The 21st International Offshore and Polar Engineering Conference,
Maui, Hawaii, USA.The 21st International Offshore and Polar Engineering Conference, Maui, Hawaii, USA.

# Laboratory Modelling of Pipe-clay Seabed Interaction in Axial Direction

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## ABSTRACT

The current trend of bottom embedding of offshore petroleum pipelines are increasingly being challenged by the expansion of the pipeline at elevated operating conditions of temperature and pressure. For simplicity, the expansion challenges could be classified into axial walking and lateral buckling, relevant to the axial and lateral components of interaction. This paper summaries current knowledge on the axial resistance of surface laid pipes and, in general, the pipe-soil interaction in axial direction. The experimental works obtained from literature are detailed and modelling techniques are reviewed. Finally, the development of Monash Advance Pipe testing System (MAPS) for the further investigation of axial response is explained and the testing methods are discussed.

KEY WORDS: Axial walking, Physical model, Pipelines, Interaction

## NOMENCLATURE

| | |
|---|---|
| $\alpha$ | Adhesion factor |
| $A_c$ | Contact area between the pipe and soil |
| $\delta$ | Friction angle between pipe and soil |
| $\phi$ | Friction angle of soil |
| $\mu$ | Friction coefficient between pipe and soil |
| $D$ | Pile/Pipe diameter |
| $V$ | Pile velocity |
| $w'$ | Submerged pipe weight |
| $S_u$ | Undrained shear strength |
| $\zeta$ | Weight modification factor |

## INTRODUCTION

The increasing demand for hydrocarbon resources means that pipelines are being developed from deep offshore resources and hence longer pipelines. Thus the offshore pipelines transporting the oil and gas require to be operating at rising temperature and pressure to prevent the solidification of petroleum. At these elevated conditions, the pipe wall experiences significant thermal stresses and hence resulting in expansion. As surface laid pipelines are partially embedded in the seabed, any natural tendency to expansion will be restrained by the interaction between the pipe casing and the seabed soil. Free expansion is not favourable for pipeline integrity as it could lead to instability in the pipe route and failure of the end region at extreme. The conventional method of addressing the expansion problem is by spooling anchors and a possible alternative is to snake-lay the pipeline and allow engineered lateral buckling to take place. In any case, a full understanding of the axial pipe-soil interaction is required for an efficient design solution.

The behaviour of the surface laid pipelines could be classified into two themes; 1. axial behaviour relevant to the expansion along the pipe axis and 2. lateral behaviour relevant to the expansion induced buckling in the lateral direction. The common method of incorporating pipe-soil interaction is by using frictional coefficients for axial and lateral directions. British Standards PD8010 provides some guideline on the friction coefficient for both axial and lateral resistance based on UK's North sea pipelines. The axial resistance leads to stress build up along the expanding pipe axis. The axial resistance along a pipeline is not uniform and the ends are not fixed, thus the pipeline experiences varying degree on expansion. When the pipeline undergoes thermal cycles during start up/shut down, the expansion and contraction along the pipeline is not uniform and this leads *Axial walking* where the pipeline tends to move toward one direction. Instances where the pipeline ends are fixed and axial forces in the pipeline exceeds the critical buckling load and buckles laterally and this is commonly known as *Lateral buckling*. The lateral pipe-soil interaction has been well investigated in the past and industry's common method of lateral buckling mitigation is controlled pre-buckling or snake-lay. With increasing deep water explorations and increasing number of long distance pipelines in the near future, detailed understanding of axial pipe-soil interaction is warranted. Better understanding of axial behaviour pipelines will enable designers to make efficient designs.

This paper outlines the current state-of-the-art of axial pipe soil interaction and physical modelling techniques reported in the literature. The experimental setup developed at Monash University to investigate the axial pipe clay seabed interaction is introduced and the modelling procedures are also discussed.

## BACKGROUND

The recent investigations on laid pipe (e.g., Konuk, 1998, Bruton, et al., 2005, Carr, et al., 2006, Dendani & Jaeck, 2007, White & Randolph, 2007, Bruton, et al., 2008, Randolph & White, 2008) report the challenges and the conceptual design ideas for axial walking problem. It is commonly accepted that the axial walking can be an issue on low resistive surfaces, however Bruton et al. (2008), in reporting the findings of Safebuck JIP project, emphasized the significance of axial walking at both high and low degrees of axial resistive conditions. Generally, there will be concurrent interaction of axial, lateral, vertical and torsional movements but treating the axial and lateral interaction in isolation is a safe simplification of the complex pipe-soil interaction problem.

### Axial Walking

The axial walking can occur in drained and undrained condition in soft clay. The applicability of these conditions to pipeline behaviour will depend on the rate of pipeline expansion/contraction. Randolph and House (2001), provided the following guideline for drained and undrained condition for piles;

$$\frac{VD}{C_v} < 1 \text{ for fully drained condition} \tag{1}$$

$$\frac{VD}{C_v} > 20 \text{ for fully undrained condition} \tag{2}$$

where $V$ is the pile velocity, $D$ is the pile diameter and $C_v$ is the soil coefficient of consolidation, which predominantly depends on permeability of the soil which in turn depends on particle size distribution. While this is not directly relevant to the pipe problem, it shows the influence of some governing parameter groups on drained and undrained behaviour. Measurement of $C_v$ in laboratory should be undertaken at very low stress levels to be appropriate for the low interface stresses. This is difficult and the drainage is not unidirectional and the drainage length is uncertain as it could vary with different cycles. Thus, is it very difficult to identify and distinguish whether a loading event in the field is drained or undrained.

Oliphant and Moonachie (2006) provided scenarios where undrained responses are commonly assumed in practice, especially in the design of the motion of Steel Caternary Riser (SCR) along the Touch Down Zone (TDZ) can be considered undrained since the duration of loading is relatively short. The undrained response will also be expected during dynamic pipe laying and in stability assessment of shallow water pipelines. In deep water environments, however, seabed currents are low and depending on the soil type partially drained response could be imminent. The frequency and duration between thermal cycles will also determine whether the soil response is drained, undrained or partially drained. In reality the axial pipe-soil interaction is highly depended on a range of parameters and difficult to characterise under any pure loading systems. Thus detailed investigation of interaction between pipe and clay seabed is essential for correct and efficient pipeline design.

*Undrained* analysis of pipeline-soil system is identical to the classical undrained method to define the axial resistance capacity of pile shaft in cohesive soils known as total stress "alpha" method. Here the axial force will be calculated as a product of the shear strength $S_u$, the contact area between the pipe and soil $A_c$ with a multiplier adhesion factor $\alpha$ relevant to the pipe surface roughness (Audibert, 1980) as given in Equation (3). Fig.1 shows the schematic diagram of pipe-soil system.

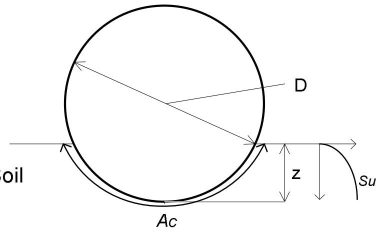


Fig. 1: Schematic diagram of pipe-soil system

$$F^u = A_c S_u \alpha \tag{3}$$

where contact area is

$$A_c = D\cos^{-1}(1-\frac{2Z}{D}) \text{ for } 0 \le Z \le \frac{D}{2}$$

and

$$A_c = \frac{\pi D}{2} \text{ for } Z \ge \frac{D}{2}$$

As the pipe is displaced during breakout, it is assumed that the shear strength reduces to the remoulded shear strength, giving peak $\left(F^{up} = A_c S_u \alpha_p\right)$ and residual values of resistance $\left(F^{ur} = A_c S_u \alpha_r\right)$. The distance to mobilize the peak and residual resistance are important parameters for undrained walking. Oliphant and Moonachie (2006) indicated that the peak undrained resistance of very soft clay could be typically mobilised within displacements of 3 to 5mm followed with the relatively constant residual stages accountable for large axial displacements. But, Dendani and Jaeck (2007) reported the peak resistance mobilisation distance as a function of diameter in the ranges of 0.3 to 0.8% and 2 to 3% for shallow and deeply penetrated pipelines respectively. In both instances the adhesion factor $\alpha$ is depended on the surface roughness of the pipe coating and found to be varying between 0.7 to 1.0. Further the initial embedment has an indirect influence on the undrained walking through the effective area $A_c$ in contact.

Although modelling of undrained conditions appears to be relatively straightforward, the main uncertainty would be determining the undrained shear strength at various consolidation levels. The undrained shear strength is proved to be increasing with depth. Thus the duration between loading cycles are expected to influence the soil response by dissipating pore pressure and causing additional consolidation. This ultimately affects the subsequent breakout resistance by increasing the soil shear strength and by changing the effective contact area at the pipe invert.

*Drained* analysis of pipe-soil system is identical to the effective stress "beta" method for axial resistance capacity of pile shaft in cohesive soil. The drained model utilises friction to define the axial resistance for cohesive soils as a product of the contact force and the soil friction coefficient $\tan\delta$ at a secant peak value at breakout ($\delta_p$) and then a reduction to a residual value ($\delta_r$) with higher displacements. In contrast to pile design, the contact force between the pipe and the seabed are known to be equal to the submerged pipe weight ($w'$). But Gourvenec and White (2010) and Krost et al (2011) indicated that the total contact force for axial waking could be higher than $w'$ due to the effect of wedging on the pipe wall due to the curved surface of the pipe geometry. The frictional resistance is given in Equation (4).

$$F^d = \mu\zeta w' \tag{4}$$

Compared to undrained, defining the drained walking is relatively straightforward. But its consistency is heavily determined by the rate of walking and the pore pressure regime around the pipe wall. According to Bruton et al (2008) the rate of walking should be as small as 0.2 mm/s for the drained condition to be applicable, which is not certain without any experimental evidence. Further, the complexity of all is associated with determining the interface friction coefficient representative to the test conditions at low effective stress levels (0-10 kPa). Bruton et al (2008) indicated that at submerged low effective stress conditions, the friction angles could be as high as 40 to 50˚, which is not very common for normally consolidated soft clays. Nevertheless, this apparently high friction coefficient in the drained model is not consistent too as it is expected to fluctuate with changing pore pressures (related to OCR) at the pipe-soil interface. The positive excess pore pressure affects the shearing by reducing the effective contact stresses at the interface, on the other hand development of negative pore pressure / suction could affect the subsequent cycles by increasing the breakout resistance. The influence of suction on breakout resistance is a subject overlooked in the past to simplify the problem and cannot be left out from the bigger picture for on bottom stability analysis of partially embedded pipelines.

As noted earlier, both undrained and drained conditions may be relevant under various loading conditions and generally provide very different values for axial resistance. The important transition from undrained to drained condition is not clearly established yet. To make the problem worse, pipelines are meant to work under different heating and cooling cycles with substantial shutdown periods related to production. Konuk (1998) and Carr et al (2006) explained the effects of heating cycles on axial expansions of pipelines by using temperature depended analytical models. Konuk (1998) studied the walking response of pipeline by using simple frictional models with thermal expansion on a soil medium. The portion of the expansion could be effectively recovered while the non-recoverable expansion accumulates along the axis. This study re-established the understanding of walking behaviour under cyclic loading conditions and conceptualized the non-recoverable part as global walking. Later Carr et al (2006) explained the effects of heating cycles on axial walking, where the anomalous heating with gradual cooling related to the production cycles lead to nonlinear expansion and linear contractions, so as the breakout and residual forces get propagated over the length of the pipeline.

## CURRENT STATE OF THE ART

The pipe-soil interaction behaviour is discussed in the recent DNV-RP-F105 code of practices for free spanning pipelines. The soil is mainly classified as cohesive (clays) or cohesionless (sands). The DNV standard further classifies the cohesive soil considering prevalent soil parameter from very soft to hard. Table 1 provides the soil properties according to DNV-RP-F105 soil classification.

In deep seabed conditions however the soil property is highly plastic with low shear strength (< 12.5 kPa) found to be increasing with the vertical profile. But, for the partially embedded pipelines, the soil down to a depth of 0.5 to 1.0 times of the pipe diameter is more relevant to the context and falls under the category of very soft clay due to the low shear strength at these shallow depths.

A very limited knowledge is provided by DNV-RP-F105 for axial walking on clay seabed. Here the pipe walking on cohesive soil is mainly considered as undrained and the axial frictional component is explained to be proportional to the undrained shear strength. No information is provided to classify the undrained and drained loading considering the rate of pipe movements. In current practice direct and simple shear testing are widely employed to characterise the interface behaviour between the concrete coated pipe walls and remoulded marine clay sample. As noted before, the challenge is accurately determining the interface behaviour of the seabed pipelines as representative to the test conditions of low effective stress levels. Generally the direct and simple shear testing machines developed for soil and rock interface testing could have levels of machine frictional resistance compared to the interface shear resistance at low effective stress levels. Therefore, it would be necessary to adopt special procedures to cater for these requirements.

Table 1: Subsea cohesive soil properties (adopted from DNV-RP-F105)

| Soil type | $S_u (kNm^{-2})$ | $\gamma'_{soil} (kNm^{-3})$ | $\nu$ | void ratio |
|---|---|---|---|---|
| Very soft | <12.5 | 4-7 | 0.45 | 1.0-3.0 |
| Soft | 12.5-25 | 5-8 | 0.45 | 0.8-2.5 |
| Firm | 25-50 | 6-11 | 0.45 | 0.5-2.0 |
| Stiff | 50-100 | 7-12 | 0.45 | 0.4-1.7 |
| Very stiff | 100-200 | 10-13 | 0.45 | 0.3-0.9 |
| Hard | >200 | 10-13 | 0.45 | 0.3-0.9 |

Pedersen et al, (2003) and Najjar et al (2003) suggested a tilt table method (Fig. 2) to conduct drained tests on interfaces of soft clay and flat steel plates coated with a number of propriety polymeric materials used for coating seabed pipelines at low effective stresses. These tests measured internal soil friction angles in the range 40˚ and 43˚ depending on the coating used, indicating the failure occurred mainly at the interface. Some of the deficiencies of this method include eccentric application of load, the change of the normal stress with the tilt angle, inability to conduct cyclic loading with full reversal and the lack of control of bearing failure of soil during loading.

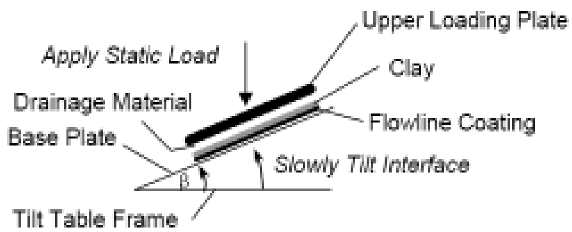



Fig. 2: Schematics of the tilt table test method (adopted from Najjar et al., 2003

Special alterations could cater in direct shear or simple shear testing to reduce the frictional resistance to characterize the interaction behaviour. But it could only underestimate the axial walking behaviour by neglecting the low effective stress at the interface, pipe geometry, drained/undrained response and cyclic loading conditions. Moreover there is significant uncertainty about the use of these state conditions in the presence of varying seabed soils, ill-defined boundary conditions and change in loading rates and durations. Emphasising, methods considering cyclic loading with stress reversal analogous to the thermal cycles, with influential measures for drained and undrained response to be developed for any future attempts to characterise the interaction behaviour in detail.

## PHYSICAL MODELS

Physical models provide good means to examine performance of prototypes for situations where field specific data are difficult to obtain. In the earliest of offshore engineering, the most common lateral walking phenomenon has been physically modelled to establish the fundamental understanding by load displacement relationship. But later the application of centrifuge to simulate offshore problems has paid much attention as it can scale down the test (1/100 or 1/150 size) with reduced real time reading (Allersma, 2004, Bruton, et al., 2005, Takatani, 2006, White & Randolph, 2007, Dingle, 2008, Merifield, et al., 2008, Randolph & White, 2008, Zhou, et al., 2008). However, for the axial walking-seabed interaction the centrifuge is not considered to give realistic values as the thin interface between the pipe and soil plays a dominant role, which depends on the parameters such as pipe roughness and soil particle size. These parameters including the soil particle size are difficult to scale down, which is required for accurate characterisation of the finite shear induced pore pressure developments at elevated gravity.

Brennodden et al (1986) and Wagner et al (1989) developed a large scale physical model to investigate the soil resistance for the lateral motion of untrenched submarine pipelines. The test facility illustrated in Fig. 3 permitted arbitrary force and displacement controlled time history applied to the pipe section with parallel recording of the reaction forces and displacements. Both monotonic and cyclic lateral loading were considered and the lateral movement was induced by a one dimensional hydraulic actuator. The main design consideration examined was Mohr-Coulomb envelop with friction angles related to soil properties.

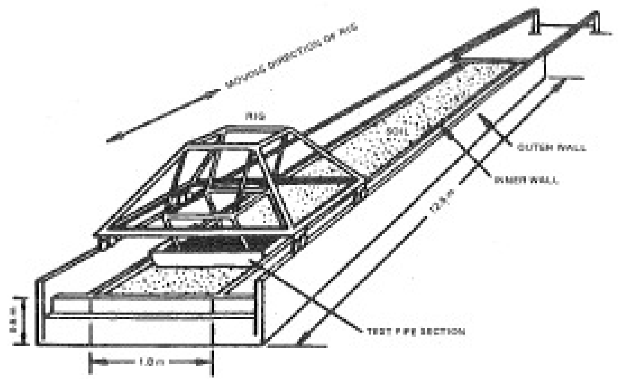



Fig. 3: Brennodden's test setup (adopted from Brennodden et al, 1986)

This study reported the effects of consolidation during shut down cycles, where the likelihood of suction caused the rise in breakout resistance in successive cycles. The results (Fig. 4) presented a high recorded breakout resistance with increasing shutdown cycles compared to the continuous cycles resulting unconsolidated shearing. Though the breakout resistance changed with the shut down time, the residual soil resistance tends to become constant as the pipe moved further. In the context of pure lateral buckling the high reported break out could be explained by the increase in passive resistance associated with the local consolidation below the pipe invert. Thus this study led to the classical way of thinking by including a passive soil resistance component $F_p$ to the classical approach of friction depended lateral resistance $F_f$. But in axial walking problem similar local consolidation below the pipe embedment could affect the undrained properties (Eq. 3) by changing the contact area as well as suction associated with the pore pressure dissipation.

A similar test for lateral loading of self buried pipelines was reported by Morris et al (1988). In this study too, both load and displacement controlled movements were initiated by a hydraulic actuator. However, a high plasticity soil with similar properties in place of actual seabed soil was used. This approach can be considered as an important transition of physical modelling techniques for offshore applications. In contrast to the Brennoddens's testing, the shear strength was measured by a motorised vane shear machine with subsequent water content measurements, which were used to crosscheck the spot measurements.

Brennodden and Stokkeland (1992) first ever reported laboratory experiments to verify the curve lay process. This study is considered to be one of the first attempts to characterise the axial walking behaviour using a laboratory model. They used only the monotonic loading by an hydraulic actuator, but innovatively, one dummy section of one half of the pipe length (1m) was used to avoid the end effects resulting from earth pressure at the pipe end during axial motions (Fig. 5). The resistance force encountered was quantified using a load cell fixed between the pipe and the dummy section. Furthermore, the influence of the pipe surface properties in the axial direction were accounted for by providing a single concrete coating to simulate the field conditions, and the pipe was free to move in the vertical and axial directions as the rotation of the pipe was restrained by the connecting rails.

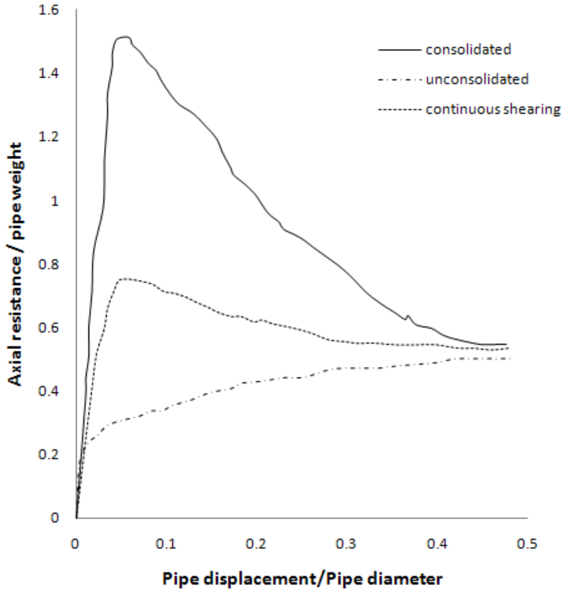



Fig. 4: Soil resistance vs. displacement (adopted from Brennodden et al, 1986)

Due to the limitations of the low sensitive hydraulic actuator the breakout mobilisation distance was studied only under a constant rate of displacement providing undrained conditions, thus the drained aspect of the problem was overlooked. The axial movement provided peak and residual values of axial resistance as shown in Fig. 5. The reported mobilisation distance of 5 mm agrees with the recommendations of Oliphant and Maconochie, (2006) and Bruton et al, (2008). The peak and residual values were explained by the change in the adhesion factor, but not by the change in shear strength. However, as noted before the adhesion is a function of the surface conditions (Audibert, 1980, Dendani & Jaeck, 2007). In addition, no apparent changes in surface properties were observed. This highlights the need for further research on the development of peak and residual displacements.

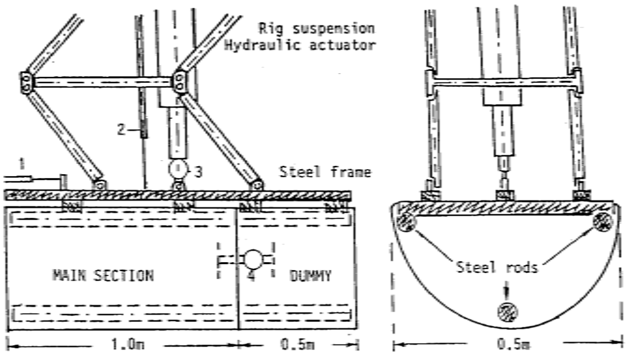



Fig. 5: Brennodden's axial walking test setup (adopted from Brennodden and Stokkeland., 1992)

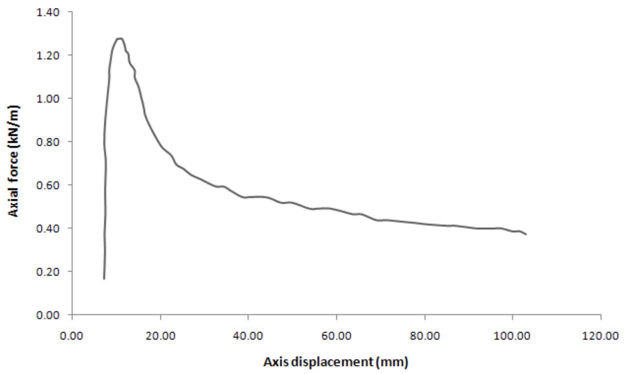


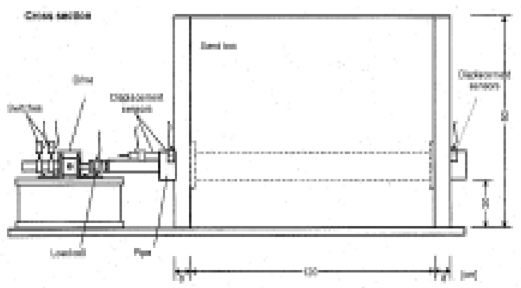

Fig. 6: Axial force vs. axial displacement (adopted from Brennodden and stokkeland, 1992)

Similar to the lateral loading explained before, it was observed that the change in breakout resistances corresponded to the delays between adjacent shearing. But in contrast to the passive resistance, this behaviour could be explained by the relative consolidation in between the adjacent loadings, which would have caused an increase in pipe embedment and contact area. Thus the resistive force then needs to be mobilised over this increased contact area. It appears that the breakout resistance has increased as a result of the soil shear strength increase along with pipe embedment. In fact, Dendani & Jaeck, (2007) indicated that the shear strength increased with depth on the basis of T-bar testing proposed by Stewart and Randolph (1994). In comparison, the displacement controlled analysis is found to be better than that based on loads for the effective measurement of interface forces.

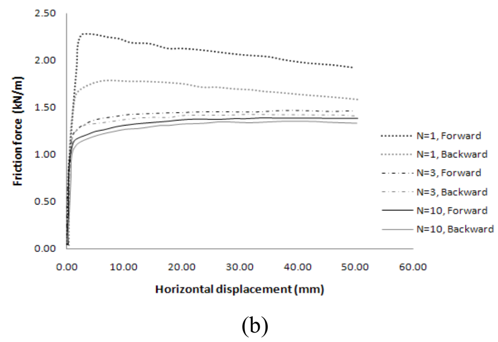
As reported by Dendani and Jaeck (2007), the Norwegian Geotechnical Institute (NGI) fabricated a system to test the axial and lateral motions of pipelines on laboratory created soil seabed obtained from north sea and western Africa . The system contains both load or displacement controlled electric actuators that are sufficiently accurate to move the pipe in vertical and horizontal directions. The main objective was to obtain soil resistance curves for the axial and lateral movements. In this case as well, the axial walking problem was explained on the basis of pure undrained motion, whereas the peak and residual mobilisation distances were studied for the definition of the adhesion factor. Thus the drained aspect of the problem was neglected and the subsequent local consolidation effects were not well interpreted. The testing could have been better explained if it was performed with pore pressure measurements, which would help quantify the stages of drained and consolidation during finite shearing.

Recently Weidlich and Achmus (2008) have conducted physical modelling for axial movements of buried pipelines on sandy soil, and the stress distribution around the pipe was interpreted using a ducted pressure sensor for the first time. Although this study is not directly relevant to the axial walking of bottom embedded pipelines on clay seabed, the testing methods used can be adapted to study the drained walking behaviour in detail.

The test setup is shown in Fig. 7a. The expansions were simulated by using a special actuator system. In contrast to Brennodden and Stokkeland, (1992) who used a dummy section, in this case, the pipe was extended through the test box in order to avoid the end effects due to earth pressure during pipe movement. The test was performed with poorly graded sand, and tamping was employed to obtain different sand compaction densities. This process was easier than to testing with cohesive soils that require substantial consolidation time to attain pore pressure equilibrium. Fig. 7b illustrates the measured friction force against the horizontal displacement of pipe at an embedment (w/D) ratio of 1.5. The maximum resistance was reported at the first movement and imminent difference in resistance was recorded between the forward and backward movements. And it was found that the forward resistance was always higher than the backward resistance. In cohesionless soil however, this behaviour could be explained by assuming grain reorientations during the forward and backward movements. These grain reorientations appear to have led to changes in stress and density states resulting in a fall in ultimate friction. Unlike buried pipelines that experience heavy overburden stress, in deep seabed the pipe is partially embedded with minimum vertical effective pressure at the interface between the pipe coating and the normally consolidated soil. However, even with partial embedment, the pipe can experience such axial behaviour due to changes in effective contact area and undrained shear strength. The peak resistance falls with consecutive cycles and eventually attains a residual state. Similar remoulding and grain orientation could be expected in cohesive soils too, but the shutdown related consolidation might induce soil suction resulting increases in successive breakout resistances. Thus the direct adaptation of frictional models (drained) is an oversimplification of the problem and the cohesionless sand may not behave like high plasticity clay found in the deep seabed.



(a)




(b)

Fig. 7 a. Weidlich's test setup b. load displacement curves (adopted from Weidlich and Achmus,2008)

As a part of the safebuck JIP (Cheuk, et al., 2007), large scale model tests were conducted for lateral sweeping of pipelines. The purpose was to investigate the combined lateral and related vertical movement of a pipeline during large amplitude cyclic sweeping under a constant vertical force. Commercially available E-Grade kaolin was used to prepare the model seabed that has similar properties to the clay extracted from the gulf coast of West Africa. The vacuum consolidation was found to be effective to speed up the self weight consolidation considering the time required to simulate the seabed conditions.
The test was performed under fully submerged conditions as illustrated in Fig. 8. An electric actuator controlled by a stepper motor was employed and the vertical motion of the test pipe was permitted via linear bearings. This study first ever employed the pore pressure transducers (PPT) to quantify the pore pressure dissipation during initial consolidation and lateral loading. When following a shutdown, an increase in breakout resistance occurred similar to the peak of continuous shearing, indicating an abrupt increase in suction with the shutdowns. Thus this study recommended the use of both positive and negative PPTs specially mounted at the pipe surface to measure the pore pressure dissipation.

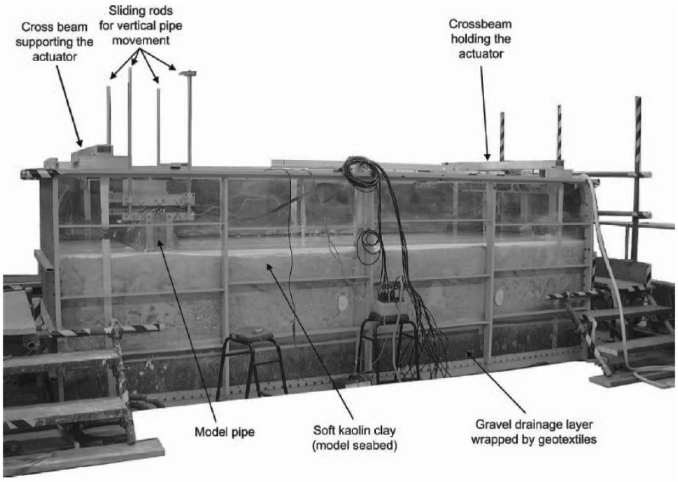



Fig. 8: Large scale test rig of Oxford university (adopted from Cheuk et al., 2007)

Though there are well developed physical models reported in the past for pipe interaction in clay seabed, it is clear that there is a lack of literature to establish the details of axial pipe soil interaction behaviour. The drained and undrained rate of loading is still not clearly defined. Unfortunately the only reported axial walking physical model of Brennodden and Stokkeland (1992) did not investigate the importance of cyclic loading conditions where the stress reversal and rate of change in shearing direction would seriously affect the load displacement behaviour. Furthermore, the importance of the effects of suction on breakout resistance found in large scale lateral loading (Cheuk et al ,2007) on the pipe behaviour in axial direction is not established. The unknown effects arising from the depth dependent shear strength characteristics and additional penetration from shutdown consolidation constitute to a knowledge gap that needs to filled through a detailed investigation accounting for both drained and undrained loading conditions.

## MONASH ADVANCED PIPE TESTING SYSTEM (MAPS)

Physical modelling to investigate the axial walking under drained and undrained condition is underway at Monash University, Australia. A sophisticated 2D electrical actuator with a precision of 0.01 mm/sec (to account the slow axial walking process) was devised to simulate the pipe motion on a laboratory made clay seabed (See Fig. 9). A horizontal linear motor capable of driving the shaft with a drive force between 300 to 500 N for a stroke length of 200 mm is provided. The vertical motion is controlled by a motor providing 200 to 300 N drive force to an expected stroke length of 200 mm. Both load and displacement controlled cycles could be performed at different rates, and the discrete or synchronised movements of the motors could be controlled by a computer. The system is suitable for element testing of typical prototype pipe diameters.
A pipe length of 350 mm was seen appropriate, and it was found from the literature review that the effects of end pressure are seen significant in any axial simulation for buried or bottom embedded pipes, hence dummy pipe sections of 200 mm are expected to be appropriate to connect at the ends to modify the boundary condition and to be free from end effects as recommended by Brennodden and Stokkeland, (1992). Fig. 10 shows the pipe section and the dummy pipes. The pipe box of 1 m x 1 m x 0.8 m was selected after studying finite element model (FEM) of the pipe-soil system to eliminate boundary effects. The seabed preparations will be carried out in stages, where the bottom 200 mm will be filled with sand (8/16 size) to provide the drainage layer, and the clay mixture will be homogenised for twice the liquid limit and will be spread on the sand layer while having a water level above the soil to avoid any air entrapment. To speed up the consolidation process vacuum consolidation by means of suction pumps was seen appropriate as reported by Cheuk et al (2007) with it is expected to take 20 to 30 days to achieve the target soil shear strength of 10 to 20 kPa at the surface. The soil shear strength profile is expected to be probed by a T-bar proposed by Stewart and Randolph (1994) and further spot measurements are expected to be obtained using a vane shear apparatus.


Fig. 9: MAPS testing system

The test pipe will be first allowed to settle by its self weight to measure the as laid initial embedment. Currently the initial pipe settlement is calculated assuming undrained soil behaviour, although in real situations, consolidation takes places with time leading to additional embedment. This coupled phenomenon is examined by the authors using FEM analysis. The pore pressure transducers (PPTs) are used to determine the end of consolidation.
Once the pipe attains the constant embedment the cyclic shearing motion could be applied by the horizontal actuator. The shear in the pipe section is determined by the difference between load cell readings (fixed between the dummy sections and test pipe). Concurrent pore pressure measurements at preselected critical points (from FEM

analysis) are also recorded.

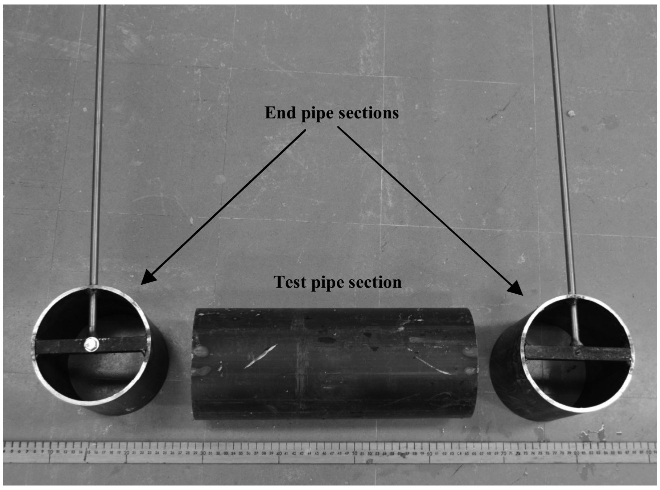



Fig. 10: Test pipe section and end section

The number of cycles and the appropriate shutdown periods are estimated from the typical production cycles reported by Carr et al (2006). There is no much literature available for field specific rate of axial walking, excepting to the information provided by Bruton et al (2008), who reported the extreme case scenario of pipeline walking in the range 0.01mm/s to 0.7mm/s. Therefore, the relevant actuators are programmed between these two extremes with increments of 0.05mm/s. It is intended to use two different pipe diameters with concrete weighted coatings classified as soft, medium and rough by the industrial coating companies. Three different soils have been chosen to represent natural seabed soils, namely (1) Prestige NY kaolinite that has similar properties to the extracted deep seabed samples from North western shelf of Australia, (2) Coode Island silt commonly found soil unconsolidated marine soils in Melbourne region similar the North western shelf silt, (3) the deep seabed silt itself.

## CONCLUSION

The axial pipe soil interaction behaviour is important for on bottom stability analysis of partially embedded offshore pipelines. In this paper, a detailed review of the literature is reported for axial waking behaviour. The rate of pipe expansion could be used as a parameter to define the axial waking behaviour under drained or undrained conditions. Unfortunately, not much literature is available to classify the axial rate of walking where soil would remain drained or undrained. In the context of undrained loading, the depth dependant undrained shear strength and adhesive conditions of the pipe wall are important to be accounted for. The undrained breakout and residual resistive forces are commonly explained as function of adhesion factor. A grain orientation and reorientation that normally expected in a drain soil could also be adopted to explain the similar break out and residual drained behaviour of cohesive soil; however the suction which is found to be influencing the lateral behaviour cannot be underestimated for subsequent breakout resistance for axial walking. Furthermore, the influence of production driven cyclic loading and shutdown are important for more realistic axial waking behaviour by affecting the subsequent break out resistance. Therefore a detail study to understand the axial pipe soil interaction behaviour is important to address the knowledge gaps identified.
Physical modelling techniques used in the previous studies of pipe soil interaction behaviour are detailed. Inspite of their direct relevance for pure axial pipe soil interaction behaviour, the extensively reported lateral loading testing methods could be further analysed to understand the axial behaviour in detail. The initial embedment is an important factor and the time delay between initial lay and subsequent cycle expected to be influencing the interaction behaviour between pipe and soil. In addition, the importance of shutdown cycles and subsequent pore pressure dissipation are proven to be significant for lateral buckling and have to be accounted for axial walking as well.
A test setup to model the axial waking behaviour is underway at Monash University. The end effects due to using element pipe testing will be eliminated by dummy sections which will be connected at the ends of the test pipe. The resistive force that the pipe experience will be quantified by the load cell attached between the end sections. Both drained and undrained loading could be performed by a special 2D actuator and will be crosschecked by the pore pressure transducer embedded in the soil and the pipe invert. The uncertainty of rate of loading, stress reversal due to cyclic loading, shutdown and related break out and residual will be studied for change in surface conditions of the pipe.

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