Effect of soil profile on the response of a sliding subsea foundation

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ABSTRACT: Pipeline end termination (PLET) structures used in subsea deepwater developments are subjected to significant axial expansion forces arising from heating up and cooling down production periods of the incoming pipelines. Resisting these forces with a fixed foundation would lead to excessive foundation sizes when axial expansions are large. Allowing the foundation to slide over the seabed as a whole could lead to a more economical solution. To design this foundation, its displacements and rotations during several cycles of large-amplitude must be precisely characterised. Series of scale model tests in the centrifuge are performed to understand the complex behaviour of this foundation. These tests focus on the influence of degree of soil consolidation on the sliding foundation response under in-plane loading.

1 INTRODUCTION

Pipeline end terminations (PLET) enable the remote connection of the pipeline on which they are installed into a subsea production system. A shallow foundation typically supports the end termination assembly and the associated piping and valve systems. Designing these foundations to safely withstand the forces exerted onto it by the incoming pipeline and jumper(s) is becoming an increasingly challenging task. The first reason is due to the soft soils which are typical of deepwater deposits (Colliat et al., 2010). The second one results from the expansion/contraction of the pipeline due to heat up and coll down production events which induce high horizontal cyclic forces in the foundation.

A first solution (Figure 1) consists in using a rigid frame which is engaged in a sliding rail system to allow the flowline expansions to be accommodated. The frame transfers the loads from the pipeline and jumpers to a shallow foundation, commonly called a mudmat, and generally equipped with a peripheral skirt to enhance the overall capacity. However this solution cannot often support these loads or allow high horizontal displacement (Feng, et al., 2013).

An alternative solution would be to allow the foundation to slide as a whole. Geotechnical design for such a sliding foundation represents additional complexity since the conventional safety concepts used in static design can no longer be directly applied. The displacements and rotations of this foundation and the force experienced during cyclic sliding events are required. Then, small scaled model of this sliding foundation are tested in centrifuge (Wallerand et al., 2015).

The purpose of this paper is to present this model, its instrumentation and its loading system. Then the complex behaviour of this foundation is studied during cyclic events for two soft soil profiles (normally or over consolidated).

Figure 1. PLET with a fixed skirted mudmat and a railing system to accommodate the expansion (Wallerand et a., 2015).

2 EXPERIMENTAL SET-UP

The tests are performed at the IFSTTAR fixed beam centrifuge, which has a nominal radius of 5.5 m. The g level, N, of the current series of test is 50 corresponding to a reduce scale of 1/50. This choice results from the optimisation between the test duration, the size of the model and the accuracy of the monitoring.

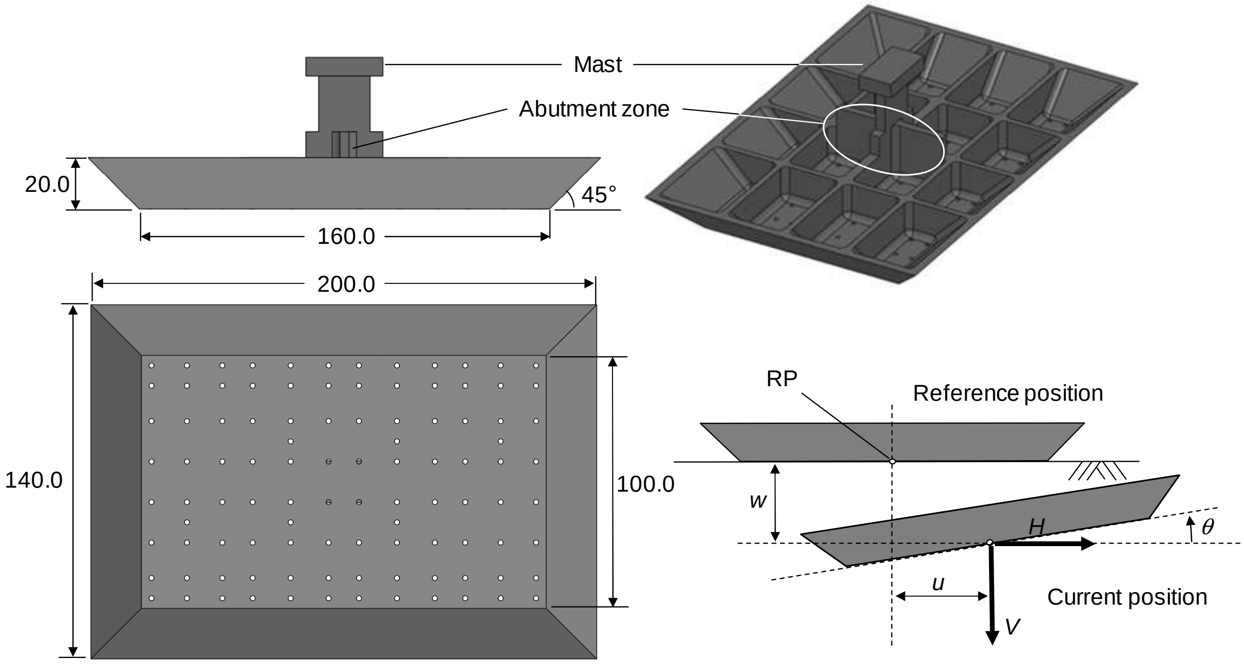

Figure 2. Sliding foundation - model dimensions.

2.1 *Sliding PLET foundation model*

A rectangular PLET foundation with breadth to length aspect ratio $B/L = 0.625$ is studied (Figure 2). The underside base plate dimensions are $B = 100$ mm and $L = 160$ mm (5x8 m^2 at prototype scale), the height is 20 mm (1 m at prototype scale). The peripheral bumper is inclined at 45° giving plan dimensions at top surface of 140x200 mm2 (7x10 m^2 in prototype scale). In addition, the PLET model is perforated by 102 holes with a 2 mm diameter which represents 2% of the base plate surface. The size has been chosen based on the installation vessel capabilities. The perforations are required in practice to reduce the hydrodynamic loads during lowering of these structures through the splash zone and the water column, but also necessary to speed-up the consolidation process of the supporting soil.

The foundation model is made with polyamide reinforced by glass fibers with a Young modulus of 5.0 GPa a density of 1290 kg/m^3. The density should be as low as possible in order to apply minimum vertical load when submerged in water. The submerged weight is 57 g which represents a vertical load V on the soft soil of 70 kN at prototype scale. By adding small steel balls inside the PLET foundation, V can be adjusted (here $V = 100$ kN). The model design with internal stiffeners guarantees the stiffness of the foundation which can be considered as rigid relatively to the soft soil conditions.

2.2 *Cartesian robot*

During a centrifuge test, several operations are often linked together, such as installation process, loading or soil characterization tests. These operations are performed with a set of different tools, each one having a unique specification (jacks for loading, CPT or T-bar test devices, etc…). On the other hand, to not disturb the clay sample consolidation, it is not allowed to stopping the centrifuge during these operations. For these reasons, a unique cartesian robot is used.

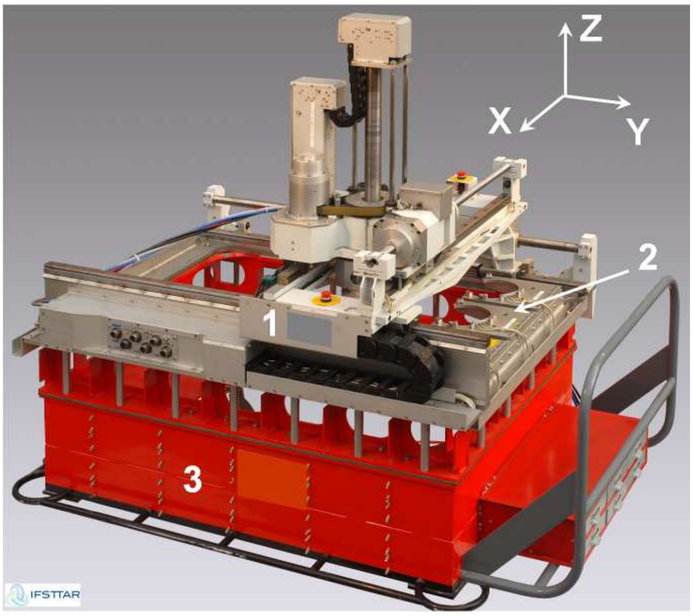

Figure 3. IFSTTAR cartesian robot.

The IFSTTAR robot (Gaudicheau et al., 2014) is installed either on a rectangular strongbox (0.8 m wide, 1.2 m long) or, as it is the case here on a circular container (Ø = 0.89 m). Figure 3 presents the main constituents of the robot: the composite beam supporting column (1), the storage space for three tools (2) and the transport carriage (3). Controlled either manually or automatically, this robot contains a storage zone with three interchangeable tools. Each tool is equipped with a standard interface to accommodate a fluid supply (water, air, oil) along with an electrical connection.

2.3 *Robot tools*

Three tools have been developed for this experiment: a sliding mudmat tool, a T-bar tool and a contour tool. The sliding mudmat tool (Figure 4) has been design to, first, carry the sliding foundation, then land it on its location and finally apply the horizontal loading at variable heights above the mudmat by pushing on a specially developed abutment zone. This design offers large versatility. First, it enables 2D movement: horizontal and vertical displacements plus in-line rotation. Moreover the rotation around the translation axes of the foundation is free to occur (even if there are no out-of-plane forces applied). The second feature of this design is that the height of the load application may be chosen between 5 mm and 30 mm (0.25 m and 1.5 m in prototype scale). The third feature is that the loading arm applies a horizontal displacement u (and then a horizontal load H) without transmitting any torque or moment. The last feature is the instrumentation of the tool and its own data acquisition system (two data acquisition modules *ADAM-4019+*). The model PLET carried the following onboard instrumentation:

- 3 axes load sensor to measure especially the horizontal load H (but also to ensure there is no transversal load),
- 4 LPTs which measure the vertical displacements of the mudmat above each corner; the mudmat horizontal displacement u is given by the Cartesian Robot,
- 4 laser transducers (inside waterproof inside waterproof boxes) which measure the berms generated during cyclic events.

The second tool used in flight is devoted to T-bar test. The cylinder dimensions are 7.5 mm in diameter and 30 mm in length (length - diameter ratio of 4) which corresponds to a projected penetrating area of 225 mm2. The penetration rate is 0.5 mm/s to ensure undrained conditions.

The third and last tool used is the contour tool. It is a laser displacement transducer inside a waterproof box. By scanning the surface of the soil, the footprint of the PLET is mapped in flight and in 3D.

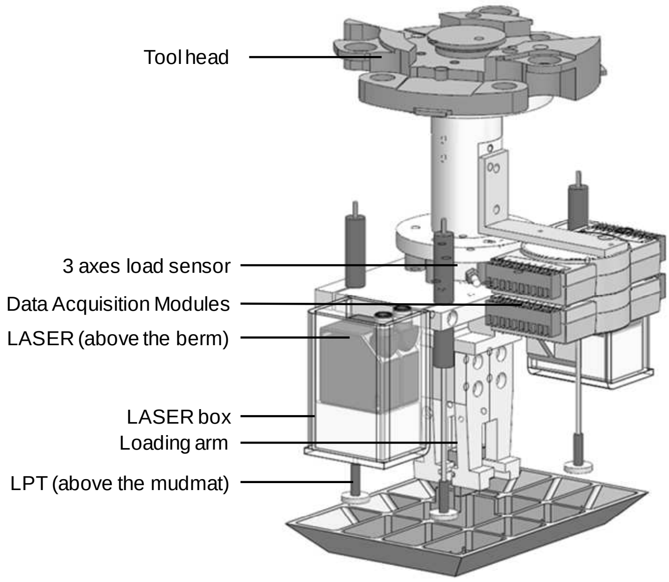

Figure 4. Sliding Mudmat Tool (in transport configuration).

3 SOIL MODELS

3.1 *Soil reconstitutions*

The soil samples are prepared by preconsolidating at 1×g several layers kaolin speswhite clay under similar stresses as in the prototype. The soil samples have a prototype height of 8m corresponding to 160 mm in model dimensions. For the experimental campaign, two types of soil models are prepared:

- with 2 layers of 80 mm, each layer is preconsolidated at 1×g under the stress corresponding to its middle prototype depth: 2 m for the top layer and 6 m for the bottom one,
- with 3 layers (2 layers of 40 mm at the top and 1 layer of 80 mm) preconsolidated under stresses reached at the depth of layer middle (respectively 1 m, 3 m and 6 m).

The result is that, at the sample surface, the 2 layers model is more over-consolidated than the 3 layers one which may be considered as a normally consolidated sample.

3.2 *Soil characterization*

After installation of the 1×g preconsolidated soil model in the centrifuge, a 50×g consolidation phase occurs. The surface settlement is measured in order to follow the consolidation degree of the sample.

Before and after the sliding loading tests, the model soil is characterised through a T-bar test Examples of the undrained cohesion profiles obtained

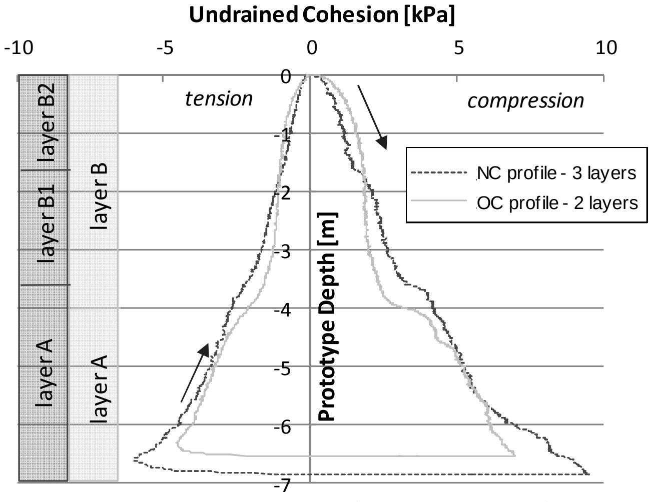

Figure 5. Undrained cohesion profiles measured in-flight with the T-bar tool.

before PLET installation are presented in Figure 5. These results clearly highlight the difference between the two soil models. Near the surface, the 2 layers soil model presents an under cohesion profile clearly over consolidated (OC) whereas the 3 layers soil model could be considered as normally consolidated (NC).

4 SLIDING MUDMAT TEST

4.1 *Test chronology*

The test chronology has already been described by Wallerand and al. (2015) and is briefly remembered bellow.

First the PLET foundation is dropped off onto the virgin seabed. It leads to some instantaneous settlement and the generation of excess pore pressures which will dissipate with time leading to further consolidation settlement of the PLET. Drainage holes in the PLET base accelerate this process. Moreover, soil may be squeezed from below the PLET base and accumulated into berms surrounding the mudmat. In practice, a period of 6 months is generally observed which correspond to 104 min in centrifuge.

Upon the pipeline operational start up, the PLET will undergo its first large-displacement episode (4.5 m, i.e. 90 mm in model scale at a displacement rate of 1 mm/s) (Figure 6). It will engage virgin soil and plough its way through it, thereby progressively accumulating material in a berm which is pushed ahead. The soil on the underside of the PLET is progressively sheared, thereby also generating excess pore pressures.

After undergoing sufficient sliding displacement, the horizontal resistance generated by the PLET foundation reaches equilibrium with the pipeline axial force. Upon reaching this equilibrium, the sliding will stop and the PLET will stay in this position until the line cools down again (14 days, i.e 8 min in centrifuge). During this rest period, excess pore pressures generated during sliding will dissipate, which could lead to additional reconsolidation settlements.

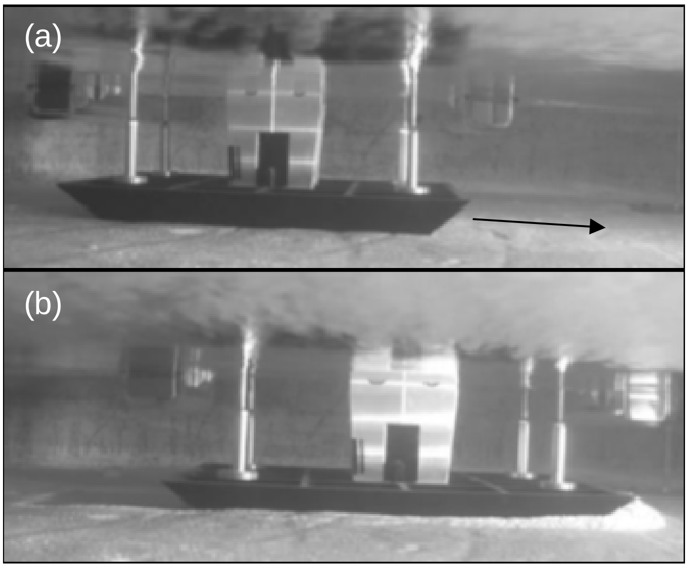

Figure 6. First large-displacement episode - (a) before and (b) after.

Cooling down of the line will lead to the opposite phenomena. However, less soil will be ploughed away by the PLET during the return slide. This berm could interact with the berm left behind on the heat-up side. The berm deposited during the heat-up part of the cycle could be partially entrained by the PLET and could collapse into the trench created by the sliding mudmat.

Subsequent heat-up and cool-down cycles will lead to further accumulation of settlement and rotation. After a number of cycles, a steady-state needs to be reached to ensure an acceptable foundation response. Moreover, a drained state should develop (Cocjin et al., 2014) where no more excess pore pressure are accumulated under the foundation during sliding.

4.2 *Typical test results*

The sliding foundation test analyzed above is the one performed on the normally consolidated clay sample. Figure 7 presents the test results. On the left panel, the mudmat settlement normalised by the mudmat breadth w/B is plotted versus the normalised horizontal PLET displacement u/B during a series of cyclic events. The highest PLET settlements are recorded on the first cycle. Afterwards, settlements are still significant but reduce with the number of cycles. Although the measurements seem to suggest the development of a steady state, this was not reached during the tests.

The PLET settlements also show that no observable reconsolidation of the soil below the PLET took place during rest periods. Significant reconsolidation settlements were reported by Cocjin et al. (2014) who used a non-perforated model PLET. Further testing is required to study the influence of the drainage holes on the reconsolidation phenomenon.

On the central panel, the mobilized coefficient of sliding friction μ is plotted during the PLET sliding. This coefficient represents the ratio of the horizontal resistance versus the vertical load applied. The response during the first cycle does not show a clearly discernable peak. During sliding on the first cycle, the response softens significantly. Reducing horizontal resistance is observed until cycle 5 after which the horizontal resistance hardens. The interaction of active and dormant berms is clearly visible both on the heat-up and cool-down part of each cycle. Interaction with the dormant berm can lead to horizontal resistances which are up to twice as high as the horizontal resistance at the start of the cycle. During a

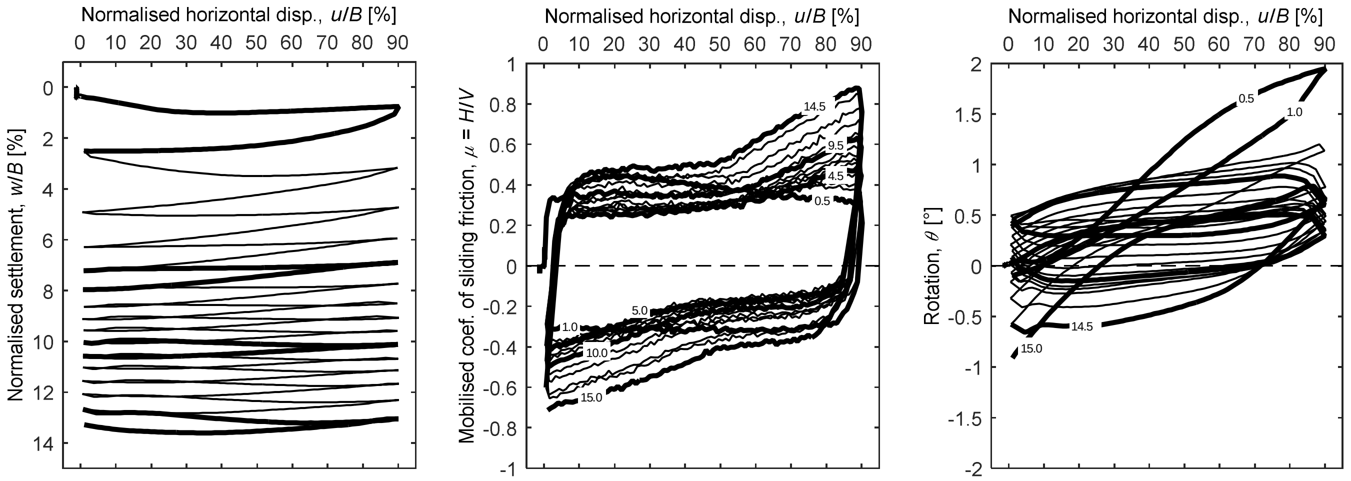

Figure 7. test results on NC clay sample - normalized horizontal displacement *u*/*B* versus normalized settlement *w*/*B* (left), mobilized coefficient of friction μ (middle) and rotation θ (right).

real-life situation, where the pipeline expansion is a load-controlled phenomenon, this would lead to reducing axial pipeline expansions for constant temperature cycles.

The right panel shows the PLET rotation θ measured from the LVDT sensors on the corners of the model PLET. The results show mostly positive (clockwise) rotation with a maximum value of 1.5°. The rotation is highest on the first cycle and reduces with every subsequent cycle. During later cycles, the sign of the rotation reverses and counterclockwise rotations are observed as the PLET approaches its rest position during the cool-down stage. This could be explained by interaction with the dormant berm on the cool-down extremity.

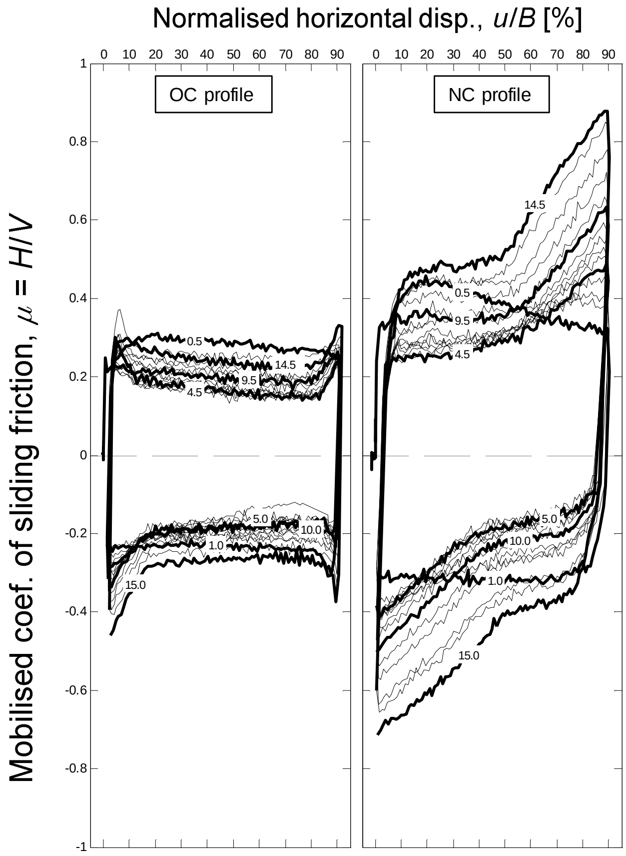

Figure 8. Comparaison of the horizontal resistence developed during sliding on OC (left) and NC (right) samples.

DISCUSION

The influence of the soil profile on the PLET response is demonstrated by comparing the horizontal resistance for tests on the over-consolidated profile (OC) and the profile close to a normal consolidation (NC). The results show (Figure 8), for the OC test, the development of peaks in horizontal resistance at the beginnings of sliding events (as well during heat up as cool down episodes). These peaks are not observed on the NC profile. During the rest periods, additional consolidations may happen on the OC sample: the excess pore pressures generated during sliding has the time to clear. This phenomenon is not

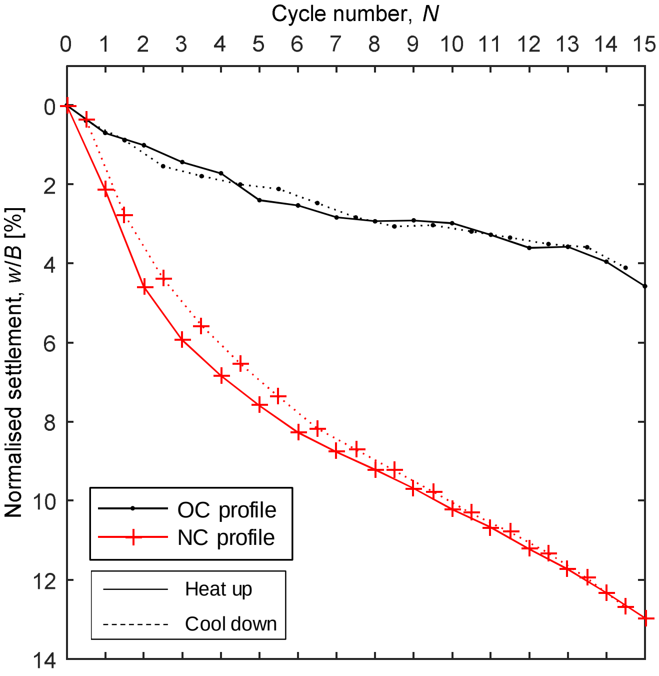

Figure 9. Accumulated PLET settlements observed during cycles.

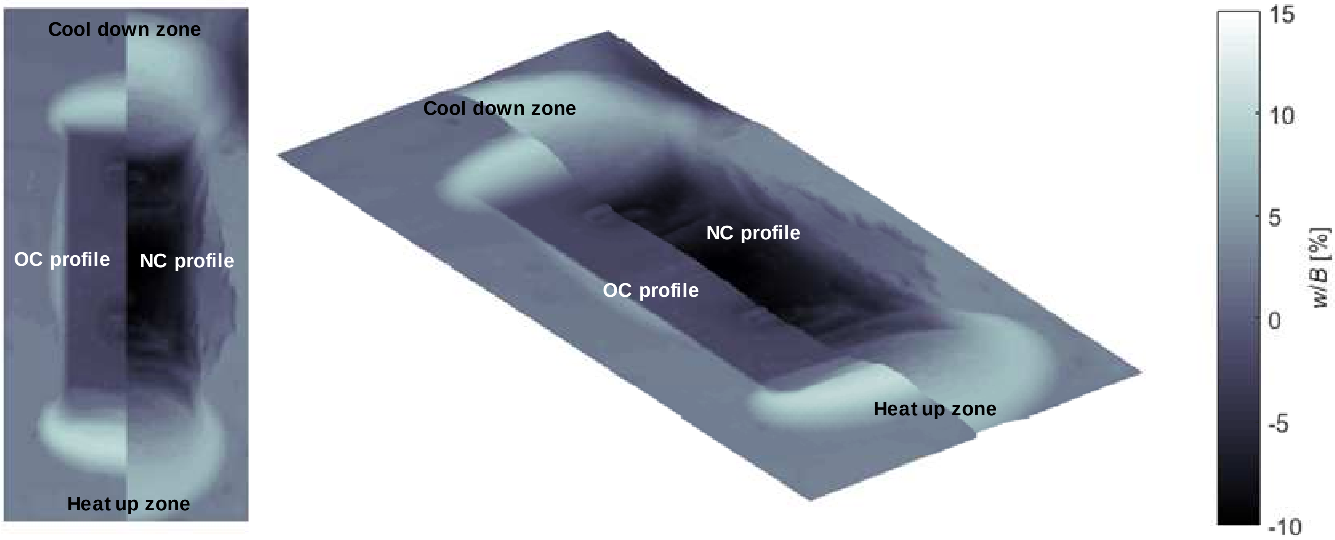

Figure 10. Surface scans of the footprints and berms of the OC and NC tests.

possible on the NC sample. The key role of the drainage holes should be better studied by other tests.

The over-consolidation of the soil mass also plays an important role vertical settlement accumulated over 15 cycles (Figure 9). On the NC profile, the PLET accumulates twice much settlement. The most significant reason is that the bearing capacities of these two samples are clearly different. The bearing capacity of the OC sample is higher. This result has observed during the Tbar tests (Figure 5).

The berm geometry (Figure 10) is also influenced by the soil profile. The NC profile with weaker soil close to the surface leads to berms which are much flatter and have a higher horizontal extent. For the OC profile, the stronger material being pushed up during sliding leads to a higher and more compact berm.

5 CONCLUSION

Pipeline end termination foundations in deepwater developments could benefit from allowing controlled movement of the foundation as a whole during heat-up and cool-down of the associated pipelines. The main challenge in the design of sliding mudmat foundations is the prediction of the foundation trajectory and the forces in the connections throughout the design life of the structure. The reduced-scale model testing carried out in the geotechnical centrifuge provided useful insights in the effect of several key parameters on the response of a foundation during large-amplitude sliding.

One of these key parameters is the soil profile (its over-consolidation ratio OCR or yield stress ratio YSR). Over-consolidation of the clay close to the surface leads to reduced settlement during sliding (compared to a normally consolidated case) and the formation of narrower berms. Peaks in horizontal resistance are only observed for the over-consolidated soil profile. Berm collapse is more extensive for the normally consolidated profiles and the PLET will engage the collapsed material earlier.

ACKNOWLEDGEMENTS

The authors greatly acknowledge Subsea 7 for allowing them to prepare this paper. Nevertheless this paper reflects the opinion of its authors and does not imply endorsement by the company to which acknowledgements are made.

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