modelling performed at Monash University to interpret the pipe-soil interaction behaviour. A special test setup (MAPS) was developed to model axial walking of pipe on clay seabed. Drained and undrained behaviour loading was analysed with different rates of axial movements. Based on the outcomes, the pre-peak, peak and residual components of the load displacement curve are explained using a simplified theoretical frame work.

RÉSUMÉ

Pipelines offshore sont de plus en plus nécessaire pour fonctionner à haute température, la pression et la dilatation axiale associée est une préoccupation majeure pour la conception. Il est essentiel d’avoir une compréhension approfondie du phénomène d’interaction sol-conduite pour contrôler rampante et le flambage des échecs. Cet article présente la modélisation en laboratoire effectuées à l'Université Monash à interpréter le comportement d'interaction conduite-sol. Une configuration de test spécifique a été (MAPS) développée à la marche modèle axial du tuyau sur terre battue fonds marins. Chargement comportement drainés et non drainés ont été analysées avec des taux différents de mouvements axiaux. Sur la base des résultats, les composants pré-pic, pic et résiduelle de la courbe de déplacement de charge sont expliquées comme un cadre de travail théorique.

1 INTRODUCTION

Pipelines are one of the most important, infrastructures in offshore industry. Due to the increasing demand for hydrocarbon resources, exploration has accessed into deep seabed resources where longer pipes are required to operate at high temperature and pressure to prevent the solidification of petroleum.

At such elevated operating conditions, the pipe wall would experience significant thermal stresses which they tend to relieve by expanding along the pipe axis. During its operational life span, a pipeline would undergo several such thermal cycles that would result in corresponding expansion and contraction of the pipe wall. At the end of every thermal cycle, some part of the expansion may be recovered, while the irrecoverable expansion would accumulate at the free ends to cause the pipeline shift towards one direction, known as axial walking. Instances where the pipeline ends are fixed and axial forces exceed the critical buckling load, the pipe buckles laterally in the form commonly known as lateral buckling.

Though the lateral pipe-soil interaction has been well investigated in the past, and methods such as pre-buckling or snake-lay are already in practice to mitigate the buckling phenomenon (Bruton et al. 2008; Bruton et al. 2005; Randolph and White 2008; White and Randolph 2007), the research into axial interaction behaviour are only at its infancy where the available models only explains the break out resistance under drained and undrained limit states. In recent years however, more emphasize has been placed on the axial interaction behaviour and its significance to control the overall buckling tendency of a pipeline. In particular, Bruton et al. (2008), in reporting the findings of Safebuck JIP project, highlighted the importance of axial interaction behaviour to help any subsequent upheaval buckling (UHB) analysis, lateral buckling design, pipeline pull out and retrieval analysis.

Several complications for the research into pipe axial interaction phenomenon can be identified. Foremost, it is complicated to model the low interface effective stresses induced by the buoyant effect on the pipeline, or to prepare the low shear strength (0 to 10 kPa) soil that represents the deep seabed conditions. Since such low stress and strength properties are not common to the conventional geotechnical applications, the axial interaction phenomenon cannot be suitably tested by means of conventional shear tests. Another practical difficulty to interpret the axial interaction behaviour is the complication to account for the stress reversal and the varying rate of axial displacement. Depending on the pumping and cool down cycles, the pipeline would exhibit varying rates of displacement at different sections of the pipe axis.

In this regard, the current paper presents a laboratory modelling performed at Monash University to interpret the pipe-soil interaction behaviour and its dependency on the influencing factors. Experiments were performed on a lab-made soil profile characterised to the properties of deep offshore seabed. Instead of simulating the actual thermal expansion, pipe axial displacements were mechanically imposed using a specialised 2D electric actuator (Monash Advance Pipe testing System), purpose built to handle both the drained and undrained rates of axial loadings. Based on the outcomes, the pre-peak, peak and residual components of the load displacement curve are explained as a simplified theoretical framework.
2 TEST SETUP

Initially, a 2D electric actuator Monash Advance Pipe testing System (MAPS) capable to induce displacements in both horizontal and vertical directions with a precision of 0.01 mm/s was devised. A steel pipe length of 350 mm was selected for the tests. It was found from the literature (Brennødden and Stokkeland 1992; Brennødden et al. 1989; Cheuk et al. 2007) that the effects of end pressure are significant in any axial simulation of buried or bottom embedded pipes. Thus, as recommended by Brennødden et al. (1989), dummy pipe sections of length (200 mm) more than half of the test pipe sections were connected to the test pipes to eliminate the boundary effects. Figure 1 shows the arrangement of the pipe test section and the dummy section.

![Figure 1. Pipe and end sections](image)

The end pipe sections are connected to the test section via Load cells (Figure 2), and the axial resistance acting on the middle pipe section was measured using the difference between the load cell readings. Only smooth pipe surface conditions with no surface coating were tested. A test box with inner dimensions of 0.8m (L) X 1m (W) X 1m (H) was used for the model seabed preparation. The soil was selected for its resemblance to the properties of the seabed silt sourced from the North Western Shelf of Australia. Initially this kaolin was homogenised for twice the liquid limit and spread on the sand layer while having a water level above the soil to avoid any air entrapment. The consolidation process was carried out in stages unless the desired final consolidation height of 450 mm is reached. Both vacuum and load induced consolidation were performed. As reported by Cheuk et al. (2007) the pumping was performed for 20 to 30 days to achieve the target soil shear strength at the surface. The soil shear strength profile after every consolidation cycle was probed by T-bar penetrometers (Stewart and Randolph 1994) and vane shear spot measurements.

![Figure 2. Connection of load cell between the test and end sections](image)

The commercially available Prestige NY kaolin, sourced from Granville, New South Wales was used for the model seabed preparation. The soil was selected for its resemblance to the properties of the seabed silt sourced from the North Western Shelf of Australia. Initially this kaolin was homogenised for twice the liquid limit and spread on the sand layer while having a water level above the soil to avoid any air entrapment. The consolidation process was carried out in stages unless the desired final consolidation height of 450 mm is reached. Both vacuum and load induced consolidation were performed. As reported by Cheuk et al. (2007) the pumping was performed for 20 to 30 days to achieve the target soil shear strength at the surface. The soil shear strength profile after every consolidation cycle was probed by T-bar penetrometers (Stewart and Randolph 1994) and vane shear spot measurements.

2.1 Pipe layout

The test pipe, dummy pipes and the assembled pipe set up were weighed under submerged conditions and the results are presented in Table 1.

![Figure 3. Test setup](image)

Table 1 Pipe weight

<table>
<thead>
<tr>
<th>Part</th>
<th>W’(N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth Test / Dummy pipe</td>
<td>182</td>
</tr>
<tr>
<td>Smooth Pipe assembly</td>
<td>203</td>
</tr>
</tbody>
</table>
The assembled pipe setup was then placed (Figure 5) on the model seabed and the immediate settlement due to self-weight was measured. Once the immediate embedment was attained, soil consolidation was permitted and the corresponding pipe settlement was measured against time.

The pipe was axially displaced to investigate the axial interaction behaviour once it reached final embedment. Initially a relatively slow pipe movement rate of 0.01 mm/s was induced on the pipe to examine the cyclic load-displacement behaviour. Once this test was completed, a shutdown period was maintained and subsequently, the next test was undertaken by increasing the rate of loading. This approach was repeated for a series of loading rates with shutdown periods in between. Thereafter, the embedment depth was increased by pushing the pipe further into soil by the actuator. After the consolidation has been completed, a series of tests were undertaken for a range of displacement rates between 0.01 mm/s to 0.5 mm/s.

3 RESULTS

The results of both the T-Bar profiling and the Vane shear spot reading are presented in Figure 6. From the results it is evident that the Vacuum consolidation was found not effective in achieving the required shear strength of the soil. The use of surcharge pressure was, however, observed to be strengthening up the soil at the surface and along the depth. The results of the Vane shear measurements and the shear profiling of the T-bar are extrapolated and the soil shear strength at the surface level was calculated as 0.487 kPa.

In order to better characterise the governing conditions on axial interaction behaviour, the results are analysed only for the three distinct features of load displacement relationships. Their variance with embedment depth and displacement rate are interpreted and presented in the following subsections.

3.1 Residual

The pre-peak linear component of the load displacement behaviour can be better interpreted using the axial stiffness. For various embedment depth the change in axial stiffness with different rate of displacement are interpreted and presented in Figure 8. At a particular embedment, it is apparent that the axial stiffness of a pipe is relatively unaffected by the rate of displacement. However, with increasing embedment depth the pipe axial stiffness was found to be increasing, yet remained consistent at a particular embedment.
Figure 8. Axial stiffness vs rate of displacement of a smooth pipe

The pre-peak pipe load displacement behaviour of pipe-seabed interaction may be compared to that of the linear response of a vertically loaded pile in an elastic soil medium. Therefore, similar to the pile behaviour, the pre-peak displacement behaviour of a pipeline should also be primarily governed by the soil shear modulus (Randolph and Wroth 1978). Muir Wood (2004) indicated that the shear modulus of the soil should be unaffected by the rate of loading whether it gives a drained and an undrained soil response. Since the axial stiffness depends primarily on the shear modulus, the observed consistency of the axial stiffness of a pipe at various rate of displacement may be justified.

3.2 Residual resistance

The residual resistance of a load displacement relationship was identified to be reducing with cyclic loadings. Therefore, in the current analysis results are compared only for the ultimate consistent residual resistance where stability was achieved under the current loading conditions. The residual resistance different embedment depths are estimated for various displacement rates and presented in Figure 9.

Figure 9. Residual resistance vs rate of displacement of a smooth pipe

Here, the change in residual resistance of a particular embedment depth is compared against varying displacement rate. Irrespective of the displacement rate, the residual resistance of the pipe was found to be increasing with the embedment depth.

Also observed in the above figure is the influence of the rate of axial displacement on the pipe residual resistances. At low rates of pipe axial displacement, the residual resistance is comparably higher than the ones with higher displacement rates. A transition from high to low axial resistance is evident as the rate of pipe displacement increases.

The observed change in residual resistance at various rates of axial displacement and pipe embedment could be further explained for the drained and undrained soil behaviour. At fast rate of pipe axial displacement, the time required for the pore pressure dissipation is momentary, so the soil should have sheared under undrained conditions. Since the undrained shear strength increases with the increase in embedment, at faster rate of displacements a corresponding increase in residual resistance with pipe embedment can be expected. On the contrary, at low rates of displacement, drained shearing is more likely where the residual resistance depends only on the frictional properties between soil and pipe surface. Therefore, the drained soil resistance of a pipe is unaffected by the embedment depth, rather depended only on the pipe contact area.

3.3 Peak resistance

Peak resistance is the other important feature characterising the pipe load-displacement behaviour. As indicated in the previous sections, in almost every condition, the peak residual resistance was observed at the initial displacement cycle. With increasing shear cycles, the peak at each cycle was found to gradually reduce and eventually attain a consistent residual resistance.

As a common feature, the peak resistance of a pipe at a particular embedment was found to reduce with increasing rates of pipe axial displacements. Further, for a particular axial displacement rate, the pipe peak resistance increased with the increase of the embedment depths. Since a peak resistance is associated with a corresponding residual resistance, using just the peak resistance for comparison would not be entirely appropriate for characterisation of the peak response. In order to characterise the importance of soil consolidation and rate effect on the peak response, the results are presented as the excess quantity of maximum vertical force minus the residual force normalised by the submerged pipe weight.

The difference between peak and residual resistances are presented in Figure 10. From the results, it can be seen that the difference between peak and the residual resistance is positively related to the depth of pipe embedment. Although these results indicate a generic understanding about the dependency of peak response, it should be noted that the embedment and displacement rates of the experiments are corresponds to the soil over...
consolidation and drained or undrained behaviour respectively.

It can be seen that the normalised peak load proportionately increases with the increase in pipe embedment as expected. The results also indicate that at low axial displacement rates (i.e., drained loading), the normalised excess peak loads are unaffected by the nature of soil consolidation level. However, this load is significantly affected by the level of consolidation of soil when undrained shearing has taken place.

### 4 GENERIC PIPE LOAD DISPLACEMENT BEHAVIOUR

On the basis of experimental understanding, a generic pipe load-displacement that can be used to characterise the pipe walking behaviour is formulated and proposed in the following section. As indicated in the previous section, all the pre-peak, peak and residual components that govern the pipe load displacement are explained for their dependency on the corresponding loading conditions.

A qualitatively representation of the generic pipe load displacement relationship is given in Figure 11. The change in trend in pipe axial load-displacement behaviour with respect to the embedment depth and the rate of axial walking is explained.

From the experimental observations, it was understood that at a particular embedment depth, the rate of pipe axial displacement (i.e., drained and undrained soil response behaviour) has no or negligible influence on the pre-peak load displacement behaviour. Therefore, in the generic load-displacement behaviour, the pre-peak response was represented by a straight line independent of the rate of loading. However, it should be noted that the pre-peak behaviour is consistent only for a particular embedment depth. With varying embedment depths, the contact area which is critical for the mobilisation of resistive forces, also increases and results in higher axial resistance than at a shallow embedment.

The influence of the peak resistance is depicted by height h. It was identified that at both drained and undrained conditions, the peaking (h) was influenced by the soil OCR (i.e., pipe embedment). However, when compared to the drained loading conditions, the peaking was found to be more pronounced at undrained rate of displacement.

The residual resistance is the most significant component in the generic pipe load-displacement behaviour. It was identified that the residual resistance is influenced by the rate of pipe displacement. Therefore, the residual component is classified as the drained (slow) and undrained (fast) limits of pipe displacement.

For subsea conditions, it was found that the drained resistance is always higher than the undrained resistance. Thus, the drained residual resistance can be considered as the upper limit for pipe failures. This region between the undrained to drained limit is considered as the transition zone and demarcated in the figure as the failure region governed by the rate of pipe axial displacement.

Further, the undrained residual resistance was also found to be influenced by the change in pipe embedment. For instance, under undrained conditions, pipes at shallow embedment depth exhibits lower residual resistance than at deeper depths. Therefore, in regard to the embedment depth, the undrained (lower) limits of pipe residual resistance are further classified as upper and lower undrained limits. This region is demarcated as the failure region governed by the pipe embedment.

### 5 CONCLUSIONS

This paper presents laboratory modelling performed at Monash University to interpret the pipe-soil interaction behaviour. A special test setup was developed to model axial walking of pipe on clay seabed. Initially, the model seabed was consolidated and characterised to the required soil strength. Then test pipe with smooth surface roughness property was laid on the model seabed. Axial displacement analyses were performed for various embedment depth and displacement rates. Based on the solutions, the following conclusions are drawn.

The load displacement curve consists of three main components: pre-peak, peak and residual resistances.
The pre-peak resistance was unaffected by the rate of axial loading but was influenced by the change in embedment. The peak resistance was in its highest value in the first cycle following shutdown, but was found to reduce with increasing number of cycles. The development of peak resistance was prominent for the pipes embedded in over-consolidated soil, and when the tests are conducted at a faster rate of axial displacement. The residual resistance, which is the most critical parameter in determining the pipe axial walking behaviour, was found to be influenced by the rate of loading. Based on this, both drained and undrained limits of residual resistance were established. It was also understood that the undrained residual resistance is always smaller than the drained residual resistance. The embedment depth was found to have varying influence on the drained and undrained behaviour. The experimental understanding is further simplified and generic pipe load displacement behaviour was explained for the characterisation of pipe walking behaviour and for further modelling.

REFERENCES


