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A technique for modelling the lateral stability of on-bottom pipelines in a small drum centrifuge

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ABSTRACT: The design of offshore pipelines in deepwater hinges on the interaction between the partially embedded flowline and the seabed. Conducting full-scale experiments to obtain such information can be very expensive and time-consuming considering the size of the experiment and the cost to extract a vast amount of natural material from offshore. This paper describes an experimental apparatus that allows the lateral load-displacement behaviour of a section of on-bottom pipeline to be investigated at small scale using a geotechnical drum centrifuge. The novel apparatus has been developed to apply lateral loading whilst permitting the pipe to move vertically to simulate the field conditions. The apparatus permits lateral sweeps of more than 8 diameters for a pipeline with a typical diameter of 11 inches to be conducted. The experimental technique is illustrated with a typical set of results and a direct comparison with those obtained from full-scale testing.

1 INTRODUCTION

1.1 *Design for lateral buckling*

The motivation to understand lateral soil-pipeline interaction originates from a latest design approach to tackle thermal buckling of offshore pipelines. In order to ease the flow and prevent the solidification of wax fractions, it is necessary to maintain the oil in a flowline at high temperature and pressure. These operational conditions tend to cause axial thermal expansion in the pipe. Such expansion is normally restricted by the side friction at the soil-pipe interface as well as the end connections that hold the pipe in position. Consequently, axial compressive stresses are generated leading to a vulnerability to buckling in either the vertical or lateral direction. The bending action represents a threat to the structural integrity of the pipeline; leakage of the containment is highly undesirable from the economic and environmental points of view.

Conventionally, the technique of trenching and burial is an effective way to avoid thermal buckling by providing additional resistance derived from the self-weight and the shear resistance of the soil cover, as well as the passive resistance of the trench walls. This approach has, however, become very expensive as offshore exploration develops into much deeper water. An alternative solution to thermal buckling of sub-sea pipelines is to control and monitor the development of buckles. This can be accomplished by laying the pipeline in a prescribed configuration on the seabed. The imposed initial imperfections govern the location and the size of the buckles. Excessive bending can therefore be avoided. This novel approach offers a more cost-effective solution, but requires a better understanding of the interaction between soil and pipeline in the lateral direction.

Full-scale physical model tests have been conducted to shed light on the behaviour of a self-weight embedded pipe section under lateral movement (Cheuk 2005, Cheuk et al., in prep.). Cyclic sweeping with a large amplitude of up to 2 m was carried out to mimic expansion and contraction of the pipeline when it is heated and cooled consecutively. Some key phases have been identified which suggest that the lateral load-displacement response of an on-bottom flowline is more complex than current design methods assume, and is complicated by the creation of soil berms, which provide additional lateral restraint. These findings provide useful information for carrying out lateral buckling design of a pipeline. Although the full-scale physical model provides a direct mean to assess the interaction between on-bottom pipelines and the seabed, preparation of each test took more than a month, mainly spent on consolidating several cubic meters of low permeability soil. In addition, recovery of sufficient material for a site-specific assessment is impractical. All these factors hinder an expansion of the current data base and a refinement on the design methodology.

1.2 *Objectives*

Centrifuge testing offers the potential for a quick and site-specific assessment of the lateral pipe-soil interaction using the volume of soil recovered by a single core sample. This paper describes a centrifuge package that allows lateral soil-pipeline interaction to be studied in a speedy and economical manner. A set of typical centrifuge test results are presented, and compared with those obtained from a full-scale experiment.

2 DETAILS OF THE CENTRIFUGE MODEL

2.1 *MkII mini-drum centrifuge*

The MkII mini-drum centrifuge at the Schofield Centre, Cambridge University Engineering Department is equipped with a 180 mm wide ring channel of height 120 mm. It has a radius of 370 mm measuring from the base of the channel. The maximum spindle speed is 1067 rpm which corresponds to 471 *g* at the base of the channel. The centrifuge has a central pivot that allows a 90° rotation of the channel axis from the horizontal to vertical. This allows a strongbox sample to be positioned in a convenient horizontal position inside the channel before spinning. More details can be found in Barker (1998).

2.2 *Centrifuge package*

The test package designed for testing at 15 gravities is shown schematically in Figures 1(a & b). Figure 2 shows the model box prior to testing. A curved model box was fabricated to fit the circular channel of the centrifuge. The model box is separated into two chambers by a piece of glass. The test chamber has a width of 90 mm, whilst its length is about 350 mm, allowing a horizontal pipe movement of up to 8 diameters for the selected model pipe.

The model pipe was made from aluminum. It has a diameter of 19 mm, and a length of 65 mm. At 15 g, the model pipe is equivalent to a 975 mm long pipe with a diameter of 285 mm at prototype scale. The effective weight of pipe under fully submerged conditions is 635 N at 15 *g*. The ends of the pipe are covered by thin PVC discs, and are completely sealed. The pipe is equipped with a pair of stainless steel sliding tubes, which provide freedom of vertical movement during lateral sweeping.

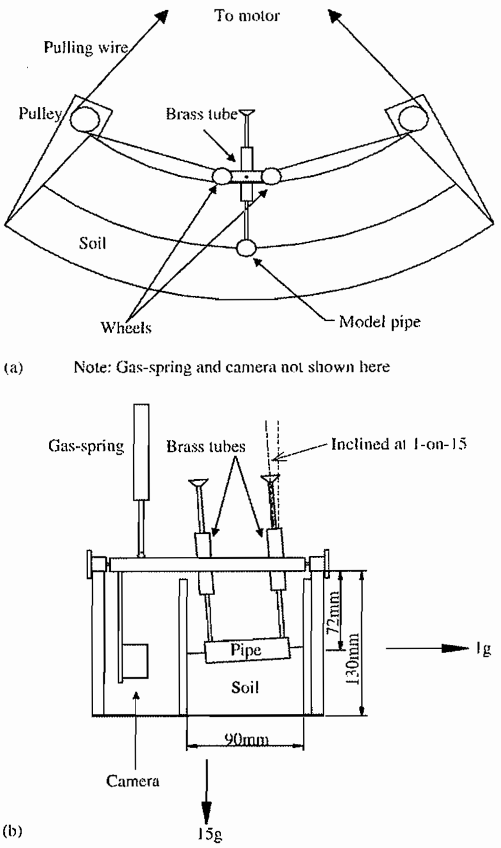

Figure 1. Schematic diagram of the centrifuge package: (a) side view, and (b) front view.

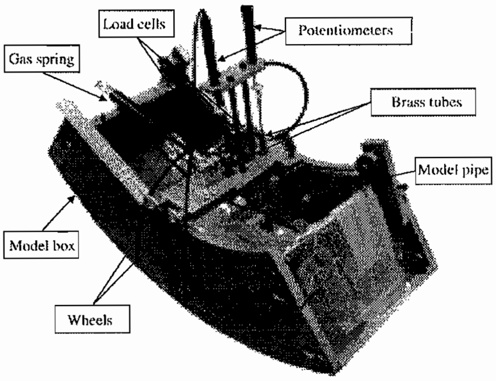

Figure 2. The centrifuge model box.

Lateral pipe movement is triggered by a motor, which is mounted at the turntable of the centrifuge. The motor acts through a pair of wires to drive a carriage to travel along the shoulder of the model box. A power supply unit and a dial gauge located outside the centrifuge are used to control the motor during the test. A gas spring, which can rotate about the motor, is pushing the carriage against the model box, ensuring that the carriage is not lifted up by the pulling wires.

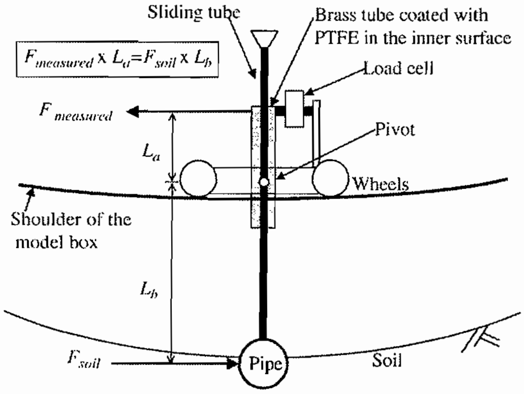

Figure 3. Pulling mechanism in the centrifuge package.

2.3 *Instrumentation*

The lateral force exerted on the pipe during lateral sweeping is measured by a pair of load cells. Figure 3 illustrates the mechanism for measuring the lateral force. During the test, the sliding tubes are inserted into a pair of hollow brass tubes at the carriage. The brass tubes with their inner surfaces coated with PTFE allow the sliding tubes, hence the model pipe, to move freely in the vertical direction, when the carriage is dragging the model pipe across soil surface.

The brass tubes at the carriage not only provide the vertical freedom for the pipe, but also act as lever systems for the measurement of horizontal forces acting on the pipe (Figure 3). The brass tubes are fixed at the carriage by a pair of pins, and are therefore not taking any bending moment. They are aligned on 1-on-15 slope so that the pipe can move freely in the direction of the net acceleration (Figure 1b). Two miniature load cells are attached to the upper ends of the brass tubes. When the pipe is pushed laterally by the passive resistance of the soil, the horizontal force is magnified and registered by the load cells as $F_{measured}$ through moment transfer in the lever systems. The actual force acting on the pipe (F_{soil}) can be back-calculated if the lever arm ratio (L_a/L_b) is known.

Two miniature linear potentiometers are used to measure the vertical movement of the pipe during sweeping. They are seating on top of the two sliding tubes. The vertical pipe movement also defines the lever arm ratio (L_a/L_b).

The horizontal movement of the pipe is measured by a draw-wire potentiometer. It moves with the carriage, while the end of the draw-wire is fixed on the side of the model box. A miniature video camera is also attached to the carriage. The camera is hanging in the neighbouring chamber, and is looking at the test chamber through the glass in an attempt to reveal the soil and pipe movement during the test. The zero offset of each instrument is checked before commencement of phase 2 in each test, which will be discussed in the next section.

2.4 *Modelling procedure*

The centrifuge test can be divided into two stages, namely the consolidation and the sweeping phase. In the consolidation stage, a model seabed was formed by self-weight consolidation at high g-levels. To ensure uniformity, the model seabed was consolidated from slurry. A soil spreader with a feeding pipe was first mounted on the turntable, whilst a funnel was fixed at the protective cover plate of the centrifuge. The centrifuge with an empty model box (Figure 2) was then spun up to 10 g. Water was flooded into the entire chamber of the centrifuge through the funnel and the soil spreader. This formed a constant water level around the model box, which remained unchanged throughout the entire course of consolidation.

The first step in the consolidation phase is the introduction of soil into the test chamber. Soil slurry, which had been mixed at very high water content (above 100%) under vacuum, was poured into the model box through the funnel. When the model box was filled up with slurry, the centrifuge was speeded up to 100 g. The centrifuge was then left running for the soil to consolidate.

After the consolidation phase, the centrifuge was stopped and the top soil was scraped away. The soil spreader was then replaced by the motor. The carriage was also assembled with the model pipe sitting on top of the soil surface. Since the weight of the model pipe was 15 times lighter than it would be during sweeping, the initial pipe embedment was insignificant at this stage.

The second phase of the test began by spinning up the centrifuge to 5 g at which water was slowly flooded into the test chamber through the water supply. The centrifuge remained at 5 g until the soil is fully submerged again, which was indicated by the presence of water above the pipe shown in the on-board camera. The g-level was then increased to 15. The pipe was allowed to settle under its own weight until it became steady. Sweeping then commenced at a velocity of about 1 mm/s at model scale. A 1-minute pause was allowed between sweeps.

3 CENTRIFUGE TEST RESULTS

The modelling technique described in the previous section allows a complete and quick assessment of the behaviour of an on-bottom pipe from initial pipe embedment to cyclic lateral sweeping of large amplitudes. This section presents the results obtained from a typical test (denoted as test K2) in prototype units unless stated otherwise.

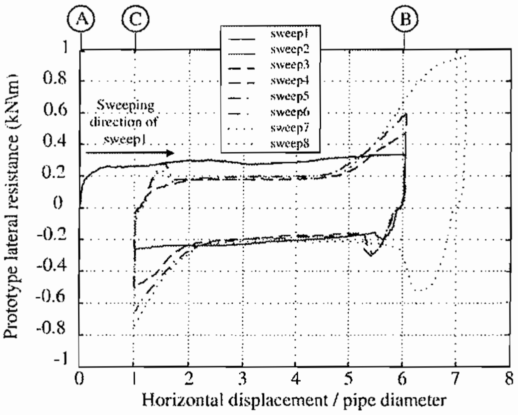

Figure 4. Load displacement response obtained from centrifuge test (test K2).

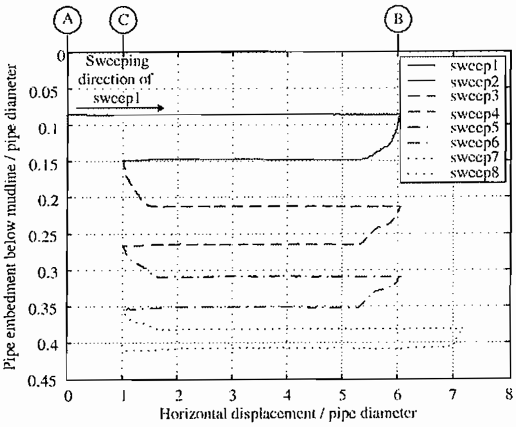

Figure 5. Pipe trajectories obtained from centrifuge test (test K2).

3.1 *Consolidation and initial pipe settlement*

During the consolidation phase, kaolin slurry was consolidated at 100 g for 2 hours, corresponding to about 833 days at normal gravity. Upon completion, the centrifuge was stopped and the top 13 mm (model scale) was scraped off to achieve a finite shear strength at the soil surface. As the centrifuge was spun up again to 15 g, the model pipe with a submerged weight of 651 N/m attained a steady state embedment of 23.3 mm. Murff et al. (1989) proposed a relationship between pipe embedment and effective pipe weight normalised by the undrained shear strength of soil. Using their equation, a surface shear strength of 1.27 kPa is inferred. This is slightly smaller than that estimated from post-test moisture content measurements, which is 1.62 kPa. The higher value can be attributed to the inclusion of stronger soil at deeper depths during water content measurements. No direct profiling for shear strength distribution was conducted in the centrifuge model, which is one of the further developments.

3.2 *Load-displacement response and pipe trajectories*

The centrifuge test consists of 4 cycles of sweeping. Figures 4 and 5 show the load-displacement response and the pipe trajectories respectively.

Figure 4 shows that the pipe sets off from its initial position (Location A) with a breakout force of 0.26 kN/m. This is accompanied by insignificant vertical pipe movement (Figure 5). The lateral resistance then increases gradually until it reaches the destination at Location B. In the second sweep, the load-displacement response resembles that obtained in sweep1 except that a small peak resistance is recorded which is followed by a minor reduction in lateral resistance. The pipe settles for more than 17 mm (0.06D) in this sweep, illustrating the freedom to move in the vertical direction while a lateral force is applied to the pipe.

After the first cycle, force-displacement curves of similar shape are obtained. These curves are characterised by a peak breakout resistance which increases with the number of cycles, a steady accretion state at which the lateral resistance increases gradually and a passive resistance zone with a greater force-displacement gradient.

The increase of breakout resistance with the number of cycles can be readily explained by the monotonic downward displacement of the pipe as shown in Figure 5. As indicated by the pipe trajectories, the pipe starts each sweep with a small embedment. As it sweeps laterally, it pushes certain amount of soil to the berm on either side of the test chamber. When the pipe tries to break away from the berm on the return travel, suction force, which contributes significantly to the breakout resistance, is generated at the pipe-berm interface. This suction force is proportional to the contact area between the pipe and the soil berm, which increases with the number of cycles as the berms are growing in size.

The steady accretion state is caused by the formation of a soil berm in front of the pipe. This active berm with a growing size moves forwards with the pipe during lateral sweeping leading to an increasing lateral resistance. The lateral resistance at the steady accretion state lies between 0.16 kN/m and 0.24 kN/m.

On the other hand, the passive resistance zone is a result of the existence of a soil berm on each side of the test chamber created by previous sweeps (Locations B & C). The passive resistance given by the soil berms increases the lateral force at a gradient ranges from 0.8 kN/m/m to 1.5 kN/m/m. When the pipe tries to push through the berms in sweep7, the rate of increase in lateral resistance stays almost constant.

4 FULL-SCALE TEST RESULTS

4.1 *Full-scale model*

As part of a research programme to study lateral soil-pipeline interaction, a series of full-scale tests were conducted at the Schofield Centre, Cambridge University Engineering Department. The experimental chamber had a plan area of 1.25 m × 4.5 m with a height of 1.5 m. The model seabed was mimicked by about 6 tonnes of kaolin clay consolidated to an undrained shear strength of about 1–2 kPa using a vacuum consolidation technique.

A pipe section cut off from a prototype flowline was used in the full-scale experiments. The 0.98 m long model pipe section had an outer diameter of 283 mm with a submerged unit weight of 638 N. Both ends of the pipe were attached with a pair of vertical shafts which were connected to an actuator for applying horizontal force whilst permitting the pipe to move vertically. The lateral motion was triggered and controlled by a stepper motor connected through a high-ratio gearbox to the belt drive.

Prior to lateral sweeping, the model pipe was allowed to settle under its own weight until the pore pressure transducers attached on the soil-pipe interface indicated that the excess pore water pressures had dissipated. Lateral sweeping then began at a constant horizontal displacement rate of 1 mm/s. The horizontal force measured by a pair of load cell, and the corresponding lateral and vertical movements were recorded. Full details of the experiments can be found in Cheuk (2005).

4.2 *Load-displacement response and pipe trajectories at full-sale*

The initial pipe embedment in the full-scale test (denoted as test JIP2) was 90 mm, which was caused by an effective pipe weight of 651 N/m. A laboratory T-bar penetrometer revealed that the surface of the model seabed had an undrained shear strength of about 1.2 kPa. However, this was underlain by a 100 mm thick soil layer with a shear strength of only 0.65 kPa. This is presumably the cause for the higher initial pipe embedment compared to that obtained in the centrifuge test with exactly the same effective pipe weight.

The load-displacement response exhibited by the pipe during three cycles of lateral movement is shown in Figure 6, whilst the pipe trajectories are plotted in Figure 7. The pipe begins the lateral sweeping through the mobilisation of a peak lateral resistance of 0.57 kN/m (Location A). Pore pressure transducers were attached at the pipe wall in this full-scale test. The measurements of negative excess pore pressures reveal that the suction generated behind the pipe contributes significantly to the breakout force. The formation of a gap between the pipe and the soil behind it subsequently destroys the suction, and hence leads to the force reduction observed in the force-displacement diagram. Following this small reduction, the lateral resistance increases gradually until the end point of sweep 1 (Location B). On the return travel, a peak resistance of 0.5 kN/m was measured, followed by a reduction in lateral resistance. Once again, the lateral resistance increases gradually during the steady accretion phase, until the pipe terminates at Location C, which is 2.75D away from the initial starting point. The corresponding pipe trajectories suggest that there might be more friction resistance in the vertical sliding rods of the actuator when the pipe travels from right to left.

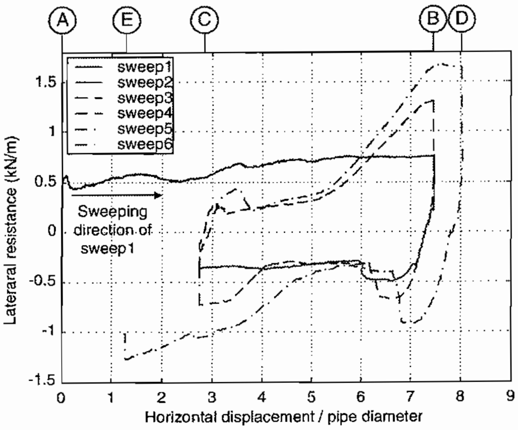

Figure 6. Load displacement response obtained from a full-scale test (test JIP2).

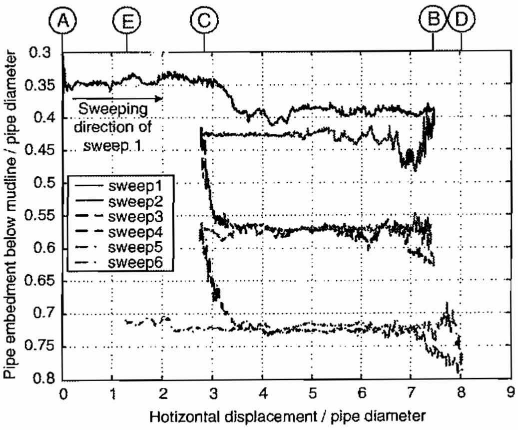

Figure 7. Pipe trajectories obtained from a full-scale test (test JIP2).

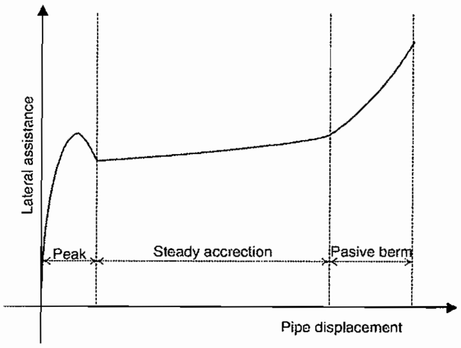

Figure 8. Key phases during lateral sweeping of a self-weight embedded pipe.

In the subsequent sweeping cycles, the three characteristic states identified in the centrifuge test are also observed in the load-displacement curves. Peak resistance followed by strain softening is observed in all 4 sweeps (sweeps 3 to 6). This is followed by a gradual increase in lateral resistance during the steady accretion state at which the resistance lies between 0.2 kN/m and 0.4 kN/m. A sharp increase in lateral resistance is recorded as the pipe approaches the soil berms created in previous sweeps near Location B in sweeps 3 and 5, and near Location C in sweeps 4 and 6. The force-displacement gradients at the two soil berms are about 2.1 kN/m/m and 1.1 kN/m/m at Locations B and C respectively.

When the pipe is brought through the soil berms at Locations D and E in sweeps 5 and 6 respectively, a high lateral resistance of greater than 1.5 kN/m is measured.

5 COMPARISONS AND DISCUSSION

The previous sections demonstrate that the behaviour of a self-weight embedded pipe during cyclic lateral sweeping in the centrifuge model is very similar to that exhibited in the full-scale test. A number of key phases can be identified as summarised in Figure 8. The three important stages are:

1. Breakout
2. Steady accretion state
3. Passive zone of existing soil berm

5.1 *Breakout*

With a certain amount of initial settlement due to its own weight, the pipe breaks away at a peak resistance which is mobilised at a small mobilization displacement. This peak is very often followed by a small reduction in lateral resistance upon further pipe movements. Pore pressure measurements suggest that this softening behaviour is caused by the loss of suction at the soil-pipe interface as a cavity is opened up.

Table 1. Comparisons between centrifuge and full-scale test results.

Quantity	Centrifuge (Model)	Full-scale (Prototype)	
Effective pipe weight (kN/m)	0.0434	0.651	0.651
Pipe diameter (mm)	19	285	283
Surface shear strength, s_u (kPa)	1.27	1.27	1.2*
Breakout force in 1st sweep (kN/m)	0.0173	0.26	0.57
Lateral resistance at steady accretion state (kN/m)	0.011–0.016	0.16–0.24	0.2–0.4
Force-displacement gradient at steady accretion state (kN/m/m)	0–0.003	0–0.09	0–0.24
Force-displacement gradient due to passive soil berms (kN/m/m)	0.053–0.1	0.8–1.5	1.1–2.1

*Note: The strong surface crust is underlain by a soft soil layer with $s_u = 0.65$ kPa.

5.2 *Steady accretion state*

At larger pipe displacements, the lateral soil resistance was found to be increasing gradually with horizontal pipe displacement. This is due to the invert of the pipe being below the surface of the soil bed ahead, so that soil is continually swept upwards into an active berm. This can therefore be described as the steady accretion phase.

5.3 *Passive zone of existing soil berm*

As the pipe approaches an existing soil berm which was created in previous sweeps, the lateral resistance exerted on the pipe increases significantly. The resistance provided by this existing soil berm increases with the number of cycles. The downward pipe displacement occurring in each cycle causes successive active berms to accumulate into a larger static berm at the extremity of the cycles. The force-displacement curve of a pipe approaching and then pushing through a static berm is dependent on the stiffness and strength of the soil.

5.4 *Comparisons between centrifuge and full-scale tests*

The measured values associated with the above mentioned phases for the two tests at different scales are compared in Table 1. The effective pipe weights and the model pipe geometry were deliberately made very similar to facilitate a direct comparison. However, it is always a constraint for a large scale physical model to achieve a soil bed with a uniform shear strength distribution. This leads to the small discrepancies between the results measured in the two models. Nevertheless, there is very good agreement in terms of the order of magnitude of soil resistance measured in both models.

6 CONCLUSIONS

An experimental apparatus has been developed to investigate the interaction between seabed and a partially embedded pipe in a small geotechnical drum centrifuge. The centrifuge model allows the resistance exerted on a laterally moving pipe to be measured with only a small core of soil sample within a short testing time. The technique has been proven, through direct comparisons of the results, to be capable of mimicking a full-scale model.

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