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MODELLING OF PIPELINE AND CABLE FLOTATION CONDITIONS

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Abstract
This paper aims to give a new perspective on physical modelling investigation of pipeline/cable flotation in post-jetted fine-grained soils. The effect of bed preparation on soil resistance was assessed by performing pipeline pull-out tests in clays at various moisture contents. Two bed preparation methods were compared. The penetration of the pipe/cable through the fluidised soil, drags water lenses into the clay and leaves the soil in a disturbed state that persists and affects the mobilization distance of the pull-out tests. The mobilization of resistance is found to be dependent on the simulation of pipeline/cable installation process and embedment ratio (H/D).

1. Introduction

Safe fast and economically convenient connection between offshore and onshore facilities is a requirement that arises with the increased presence of offshore human activities and is met with the use of pipelines and cables. Trenching and backfilling of pipelines and cables is required to provide mechanical protection in regions where fishing and ship anchoring operations are present. It may also be required to contribute to the pipeline's required thermal insulation necessary in cold regions mainly for pipelines that transport oil or other hot products (Finch and Machin 2001). The necessity to optimise the pipeline/cable trenching and backfilling processes, to achieve a faster and safer procedure, increases the necessity to better understand the soil-pipe interaction and as well as the short and long term mechanical properties of backfilled material which are highly dependent on the installation technique and soil encountered (Cathie, et al. 2005). To optimise the trenching process, reduce laying costs and improve the handling time, lighter pipeline/cable materials may be adopted. Additional ways to reduce installation cost are to adopt fast and low power demand trenching approaches such as the post-lay jet-trenching technique (Finch and Machin 2001). Jet-trenching consists of injecting high-pressure water typically from an ROV (remotely operated vehicle) to fluidize the soil beneath the pipeline/cable. The pipe sinks into the fluidized soil and comes to rest at the bottom of the trench (Powell, et al. 2002). After jetting the soil undergoes self-weight consolidation that leads to increased soil unit weight, strength and resulting increased resistance to pipe/cable flotation or operational uplift forces. Jet trenchers are preferred to the much bigger trenching and backfilling ploughs, because they are easier to handle and deploy. With this process jet trenchers can form the trench and backfill the pipeline in one pass (Maconochie, et al. 2015).

A uniform fluidized soil that is slowly increasing its unit weight may result in the potential for product flotation (where lightweight pipelines and cables are used) as the unit weight of the cable/pipeline may be lower than the unit weight of the soil. Currently guidance on avoiding flotation is limited to anecdotal values of pipeline weight designed to achieve a specific gravity (SG) of 1.7-1.8 but the origins of such recommendations are unclear. Powell et al. (2002) propose a value of SG from 1.5 to 1.7 as a minimum criterion for flotation based upon previous model flotation tests. Optimization of this SG based design approach requires accurate knowledge of how the slurry and pipeline/cable interact under different conditions and how flotation is actually defined in terms of movement or serviceability of the pipeline or cable. A proper representation of the resistance to upward movement offered by high moisture content soil slurries can help to assess flotation risks. The study was conducted to establish a clear methodology for further investigation, thus shallow embedment ratios and moisture content were adopted as variables, together with the sample preparation or pipeline installation method.

2. Flotation test – pull-out test

Ghazzaly and Lim (1975), Ghazzaly, et al. (1975), and subsequently Endley, et al. (2009) conducted tests to investigate controls on pipeline flotation. Each of these studies employed model pipes with the possibility to achieve different unit weights, but the test procedure, that they adopted, was substantially different. Ghazzaly and Lim (1975), and Ghazzaly, et al. (1975) placed their model pipe at a set position in the empty test tank where it was covered with soil to a depth of cover of one diameter above the top of the pipe. The soil was previously prepared at the appropriate moisture content in a separate tank. Endley, et al. (2009) on the other hand prepared the soil-water mixture at the required moisture content in the testing tank and inserted the pipe through the soils and locked the model pipe at the initial testing position (depth of cover (H) = 1.5-2 times the pipe diameter). After embedding the pipe, the studies previously cited, found the unit weight of the model pipe at which no flotation was present and stability was assured. No systematic investigation of the effect of pipeline depth is reported for these studies and the focus was purely on the effects of varying soil type and moisture content. The tests conducted and reported herein have been designed to compare the possible differences between the two installation and testing approaches with a view to choosing the most appropriate approach to investigate flotation issues. These tests are part of a wider investigation of flotation issues and what controls when flotation occurs. An initial stage of the investigation was to measure the resistance to uplift by constant velocity pull out tests (0.2 mm/s) of a model pipeline from various embedment depths. To highlight the differences between the two methodologies adopted by Ghazzaly, et al. (1975) and Endley, et al. (2009), the tests were planned as pull-outs, with two different sample preparation/pipe installation techniques that resemble the preparation adopted in the papers cited above. The sample test preparation are referred to as, 'Method 1' the method that reproduced Ghazzaly, et al. (1975) sample preparation and 'Method 2' the one that reproduces Endley, et al. (2009) sample preparation. Both methods were adopted to investigate the behaviour of an embedded pipe at different moisture contents and embedment depth ratio H/D, where H is the soil cover height and D is the diameter. The moisture content and embedment depth investigated are reported in Table 1.

Table 1 Model test programme

Moisture content (w) [%]	Embedment ratio (H/D) investigated with Method 1	Embedment ratio (H/D) investigated with Method 2
151	0.5 – 1.5 – 2	0.5 – 1.0 – 1.5 – 2.0
163	0.5 – 1.0 – 1.5 – 2.0	0.5 – 1.0 – 1.5 – 2.0
174	0.5 – 1.0 – 1.5 – 2.0	0.5 – 1.0 – 1.5 – 2.0
219	0.5 – 1.0 – 1.5 – 2.0	0.5 – 1.0 – 1.5 – 2.0
228	0.5 – 1.0 – 1.5 – 2.0	0.5 – 1.0 – 1.5 – 2.0

2.1 Soil preparation

The selected fine-grained soil for the tests was kaolin clay that was supplied as a fine dried powder. The properties of the kaolin used are reported in *Table 2*. At first it was necessary to create a slurry by mixing the kaolin powder with deionized water at 1:1 weight of clay to weight of water. Approximately 3kg of water was poured into the mixer and then the soil was added gradually and left to settle to the bottom of the container. When lumps of powder were no longer present on the water's surface further kaolin powder was added, until the total amount of dry clay had been added. In order to achieve complete consistency of the slurry the clay was mixed for two hours at the minimum velocity available for the mixer. The mixing velocity was maintained at the lower limit to reduce the air entrapment in the sample. Because the mixer allowed the preparation of only a limited quantity of soil, the clay was maintained in a sealed bucket with a water layer on top until the total volume soil slurry had been prepared. The minimum required volume of soil to ensure all the embedment ratios tested, in the test setup, was 0.1m^2 which corresponds to approximately 70kg of water and 70kg of kaolin powder for a total of 140kg of mixed slurry. When enough volume of soil slurry had been prepared, it was poured into the flotation testing box and thoroughly remixed with a paddle mixer in order to achieve a homogeneous clay bed. This mixing stage was carried out carefully, again, to prevent air entrapment. When it was necessary to vary the moisture content in the testing box the appropriate additional water was carefully measured out and mixed thoroughly with the paddle mixer.

Table 2 soil properties

Soil type	Liquid limit (LL)	Plastic limit (PL)	Specific gravity (G_s)
Kaolin clay	65	32	2.55

2.2 Test equipment

The test box was manufactured together with a model pipe capable of achieving variable weight, with the specific purpose of conducting flotation tests. The internal dimensions of the box were 650x400x700mm (length x width x height). The model pipe for flotation and uplift testing was manufactured with a diameter (D) of 63mm and a length of 398mm that matched the width of the test box (Figure 1).

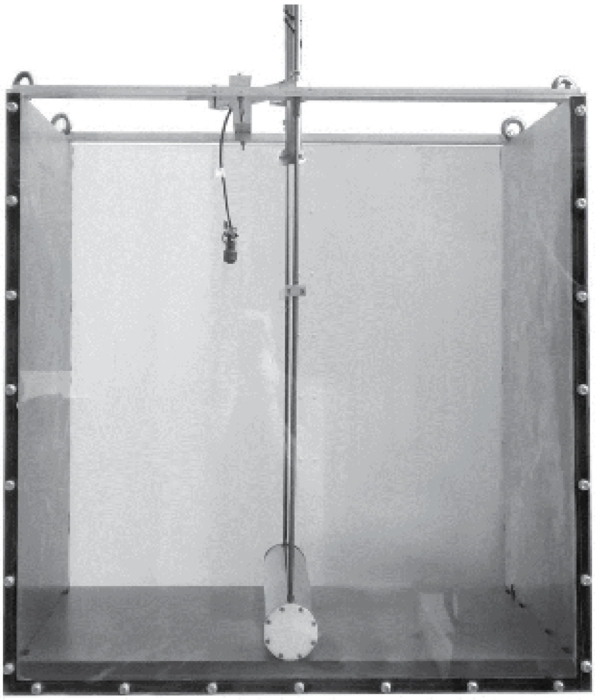

Figure 1 Front elevation of the test box with the model pipeline shown at the base of the box.

The pipe, once embedded, is connected to the surface by two stainless steel tubes (6mm diameter). The tubes have a dual function, in that they can be used to convey water in and out of the pipe. The pipe worked by incorporating a waterproof liquid container to store the water that can increase or decrease the total unit weight of the pipe. The second function of the tubes was to serve as an anchoring point for the horizontal clamp as can be seen in Figure 2a. The horizontal clamp serves both as a reference point that allows measurement of the vertical upward movement and as an anchorage or loading point for the pull-out tests. For the pull-out test reported in this paper the weight of the pipe was kept constant and the pipe filled to its maximum capacity.

The pull-out tests were performed with the aid of a Instron 5985 Universal Testing Machine (UTM) connected to the horizontal clamp of the pipe articulated union to allow raising and lowering of the pipe. The box and the pipe were designed to represent a plain strain case with just a millimetre gap each side of the pipe to avoid friction with the box wall while the pipe moved upward.

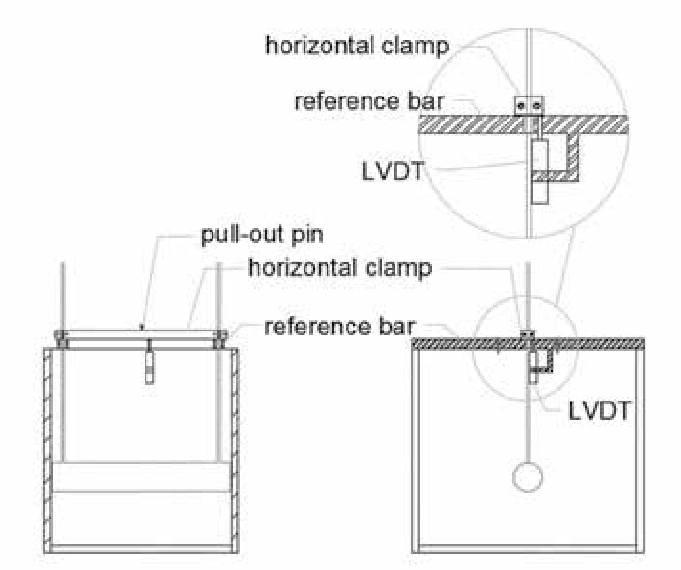

Figure 2 Flotation and pull-out test setup: (a) side view; (b) frontal view with detail of the reference bar detail shown expanded.

2.3 Test procedure

The pull-out tests consisted of two stages common for both soil bed preparation methods and an intermediate stage, employed just in soil prepared by Method 1:

- First stage – insertion, which is a downward movement of the testing pipe, to the appropriate embedment depth.
- Intermediate stage (Method 1 only), soil remixing, to create a homogeneous soil sample.
- Second stage – pull-out, which is the upward movement of the model pipe at 0.2 mm/s.

The first soil bed preparation (Method 1) replicated the test method from Ghazzaly, et al. (1975). Method 1 was used to model a pipe already embedded in a homogeneous high-moisture soil bed, it could be assumed to replicate longer-term post-installation behaviour. Thus, after setting up the box and reaching the appropriate embedment depth with the pipe (Stage 1), the soil bed was remixed on top and beneath the pipe (intermediate stage). This operation was meant to remove any deformation or variability of the soil bed persisting from the insertion stage. The pull-out test was then performed (Stage 2).

The second soil bed preparation (Method 2) requires a remixed soil bed with the pipe initially above the soil. The pipe at the first stage of the test passes through the water layer and then the soil (Figure 3). Once the target embedment ratio is reached the motion of the pipe was reversed and the pull-out stage commenced. The second method of preparation was meant to be a simple representation of the sequence of events that the pipeline/cable and the soil bed could be subjected in the event of flotation in the short-term situation just after installation.

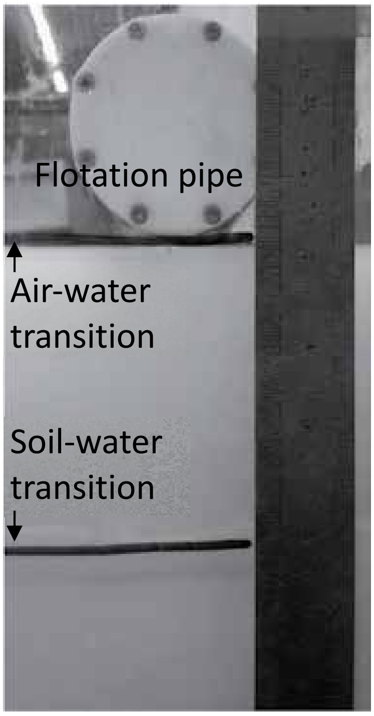

Figure 3 Pipe, soil and water prepared for a test by Method 2

2.4 Analysis of results

The data recorded during the pull-out tests were the displacement imposed by the Instron UTM at a constant velocity and the measured uplift force (*F*). The force (*F*) can be divided into two parts, the submerged unit weight of the pipe and the resistance mobilized by the soil at a certain displacement. At the beginning of each test the moisture content of the soil was sampled and the weight of the pipe recorded. The total submerged unit weight of the pipe (γ_p') in Equation (1) was calculated as the difference between the unit weight of the pipe and the bulk unit weight of the soil, Equation (2).

$$\gamma_p' = \frac{W_p}{V_p} - \gamma_s \quad (1)$$

Where: $$\gamma_s = \frac{G_s \cdot \gamma_w \cdot (1+w)}{1+G_s \cdot w} \quad (2)$$

γ_p' is the equivalent pipe submerged unit weight, W_p is the weight of the pipe, V_p is the volume of the pipe, γ_s is the soil bulk unit weight, w the soil moisture content, γ_w the unit weight of water and G_s the specific gravity of the soil particles. The mobilized resistance (*R*) [kN/m^2] of the soil is then determined from the force recorded during the test (*F*) as in Equation (3).

$$R = \frac{(F - \gamma_p' \cdot V_p)}{L \cdot D} \quad (3)$$

Where *R* is the soil resistance to uplift, *L* is the length of the pipe and *D* is the diameter of the pipe. *L* multiplied by *D* is the projected area of the pipe in the direction of the movement as in Randolph and Houlsby (1984). To compare the difference in results for uplift tests from the different bed preparation methods the load displacement curves, were differentiated and, the point where the tangent of the curve reached a vertical asymptote was defined as δ_f, (examples are present in Figure 4 and Figure 5, blue dots). These points help to compare the difference in mobilization distance of the beds prepared by Method 2 (δ_{f2}) to the pipes tested with Method 1 (δ_{f1}).

3. Results

The pipe was embedded in samples at different moisture content and at different embedment ratio (H/D), principally 0.5 – 1.0 – 1.5 – 2.0. Figure 4 and Figure 5 show the load displacement curves (y axis, embedment ratio (H/D) – x axis mobilized resistance (R)) for each test conducted at the same moisture content. The mobilized resistance axes in Figure 4 and Figure 5 have been omitted for confidentiality reasons. It can be seen that the bed preparation method has a significant effect on mobilization distance but that the effect of bed preparation becomes less obvious with increasing upward pipe displacement with all tests converging to a similar resistance. The decrease in peak uplift resistance mobilized by the pipe is likely to be influenced by the disturbance of the soil due to installation method and the trapping and mixing of water with the clay slurry during the insertion process (trapped water lenses were identified after insertion). It could be inferred that the decrease in uplift resistance, comparing the tests in Figures 4 and 5, is dependent on the increase in moisture content that reduces the shear strength which could be assessed through shear strength liquidity index relationships which are reported in the literature for example Muir-Wood (1990) Locat and Demers (1988) Jeong, et al. (2010) and Vardanega and Haigh (2014). It is apparent from Figures 4 and 5 that the installation method also has a significant effect on the apparent "stiffness response" during uplift pre-peak displacements.

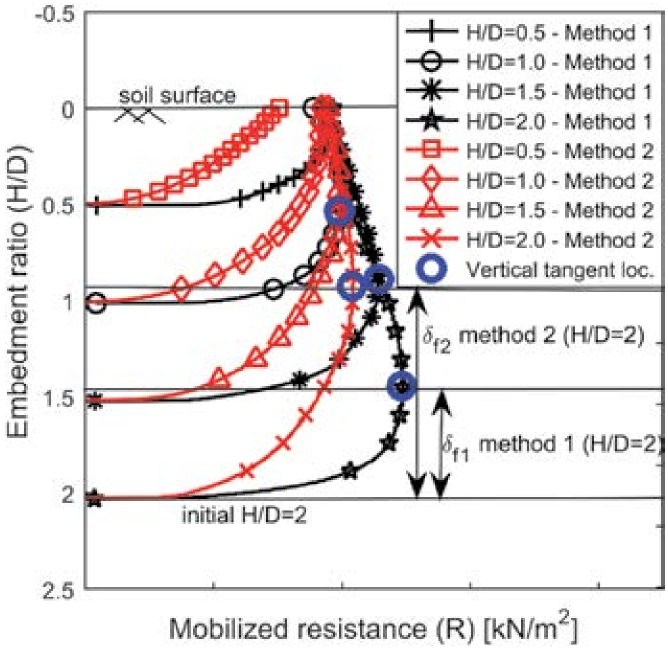

Figure 4. Summary of tests conducted at a moisture content w=163%. (Values have been omitted for confidentiality reasons)

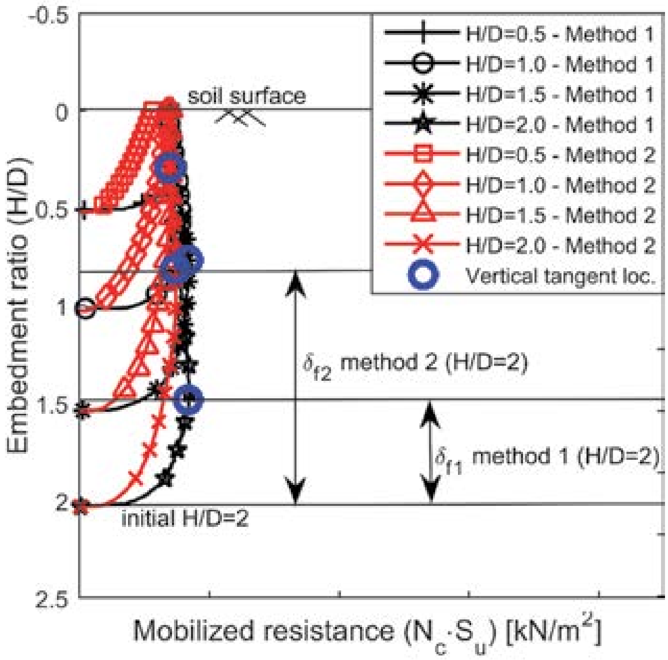

Figure 5. Summary of tests conducted at a moisture content w=228%. (Values have been omitted for confidentiality reasons)

As not all the load displacement curves reach a vertical tangent before the soil surface. A comparison has been made of the two datasets at the same initial embedment ratio where this does occur. The two embedment ratios that satisfy this criterion are the H/D=1.5 and H/D=2.0. Figure 6 shows the normalised mobilisation distance or distance to the tangent point as δf1 and δ_{f2} normalised by the pipe diameter. From Figure 6, it can be seen that no significant difference in normalized mobilisation distance is present for the two embedment ratios where the same installation method is adopted i.e. mobilization distance appears unaffected for pipe embedment greater than H/D=1.5. The mobilisation distance also seems relatively unaffected by soil bed moisture content. It can be noted in Figure 6 that Method 1 installation always produces a δ_{f1}/D under 1 diameter of displacement i.e. a "stiffer response", but with Method 2, δ_{f2}/D is always higher than 1D.

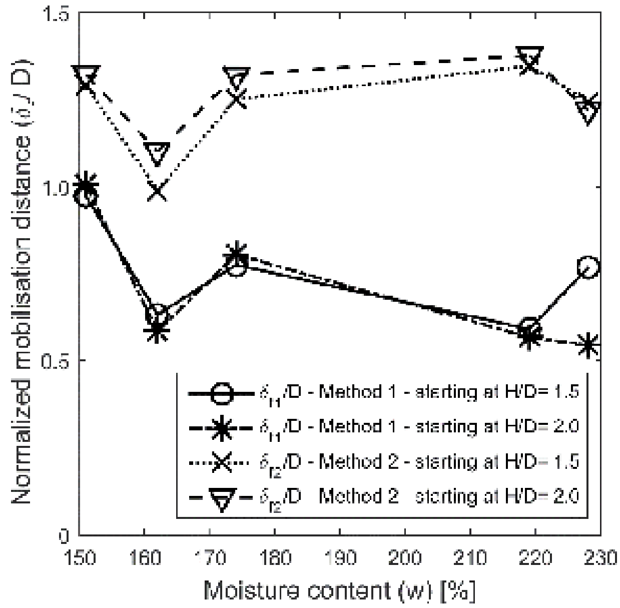

Figure 6. Normalised mobilisation distance for Method 1 and 2 installation at H/D=1.5 and H/D=2.0.

The normalized difference in mobilisation distance is shown in Figure 7 where it can be seen that δ_{f2} is always at least 0.3D higher than δ_{f1} the method obtained testing the samples with Method 2.

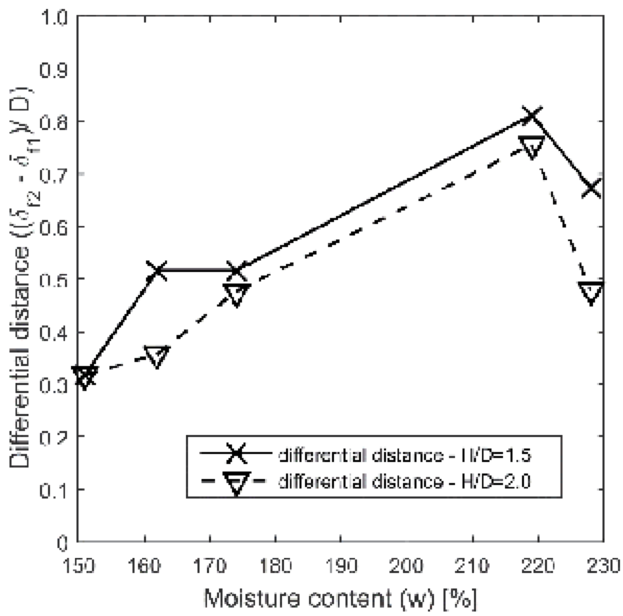

Figure 7. Normalised difference in mobilization distance between Method 1 and 2 installations at H/D=1.5 and H/D=2.0.

Comparing the two methods it is clear that for simulations of offshore jet trenching and backfilling activities the method of pipeline installation is important and can effect both the peak mobilized resistance and the amount of pipeline movement required to mobilize the same amount of resistance i.e. the apparent "stiffness response". This is relevant from a modelling and investigation perspective as it shows that it may be important to simulate the full offshore installation process. The methods presented herein may give insights into the differences between the long and short term response of buoyant or uplifted pipeline/cable. The increased mobilization distance from Method 1 to Method 2 shows that the short term condition simulated with Method 2 should receive greater consideration for both flotation and upheaval buckling.

The final output of these test is to look in flotation related issues during jet trenching operations, but a valuable comparison can be drawn looking into what are the regulation and literature for pipeline uplift resistance. DNV-RP-F110 (2007) in appendix B reports for pipeline uplift resistance in fine grained soil the values of mobilization distances ratios δ_f/H ratios (where H is the depth of cover of soil over the pipe). For different soil conditions, the values are reported in Table 3.

Table 3 DNV-RP-F110 (2007) mobilization distance ratio for different soil condition

Soil type	δ_f /H	δ_f/D (H=1.5·D)	δ_f/D (H=2·D)
Remoulded clay	0.07 - 0.08	0.047 - 0.053	0.035 - 0.04
Intact clay	0.01 - 0.06	0.007 - 0.04	0.005 - 0.03
Intact clay lumps	0.20 - 0.40	0.133 - 0.266	0.1 - 0.2

The values for intact clay lumps, which are the longest mobilization distances reported in DNV, are lower than the lower bound of the values reported in Figure 6 for both methods. It must be highlighted that the values reported by DNV-RP-F110 (2007) are not specified to be for high moisture content clay, although the trend in Figure 6 suggests that the mobilization distance is not significantly affected by moisture content at the high moisture contents investigated here. DNV-RP-F110 (2007) doesn't directly correlate the values of the mobilization distance to the long term or short-term behaviour, but it mentions it indirectly using the consolidation process as mean of reduction of the depth of cover (H), which will reduce the mobilization distance (δ_f). Although the values presented here are higher than those in DNV-RP-F110 (2007) a similar trend is noted in Figure 6 in that the Method 1 installation which involves remoulding of the clay (remoulded clay) results in shorter mobilization distances than for the Method 2 penetrated pipe that may be more representative of a sort of clay lumps in Table 3 due to the water lenses entrapped during the penetration of the pipe. Although, there appears significant differences between the normalized mobilization distances observed in this study and those published in DNV-RP-F110 (2007) it is not the first time such differences have been noted between model studies and DNV-RP-F110 (2007). For blocky backfills Brennan, et al (2017) reported values in excess of four to five times those proposed in the DNV-RP-F110 (2007). Brennan, et al (2017) also refer to debate by other authors over the scalability of mobilization distance from centrifuge tests (rather than 1g test reported herein) and suggest that it may be more appropriate to scale relative to particle size or some dimension specific to the soil. For this reason, the mobilization distances are normalized in a conventional manner for this work and it is recommended that the mobilization distances reported are not adopted until this scaling issue can be investigated further.

4. Conclusions

This paper has reported on the investigation of flotation or uplift resistance relevant to pipeline or cable installation. Two methodologies for bed preparation were investigated resembling the ones reported by Ghazzaly, et al. (1975) 'Method 1-Pipe installation and soil remoulding', and the one reported by Endley, et al. (2009) 'Method 2- Pipe insertion without remoulding'. For both methods, the measured soil uplift resistance decreases in relation to an increase in moisture content, which is associated with reduction in the shear strength which could be assessed through shear strength-liquidity index relationships at high moisture content for fine-grained soil. Where soil remoulding was used (Method 1) in the bed preparation greater peak uplift resistances were mobilised but all tests irrespective of bed preparation tended towards a single value of uplift resistance at larger deformation and on approaching the soil surface.

The bed preparation method has a significant effect on the mobilization distance with Method 2 producing a longer mobilization distance compared to Method 1 (remoulded). This increase is likely to be influenced by the disturbance of the soil due to installation Method 2, with the localised trapping and mixing of water with the clay slurry during the insertion process. Although the mobilization distance appears unaffected by pipe depth for pipe embedment greater than H/D=1.5.

The values of mobilization distance measured in these tests, are higher than any value of mobilization distance reported in DNV-RP-F110 (2007) for uplift resistance, but a similar trend is noted while comparing Method 1 to DNV remoulded clay and method 2 to DNV lumpy clay.

While trying to model the flotation phenomena in high-moisture fine-grained soil the method of pipe/cable installation has been shown to be relevant and can affect both the peak mobilized resistance and the amount of pipeline movement required to mobilize the same amount of resistance.

5. Acknowledgements

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