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Physical Modeling of Catenary Riser-Soil-Interaction

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Abstract

One of the important topics in Catenary Riser design is the SCR touch down region and its interaction with the seabed. Twenty-two pipe-soil interaction tests have been carried out. The soil used in the study is a clay from offshore West Africa. This unusual material, was artificially pre-consolidated under surcharge and then homogenised,. All tests were carried out on a stiff, aluminium pipe section. Pore pressures were measured at the pipe-soil interface at a number of locations. A load cell on the pipe support plates was used to obtain the net soil forces P (horizontal) and Q (vertical) on the pipe. The forces P and Q due to horizontal sweeping H from the centre of a preformed trench of width 3D and depth h, were the focus of investigation in these tests.

1- Introduction

The concept of the steel catenary is inherently simple. However, the dynamic movements experienced by the SCR from vessel motions and hydrodynamic loading result in a more complex behaviour of the structure compared with flow lines and pipelines. For prediction of extreme storm stresses and long-term fatigue life due to vessel motions and vortex induced vibration (VIV), sophisticated numerical methods are required to assist in the design process. One of the important topics in this regard is the SCR touch down region and its interaction with the seabed. These are the fatigue hot spots where the largest bending and tension loads occur respectively. Different studies have shown that riser strength and fatigue response are influenced by the seabed soil and its local geometry in the touch down region. The nonlinear stress-strain behaviour of soil, the consolidation and remoulding of soil (and associated changes in shear strength), trenching and backfilling, hysteresis, strain-rate and suction effects will all affect the loads imparted on the riser. Current riser analysis methods for modelling the seabed typically involve the use of a rigid or linear elastic seabed with friction coefficients assigned in the axial and lateral directions relative to the longitudinal axis of the riser. Fatigue damage is strongly affected by the seabed stiffness assigned in the analysis. The use of a rigid seabed gives greater fatigue damage in the critical touch down zone (TDZ) compared with an elastic seabed. On the other hand, extreme storm-induced stresses are not particularly sensitive to seabed stiffness but are more influenced by lateral friction coefficients when current and wave loading are in the direction transverse to the riser longitudinal axis. There exist many uncertainties regarding riser-seabed soil interaction as field observations have shown deep steep-sided trenches developed in the TDZ of the SCR in the Gulf of Mexico. Also potential riser stress-raising mechanisms such as soil suction and trench wall resistance are not currently accounted for in SCR design.

2- Experimental details

The test tank employed in this study has inner dimensions of 1.49 m (L) × 0.97 m (W) × 0.90 m (H) (Figure 1). A 150 mm layer of 10 mm gravel was first placed into the base of the tank. This 150 mm thick gravel layer provided drainage underneath the clay during consolidation Three Druck PDCR1830 pore pressure transducers (PPTs) manufactured by Druck Ltd. were mounted at the centre of the tank arranged in a vertical column at 40, 110 and 180 mm above the drainage layer. In order to achieve a natural profile of shear strength in the soil bed, it was decided to consolidate the soil from a slurry by the application of a dead weight.

T-bar tests were conducted after preparation of each soil bed to characterise the variation of the shear strength with depth. The key requirement for the T-bar tests is to engender undrained soil behaviour.

An aluminium alloy pipe with an outer diameter of 101.6mm (4inches) and a wall thickness of 12.7 mm (0.5 inches) was used in the study (Figure 3a). The length of pipe was 400 mm which is about four diameters of the pipe. The pipe is connected to a load cell and then to an actuator by two parallel plates, each of which has a thickness of 8mm. In order to capture the pore pressure changes induced by lateral sweeping, five Druck pore pressure transducers (PPTs) were installed in the pipe (Figure 1).

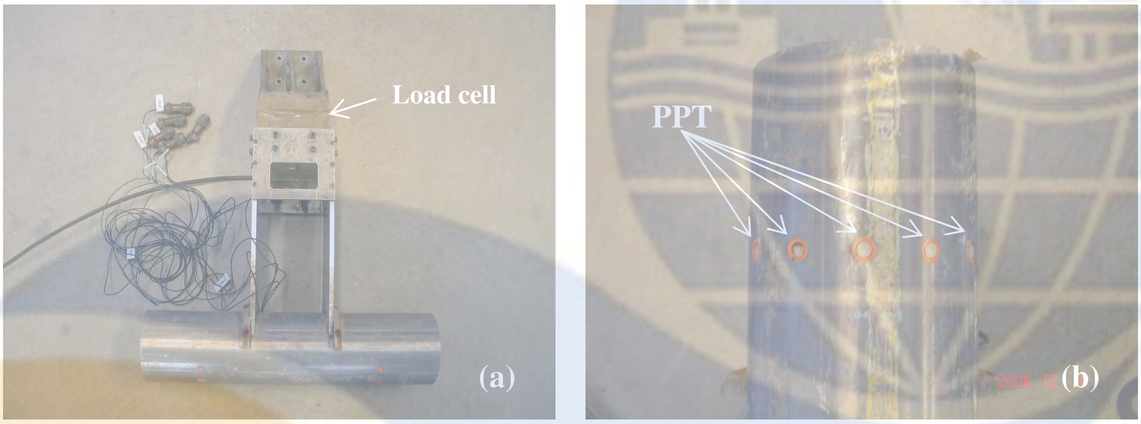

Figure 1: (a) Photo of testing pipe, (b) PPTs fixed on pipe

A two axis actuator was designed and built for this study. The actuator consists of two linear guides one above the other as the horizontal driver and a vertical linear guide (Figure 2). To obtain a synchronized horizontal movement, the two servomotors and their controllers are rigged as a master-slave operation. The master passes the position information onto the slave via the incremental sensor output. The slave reads this information via the external incremental sensor input. A program named WEMEC is used to control the actuator. The actuator can be driven either under speed or torque control. In speed control the position and the speed is specified and the actuator moves to the position requested at the required speed. In torque control the torque is specified and the drive starts to move until achieving the specific torque. The horizontal working stroke is 1080mm and the vertical working stroke is 800mm. The maximum speed for horizontal movement is 750 mm/s and for vertical movement is 1200 mm/s.

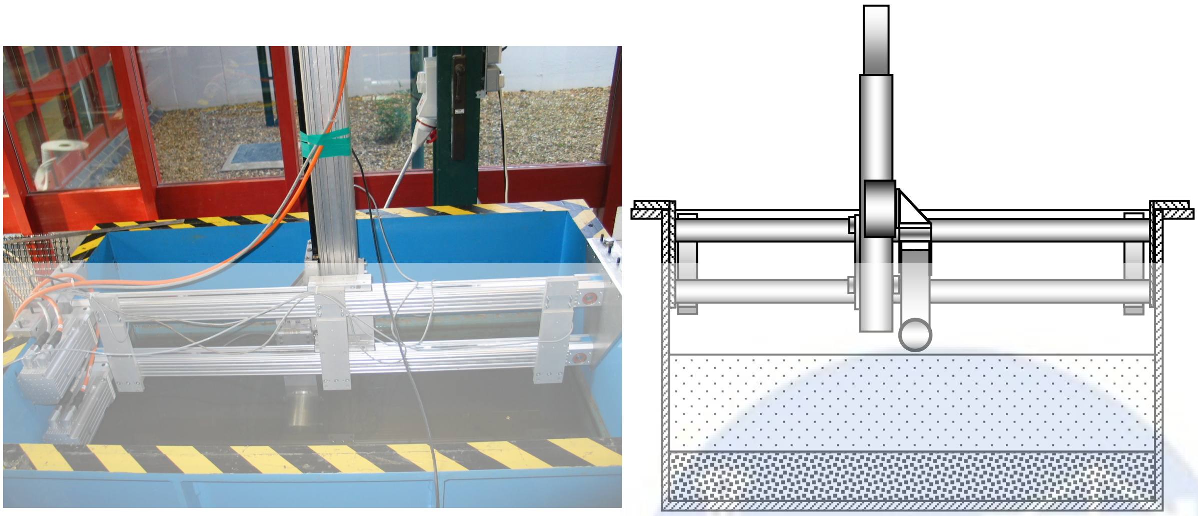

Figure 2: The actuator

Laboratory tests conducted by Fugro on the West African clay reveal that the seabed clay has a very high clay fraction (<2 μm) of 80%. The amount of organic matter is 7.2%. The soil contains mainly Kaolinite (50%), Quartz (15%) and Illite (10%), whilst Smectite, Chlorite, Calcite, Goethite and Feldspar occupy the remaining 25% of the solid fraction. Site investigations show that the West African clay has an in-situ water content of about 200% in the top 1 m, which corresponds to a unit weight of about 12.5 kN/m^3. The plastic and liquid limits are 80% and 175% respectively.

3- Test program

In total four beds of clay were prepared for this study. In these four beds 22 tests were conducted which can be classified into three groups: horizontal resistance of pipe within preformed trench, vertical pull out and vertical cyclic testing. T-bar tests were performed after mixing and the soil was left in the tank for at least 48 hours in order to dissipate some of the excess pore water pressure due to mixing. In the fourth tank the T-bar tests were carried out after finishing the test. The pipe tests were otherwise started after the T-bar tests. Four horizontal pulling tests were performed in the first bed. In the second bed the rest of the horizontal pulling tests were carried out. In the third bed, 7 vertical pull out tests were accomplished. The trenching procedure was performed by advancing the pipe at a speed of 1 mm/s in both vertical and horizontal directions.

4- Soil bed preparation and characterization

The soil in a slurry form was pumped into the test tank using a Monopump. The initial water content was 200%. In order to achieve a shear strength profile that closely represents the field situation, dead weight pressure was applied to consolidate the soil. The initial thickness of soil before consolidation was 280mm. After removing the dead weight there was still excess pore water pressure in the soil measured by the PPTs which was about 1.0 kPa near the bottom of soil layer.

Three T-bar tests were carried out on the bed after consolidation. It is clearly observed that the shear strength the top and bottom of the soil bed is about 3kPa but it reduces to 2kPa in the middle of the layer. The soil was mixed very carefully and thoroughly. The soil was left in the tank for three days in order to dissipate the excess pore water pressure induced by mixing. Two T-bar tests were then carried out at two different positions. Linearly increasing shear strength is observed from these tests. The shear strength at the top of the soil layer is about 0.5 kPa which increases to 1 kPa at the depth of 200 mm. It should be noted that although no water was added to the soil before and during mixing, the shear strength decreases significantly after mixing. Before mixing the minimum shear strength in the soil was about 2kPa, whereas the maximum shear strength after mixing is 1kPa which is two times smaller. This demonstrates the sensitivity of this West African clay.

5- Horizontal resistance of pipe within preformed trench

The tests are designed to be used in developing a relationship between horizontal and vertical resistance of soil during a horizontal pull in a preformed trench, varying trench depth and speed of movement. The tests were started by forming a trench. The pipe was first pushed in to the soil to a given depth in the middle of what would become the trench (Figure 3). Then it was pulled horizontally to a position +1D related to the middle of the trench. The vertical movement of pipe was always locked during horizontal sweeps in the trench-forming procedure. The pipe was pushed down again by the same incremental penetration as before. The pipe was then pulled horizontally to the position -1D. The total sweep of 2D was applied for the purpose of trench forming. This procedure was continued until the required trench depth was achieved. Then the pipe was pulled horizontally back to the reference point at the centre of trench. The pipe was then pulled horizontally at a given speed. Two pulls were performed from the same trench, in opposite directions. Two trenches were created in each bed, so four tests in all were carried out for each bed. Most of the tests were performed in the vertically-fixed condition.

Figure 3: Trench forming

The tests are performed with one pipe diameter of 4 inches (101.6 mm) at different locations and in different beds. The shear strength in the soil differs from bed to bed and also increases with depth in any one bed. A fair comparison of the recorded data can best be achieved by scaling the results, taking both shear strength variation and pipe size into account. The scaling rules are as follows:

- Displacement (vertical or horizontal, trench depth): Divided by diameter, D
- Force: Divided by pipe length, pipe diameter and Su at the pipe invert
- Excess pore water pressure: Divided by Su at PPTs position

The scaling gives dimensionless displacements, forces and pressures. The criteria for selecting the undrained shear strength value for the normalising procedure was the relative depth of the pipe in the soil.

The same procedure for trench forming was applied in this test. The vertical penetration before each sweep was 0.1D. The shear strength values corresponding to the current sweeping depth were used to normalize the results of the trenching procedure. In each penetration, the vertical force increases significantly and during the sweep the force decreases. The normalised vertical force during lateral sweeping lies between 2 and 3 in general, with peaks of about 5 during vertical penetration. The normalised horizontal force starts from zero and it gets to -1 in the first sweep. In the return sweep it reaches the same force +1 during the sweep and it increases to 1.8 near the edge of trench. The normalised horizontal force in the middle of the trench increases by about 0.5 in each subsequent sweep. Near the edge of the trench the increase in horizontal force in each sweep is about 1. The induction of vertical and horizontal force with respect to vertical displacement during trench forming is respectively shown in Figure 4. After stopping the pipe at the end of a sweep, the horizontal force decreases as the berm start to consolidate and creep.

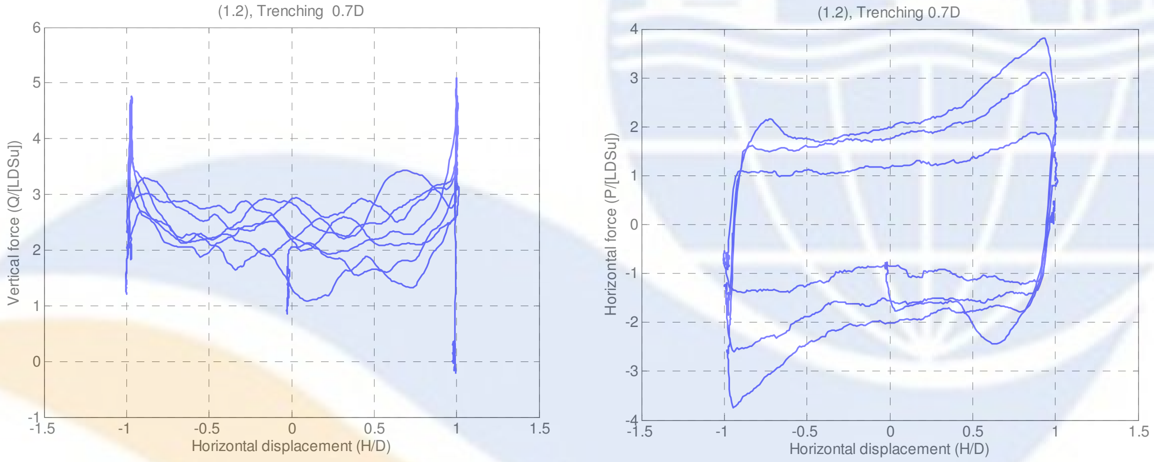

Figure 4: Vertical and Horizontal force during trench forming

Figure 5 show the excess pore water pressures registered by the PPT1 and PPT3 embedded flush with the pipe surface, as a function of horizontal displacement during trench forming. Based on the position of the PPTs on the pipe, different responses were obtained. PPTs 1 and 5 and PPTs 2 and 4 have the same height but on different sides of pipe. PPT3 is at the bottom of pipe. Pressures registered by PPTs 1 and 2 during penetration are large only when those transducers are held against the clay, and are small when the pipe is in contact on its other face. In front of the pipe, positive pore pressures were generated during the sweep. Depending on the embedded part of pipe, the normalised excess pore pressure is about 4 to 6 S_u. It is also observed that negative pore pressures were generated behind the pipe when the pipe started to move. The negative pore pressure increases with increasing depth of the trench. As the trench becomes deeper the berms at the edges of the trench become more significant. Even in a short time the berm can consolidate a little, and when the pipe starts to move negative pore pressures are generated.

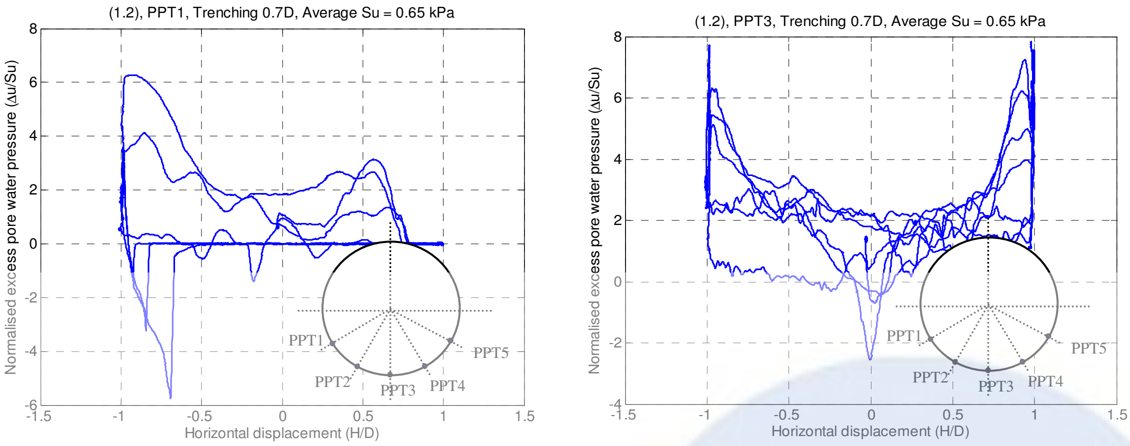

Figure 5: Normalised excess pore water pressure generation with respect to horizontal movement of pipe during trench forming on PPT1 and PPT3

After trench formation to the required depth 0.7D, the pipe was pulled horizontally with a speed of 5mm/s. The normalised vertical force increased almost linearly to 2.5 in a distance of H=1D (). It is then increased more gently registering between about 3 and 3.5 towards the end of the pull. The normalised horizontal force rises quickly, (Figure 6a), then drops a little before increasing again to about 5. The increase to 6 at the end of pull may be an edge effect. Figure (6b) show the pore water pressure generation in normalized form. PPT1 and PPT2 show negative normalised pore pressures of about 3.3 and 1.8 respectively at the beginning of the pull. In front of the pipe significant positive normalised pore pressures of about 5 were generated. The normalised pore pressure at the bottom of pipe is also positive but with a variation between 0 and 3.

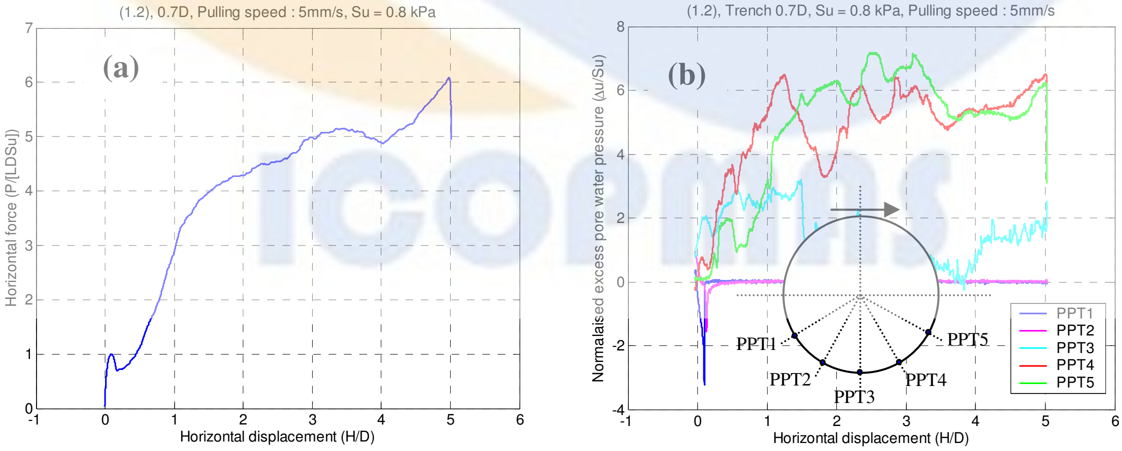

Figure 6: (a) Horizontal force (b) Excess pore pressure during horizontal sweep

6. Conclusion and discussion

The main findings in these tests are in relation to the effects of trench depth and pipe speed on horizontal and vertical pipe force. It can be observed that in a shallow trench, the vertical force increases with lateral pipe movement but in a deep trench the net vertical force variation is not significant. Linear regression gives a fair fitting for each test. The ratio of horizontal force to vertical force increases with increasing of trench depth. It must not be forgotten that the equivalent vertical force per unit length in the case of SCR touchdown will be a function of pipe weight and stiffness characteristics in the touchdown zone. In the two horizontal pull tests carried out at the "high" speed of 100mm/s, the pipe forces were about 1.5 to 2 times those of the "slow" tests. The reason for this big difference is partly because of the different mechanism of failure observed at the different speed. A part of this difference could also be due to the rate effect on the strength of clay, but the soil mechanics literature suggests only about a 17% increase of soil strength due to rate. The remaining difference would then presumably be due either to inertia or to additional viscosity associated with localisation phenomena. One candidate mechanism for the remaining speed effect is the suppression of under-water crack formation, both in the tensile zone of soil behind the advancing pipe and in the active berm being pushed forward by the pipe. In that case, there would be a certain speed of movement that would suppress cracks and result in a properly plastic deformation mechanism. Pulling faster would then only create the usual viscosity effect of about 10% per factor 10 increase in speed. Pulling slower would permit cracks, leading a weakening of the "undrained" mechanism.

7. References

Bransby, P.L. (1973). Cambridge Contact Stress Transducers. Report No CUED/C(SOILS/LN2, Department of Engineering, University of Cambridge.

Murff, J. D., Wagner, D. A. and Randolph, M. F. (1989). Pipe penetration in cohesive soil. Géotechnique, 39, No. 2, 213-229.

Randolph, M. F. (2004). Characterization of soft sedimentations for offshore applications, Proceeding ISC-2 on Geotechnical and Geophysical Site Characterization, Viana da Fonseca & Mayne (eds.)

Randolph, M.F. & Houlsby, G.T (1984). The limiting pressure on a circular pile loaded laterally in cohesive soil. Geotechnique 34(4): 613-623

Stewart, D. P. and Randolph, M. F. (1994). T-bar penetration testing in soft clay. ASCE Journal of Geotechnical Engineering, vol. 120, No.12, (Dec 1994), p 2230-2235.