New centrifuge modelling techniques for investigating seabed pipeline behaviour
Modélisation en centrifugeuse du comportement des pipelines sous-marins

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ABSTRACT
The paper outlines newly-developed centrifuge modelling techniques for simulating the dynamic laying of seabed pipelines and the near-surface properties of seabed soils, which were created in response to the increasing need to characterise this behaviour in design. Several examples in artificial and natural soils are presented, highlighting notably the remoulding behaviour and its effect on pipe embedment.

RÉSUMÉ
Cet article présente les méthodes de modélisation en centrifugeuse développées afin d'étudier certains les phénomènes d'installation dynamique des pipelines sous-marins et les problèmes de caractérisation des sols à très faible profondeur. Plusieurs exemples, utilisant des sols naturels et artificiels sont présentés, révélant l'importance du remaniement du sol sur la pénétration du pipeline.

Keywords : pipeline, clay, silt, remoulding, centrifuge, modelling

1 INTRODUCTION: PIPELINE GEOTECHNICS

1.1 *Motivation: seabed pipeline design*

Seabed pipelines form an increasingly vital part of the infrastructure associated with offshore oil and gas developments. In deep water on soft clay – a current frontier of exploration – pipelines are usually laid directly onto the seabed, penetrating by a fraction of a diameter. Designers of deep water seabed pipelines face a variety of challenges which are unique in geotechnical engineering. For example, a modern design technique to mitigate the thermal expansion of pipelines is to allow the pipeline to buckle laterally across the seabed. This approach requires accurate assessment of the pipe-soil interaction forces. Pipe embedment is often modelled using simple bearing capacity theory and axial and lateral pipe-soil interaction forces are often idealised via simple Coulomb friction, but the actual behaviour is significantly different (Bruton et al. 2007). This is notably the case during installation where the catenary shape of the pipeline and the dynamic motion during laying leads to enhanced contact stresses, seabed disturbance and soil remoulding (Cheuk & White 2008; Randolph & White, 2008).

Due to the curved surface of a pipe, the soil surrounding the pipe must deform and fail as the pipe is laid on the seabed. This deformation increases the contact area between the pipe and the soil to support the pipeline weight. This process leads to remoulding of the surrounding soil and significant heave of the adjacent soil. This remoulding is enhanced by dynamic motion of the pipe due to heave of the lay vessel which results in combined vertical and horizontal cyclic loading of the pipe at the touchdown point. This motion softens the soil and pushes material away to either side of the pipeline. This complex loading process makes the remoulding of the soil difficult to assess or to model.

The as-laid embedment of a pipeline has a strong impact on the subsequent behaviour, notably on the subsequent breakout resistance, which impacts in turn on the pipeline response to thermal expansion and hydrodynamic loading. The embedment also affects the thermal insulation. This highlights the need to develop modelling techniques capable of simulating the complex laying process to assess the as-laid embedment on which design methods can be based. Physical modelling offers such a possibility.

The paper outlines the role of physical modelling and the modelling techniques developed at COFS in providing insight into the pipe-soil interaction processes during the dynamic laying process. These techniques and insights assist pipeline designers with methodologies and parameters to assess pipeline embedment.

1.2 *Role of physical model testing in pipeline design*

Project-specific physical modelling studies can be managed in the same manner as the conventional geotechnical investigation. The scope should be chosen based on a preliminary design in which the likely pipe weights and in-service behaviour are assessed. The centrifuge modelling programme can then be tailored to replicate the anticipated lay process and the in-service pipe movements, with an appropriate range to capture uncertainties.

Physical modelling can aim to directly replicate the field conditions, in which case the results provide an immediate representation of the design situation. More commonly, it is necessary to interpret the results in light of a model for the pipe-soil behaviour, and then use that model to simulate the design situation. This latter case is more common because the actual patterns of pipe movement during operation will vary longitudinally along the line, and so it is necessary to interpolate between the patterns of pipe movement simulated in the model tests.

Several recent projects worldwide have included physical modelling of pipe-soil interaction as part of the design process, including many recent developments offshore Australia.

2 CENTRIFUGE MODELLING TECHNIQUES FOR PIPE-SOIL INTERACTION

2.1 *The UWA geotechnical beam centrifuge*

The technique of geotechnical centrifuge testing is a well-established method for modelling the behaviour of geotechnical materials at reduced scale, by correctly scaling the effective stresses, which govern the strength and stiffness of soils.

The UWA beam centrifuge, as commissioned in 1989, is described by Randolph et al. (1991). The centrifuge has a swinging platform radius of 1.8 m and is rated at 40 g-tonnes The platform

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supports standard rectangular ‘strongboxes’, which have plan dimensions of 650 × 390 mm and are 325 mm deep. Due to the relatively small size of prototype pipelines (0.6 m to 1 m in diameter), centrifuge pipe tests are performed at accelerations ranging from 20 to 40g. The strongbox then represents a field scale test bed of up to 15.6 m wide by 26 m long by 13 m deep at 40g.

2.2 *Specific developments for pipe-soil interaction testing*

Typical arrangements of apparatus for pipe-soil interaction modelling are shown in Figure 1. The model pipe is fabricated from aluminium and is rigidly connected to a loading arm. The loading arm is manufactured in-house at UWA and is equipped with strain-gauge load cells that detect very small variations of the vertical and horizontal load imposed on the pipeline.

By contrast to typical offshore structures such as piles, suction caissons or anchors, which are already modelled extensively in centrifuges, pipe-soil interaction testing has specific characteristics. They include the application of very small loads (typically 1 to 5 N at 20g) and the application of large horizontal displacements (up to 10 diameters) in conjunction with vertical displacements, both at potentially high frequency (1-10 Hz). These characteristics have required the developments of specific capabilities, both in term of motion control and data acquisition systems.

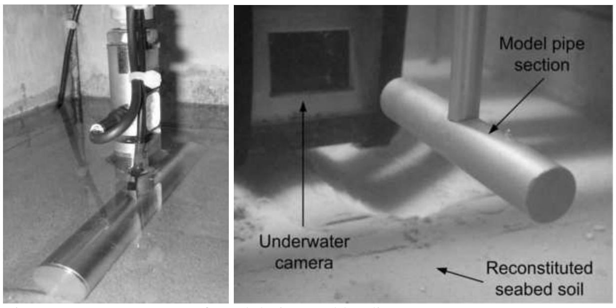


Figure 1. Arrangement of model pipe and loading arm

Dual-axis actuators are used to impose vertical and horizontal movements to the model pipeline. The actuators are controlled by a Labview interface specially developed at UWA to model pipe-soil interaction and providing displacement or load control, monotonically or cyclically, independently on both axes. Extra features include the possibility to link the displacement or load demand of one axis to the position of the second axis. This feature allows, for instance, the amplitude of cyclic lateral oscillations to vary according to the embedment of the pipe.

2.3 *Soil reconstitution methods*

Both artificial and natural soils may be reconstituted in the centrifuge strongboxes. For fine-grained soils (clay or silt), it is usual to add water to a moisture content of twice the liquid limit before mixing the resulting slurry under vacuum to achieve full saturation. Natural soils, sampled in situ, may be sieved initially to remove any coarse particles such as shells. The sample is then permitted to reconsolidate in a manner that mimics the natural sedimentation process. In the centrifuge this process is highly accelerated and is achieved within a few days. An over-consolidated sample can be achieved by the application of a surcharge prior to or during consolidation on the centrifuge.

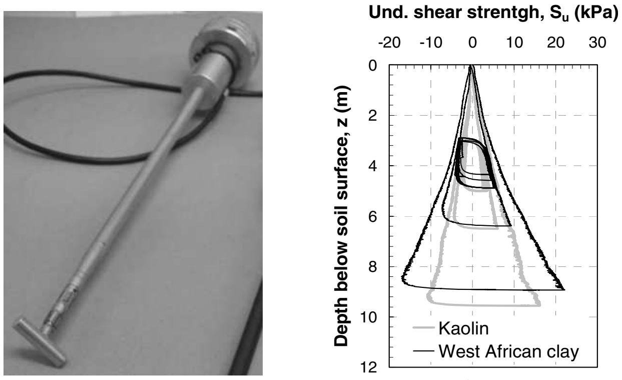
Coarse-grained soils, which do not sustain excess pore pressure for any significant period, are prepared by pluviation of the grains through air or water, or by vibration of successive layers, depending on the required density.

In all cases, the reconstitution process aims for the reconstituted sample to exhibit characteristics identical to the in situ material. A miniature site investigation is conducted within the sample, using techniques comparable to field investigations, allowing the soil properties in the field and the model to be compared.

2.4 *Seabed characterisation*

Improving the reliability of design predictions of pipeline embedment during laying and lateral buckling relies on accurate measurements of the seabed characteristics in the upper 0.5 m of the seabed, which is the zone relevant to pipeline-soil interaction.

The T-bar penetrometer, originally developed for the geotechnical centrifuge (Stewart & Randolph, 1991) is increasingly favoured in the field for characterising soft soils. The T-bar penetrometer used in the beam centrifuge (Figure 2a) consists of a cylindrical bar, 5 mm in diameter and 20 mm in length, attached perpendicularly to the end of a shaft. Strain gauges located immediately above the cylindrical bar record the net bearing pressure ($q_{T\text{-bar}}$) during continuous penetration. The undrained shear strength s_u of the soil is calculated as the net bearing pressure divided by a bearing factor $N_{T\text{-bar}}$ usually taken as 10.5 (Stewart & Randolph, 1991). Figure 2b presents typical profiles of shear strength from tests involving remoulding cycles, which aim to assess the sensitivity of the soil (Randolph et al, 2007).



(a) (b)

Figure 2. T-bar penetrometer used in the UWA beam centrifuge and typical undrained strength profiles from T-bar tests (depth in prototype scale units)

The interpretation of T-bar penetration tests to assess the strength of soft seabed soils in the upper 0.5 m can be refined beyond the use of a constant $N_{T\text{-bar}}$ = 10.5 factor. These refinements have been described by White et al. (2009) and account for the soil buoyancy and the reduced bearing factor arising from the shallow failure mechanism mobilised prior to full flow of soil around the bar. These corrections, which are marginal for assessing the strength of clay at moderate depths (>1 m) can be significant at shallow depth in soft materials. White et al. (2009) demonstrated that the omission of these effects may result in an underestimation of the shear strength in the depth range relevant to pipeline analysis.

More recently, the use of T-bar penetrometers has been extended to investigate in the centrifuge phenomena particularly relevant to pipeline behaviour, including the successive cycles of consolidation and remoulding experienced by the soil (Hodder et al., 2008) and the potential entrainment of water (and consequent swelling) during cyclic events.

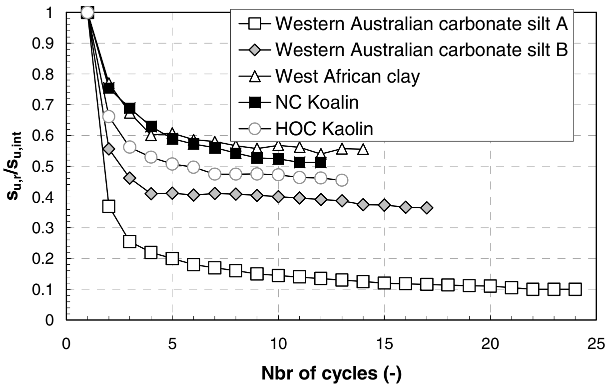


Figure 3. Degradation of strength during cyclic T-bar penetrometer tests.

Figure 3 illustrates the loss of strength (expressed as the ratio of the remoulded shear strength $s_{u,r}$ to the intact shear strength $s_{u,int}$) experienced by different soils during cycles of remoulding for artificial clay and naturals clayey silts typical of the North West Shelf region, off the coast of Australia. The most striking feature of this cyclic test is the ten-fold reduction in strength during cycling for the Western Australian carbonate silt A in contrast to the two-fold reduction in strength for normally consolidated Kaolin.

Further strength loss may be experienced by the soil as the pipeline remoulds and softens the soil, and water is entrained, increasing the moisture content of the soil. This is illustrated in Figure 4, which compares the strength loss for normally consolidated Kaolin clay resulting from deep cycles (as shown in Figure 2b), from cycles 22 mm deep, breaking at the surface and from cycles 50 mm deep, breaking at the surface (using model scale units). The deep cycles do not break the surface, so water entrainment does not occur. For the kaolin test to 50 mm depth, the strength loss has been quantified at four different depths, from 10 to 40 mm, while for the kaolin test to 22 mm, the loss of strength has been quantified at a depth of 20 mm. This test clearly indicates that the entrainment of water contributes to a continuous strength loss down to a value 5 times lower than the fully remoulded shear strength determined from deep cycles (without water entrainment). For typical normally consolidated kaolin, this strength reduction corresponds to an increase of water content by about 30%. The cycles to 50 mm depth indicate a similar trend with the magnitude of strength loss decreasing with depth. At 10 mm depth, the strength loss reaches a value similar to the one exhibited by the 22 mm cycles, but at a much faster rate. At deeper depths the degree of strength degradation reduces to eventually reach a value similar the one obtained from deep cycles. As the T-bar penetrates deeper, the backflow of soil gradually limits the water entrainment.

It is also noted that even at very shallow depth, the effect of the water entrainment seems to reach a maximum, resulting in the soil still exhibiting some shear strength, even after a significant number of cycles.

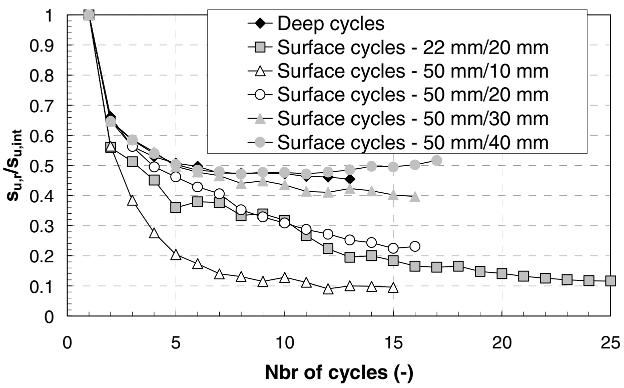


Figure 4. Strength loss at different depths in normally consolidated clay during deep and surface-breaking cyclic T-bar penetrometer tests.

At the touchdown point of an SCR, during the laying process, or during lateral thermal buckling, the soil surrounding the pipeline experiences successive series of cyclic events which are sufficiently fast to generate undrained behaviour and which result in remoulding of the soil. For the former two cases the vertical motion of the pipe, leading to greater embedment, is likely to result in water entrainment in addition to remoulding. The resistance provided by the soil to pipe embedment or lateral displacement is affected by the level of remoulding experienced.

The simple examples presented above illustrate (i) the wide range of sensitivity exhibited by different types of offshore soils and (ii) the significant loss of strength resulting from water entrainment – a phenomenon likely to occur during pipe-soil interaction but which is not capable of being quantified using current design approaches. In both cases, simple characterisation tests performed in in-situ reconstituted samples may provide valuable and reliable information for design.

3 MODELLING OF THE DYNAMIC LAY PROCESS

Two examples of physical modelling of dynamic laying process are presented from projects recently performed at COFS. Information such as pipe diameter and the location from which the soils were sampled are omitted due to confidentiality of the studies. The focus is on the trajectory of the pipeline under the action of the cyclic loads, representative of the laying process, and the final as-laid embedment. Further details about the soil resistance associated with these processes and subsequent simulations of lateral buckling are presented by White & Gaudin (2008).

3.1 *Lay simulation 1: Lateral cycles and vertical steps*

During the lay process, an element of pipe moves through the touchdown zone, from an initial contact with the seabed to a stationary position when the pipe weight is supported by an equal upwards seabed reaction force. In this first example, the dynamic behaviour of the pipe through this process was idealised as follows:

1. The number of oscillations during the entire lay process was assessed, based on the estimated pipeline laying rate, the touchdown zone length and the wave-induced oscillation frequency.
2. The profile of stress concentration in the touchdown zone due to the catenary shape was estimated, based on a structural analysis of the hanging pipeline using the planned lay tension and hang-off angle. This profile of touchdown stress was converted to a stepwise variation of vertical pipe-soil load, including three stages of k_1V_{lay}, k_2V_{lay}, and V_{lay} respectively. The vertical load was held steady within each packet of oscillations, then increased linearly over a period of one oscillation The final load, V_{lay}, was equal to the as-laid pipeline weight.
3. The horizontal oscillation was assumed to vary sinusoidal with time, decreasing in amplitude with depth, due to the increasing soil restraint, according to the inverted triangular profile.

The input behaviour is the horizontal cyclic motion and the static step-wise vertical load, which are both evident in the trajectory of the pipe invert (Figure 5). The accumulation of pipe invert embedment throughout the oscillations is summarised in Figure 6. The embedment increases continually throughout the first and second stages, with no tendency to reach a steady embedment. In the third stage, when the vertical load was reduced, a stable embedment of 0.3 m appears to have been reached. An increased number of oscillations – i.e. a slower lay rate – would lead to a greater pipe embedment during the first two stages.

The load applied at the start of the simulation, prior to the oscillations, was more than half of the as-laid pipe weight but the penetration under that load was less than 10% of the final embedment. The dynamic oscillation is the dominant mechanism of pipe embedment, and the high degree of dynamic embedment evident in these tests can be linked to the high soil sensitivity.

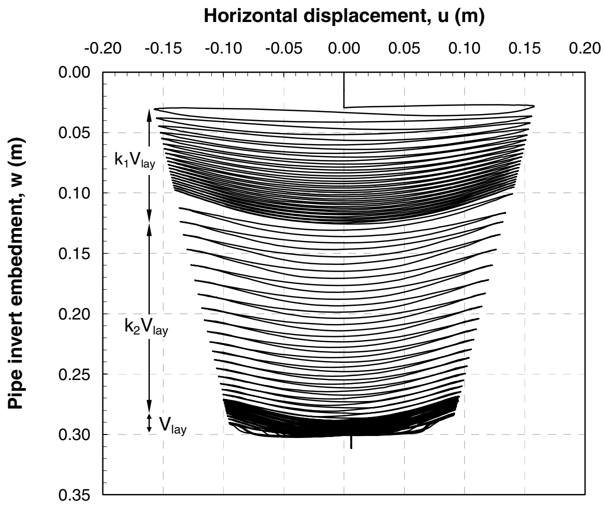


Figure 5. Dynamic lay simulation 1: pipe invert trajectory

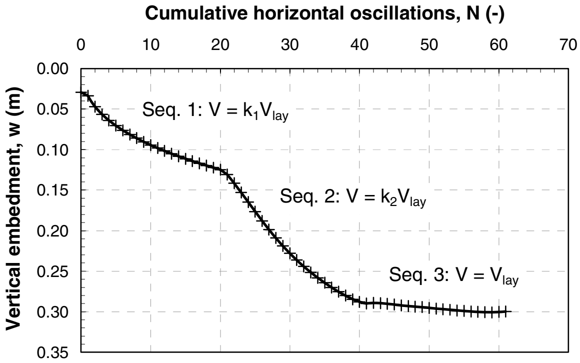


Figure 6. Dynamic lay simulation 1: Accumulation of pipe embedment

This result highlights the difficulty of assessing dynamic pipe embedment without the benefit of a model test. For this project, centrifuge modelling of the lay process provided insight into the likely range of embedment for a given lay rate and pipe weight.

3.2 *Lay simulation 2: Lateral and vertical cycles*

In this second example, the realism of the lay process was enhanced by the inclusion of the cyclic vertical load component associated with the motion of the vessel, rather than just the static component that featured in the previous example. Also, the touchdown zone was divided into six zones instead of three, with a sequence of actions specified for each of the six zones.

Each sequence included a cyclic vertical loading of a specified amplitude (from 0 to 1.55 times the as-laid pipeline weight V_{lay}) concurrent with horizontal cyclic motion, also of specified amplitude, as presented in Figure 7. The first sequence, modelling the first segment of the pipe at the touchdown zone, features a specific cyclic motion in which the pipe was pushed into the soil to a specified load of $0.7V_{lay}$ before being lifted up until separation between the soil and the pipe occured.

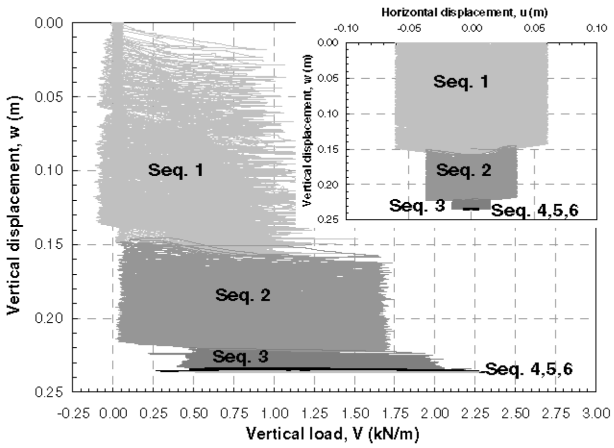


Figure 7. Dynamic lay simulation 2: Cyclic vertical loading and the associated pipe invert trajectory

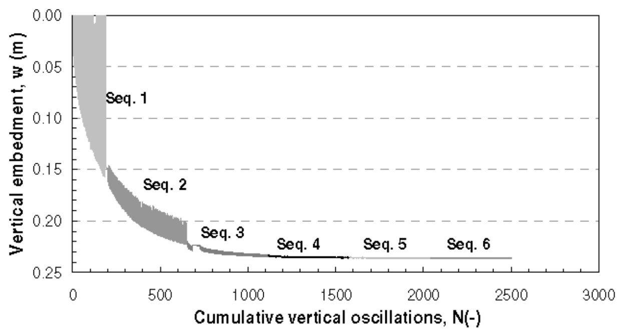


Figure 8. Dynamic lay simulation 2: Accumulation of pipe embedment

The resulting accumulation of pipe embedment is presented in Figure 8 for each sequence as a function of the number of imposed cycles – which far exceed the number of cycles imposed in simulation 1 (Figure 5) due to the slower lay rate. The key observations from Figures 7 and 8 are the suction developed at the pipe invert during the first sequence of loading, where the pipe was lifted up from the soil (which potentially affects the stresses in the pipeline), and the dominant effect of the lateral motion amplitude compared to the cyclic vertical load. The first sequence, which featured the largest amplitude of lateral motion, resulted in a deeper embedment that the subsequent sequences, which featured a higher maximum vertical load but smaller lateral motion amplitudes. In other words, for these lay conditions and this soil type, the action of pushing the soil to either side of the pipeline during lateral motion (and concurrently remoulding it) has a dominant effect on the pipe embedment in comparison to any remoulding or penetration of the soil resulting from the vertical cyclic loading.

4 CONCLUSIONS

The paper presents a brief outline of the modelling techniques and capabilities developed at the COFS geotechnical centrifuge facility to model the dynamic aspects of seabed pipeline laying. The two examples presented, extracted from recent industry projects, highlight the complexity of the pipeline motion at the touchdown zone and the effect on the as-laid pipe embedment. Since guidelines and reliable analytical models for dynamic embedment do not exist, centrifuge modelling studies provide vital insights and quantification of this behaviour that can be readily used for design.

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REFERENCES

Bruton, D., Carr, M. & White, D.J. 2007. The influence of pipe-soil interaction on lateral buckling and walking of pipelines: the SAFEBUCK JIP. *Proceedings of the 6th International Conference on Offshore Site Investigation and Geotechnics*, London., 133-150.

Cheuk, C.Y. and White, D.J. 2008. Centrifuge modelling of pipe penetration due to dynamic lay effects. *Proceedings of the 27th International Conference on Offshore Mechanics and Arctic Engineering*, Estoril, Portugal. 2008-57923.

Hodder, M.S., White, D.J., Cassidy, M.J. 2008. Centrifuge modelling of riser-soil stiffness degradation in the touchdown zone of a SCR. *Proceedings of the 27th International Conference on Offshore Mechanics and Artic Engineering*, Estoril, Portugal, 2008-57302.

Randolph, M.F. and White, D.J. 2008. Pipeline embedment in deep water: process and quantitative assessment. *Proceedings of the Offshore Technology Conference*, paper OTC 19128-PP.

Randolph, M.H., Low, H.E. and Zhou, H. 2007. In situ testing for design of pipeline and anchoring systems. *Proceedings of the 6th International Conference on Offshore Site Investigations and Geotechnics*, London, England, 251-262.

Randolph, M.F., Jewell, R.J., Stone, K.J.L. and Brown, T.A. 1991. Establishing a new centrifuge facility. *Proceedings of the International Conference Centrifuge 91*, Boulder, Colorado, 3-9.

White, D.J., Gaudin, C., Boylan, N. and Zhou, H. 2009. Interpretation of T-bar penetrometer tests at shallow embedment and in very soft soils. *Canadian Geotechnical Journal*, submitted in December 2008.

White, D.J. and Gaudin, C. 2008. Simulation of seabed pipe-soil interaction using geotechnical centrifuge modelling. *Proceedings of the Deep Offshore Technology Conference (Asia-Pacific)*, Perth, Australia.