Using the 'step zero' approach to design a centrifuge modelling program

Article · January 2014

DOI: 10.1201/b16200-51

Shah Neyamat Ullah
Central Queensland University

Sam Stanier
University of Western Australia

David J White
University of Western Australia

Yuxia Hu
University of Western Australia

Physical Modelling in Geotechnics – Gaudin & White (Eds)
© 2014 Taylor & Francis Group, London, ISBN 978-1-138-00152-7

Using the 'step zero' approach to design a centrifuge modelling program

S.N. Ullah, S.A. Stanier & D.J. White
Centre for Offshore Foundation Systems, University of Western Australia, Australia

Y. Hu
Civil and Resource Engineering, University of Western Australia, Australia

ABSTRACT: The design of a centrifuge modeling program for a clay bed with an interbedded sand layer is outlined following the 'step zero' approach. A modified sand overlying clay model was used incorporating the top clay as an effective surcharge. The tests aimed to investigate punch through failure, and the subsequent stabilization of bearing capacity. To this behavior within the limited depth of the test box a certain vertical free boundary distance (F_{BD}) is required, which controls the required ratio of soil sample depth to foundation size. In assessing this requirement based on existing calculation methods for punch through, the following four factors were found to be crucial: (i) intercept strength of clay at sand-clay interface; (ii) soil strength gradient of the clay layer; (iii) relative density of sand; and (iv) relative sand layer thickness to foundation diameter. As a result of planning and implementing a 'step zero' approach, the majority of the tests successfully captured the peak resistance and the depth of the punch-through event. The planning approach demonstrated here serves as an example for future centrifuge test design in similar scenarios.

1 THE 'STEP ZERO' CONCEPT

The 'step zero' concept is an idea that originated from Vincent Prantil of Milwaukee University (Muir Wood 2013, pers. comm.). It is focussed on the concept that before performing an analysis—whether experimental or numerical—simple 'back-of-the-envelope' calculations ought to be carried out to provide some forecast of the outcomes of the proposed analyses. Such initial predictions provide the researcher with an opportunity to reflect on whether their planned investigation is fit for purpose, or indeed whether the plan requires further refinement before actually being put into practice.

This paper describes the use of such an approach to design a series of centrifuge model tests to investigate the mechanisms of punch-through of a spudcan and a flat foundation on a bed of clay containing an interbedded sand layer. The results of the investigation highlight the potential value to be gained from employing the 'step zero' approach.

2 THE TARGET PROBLEM

Modern offshore jack-up structures typically consist of a triangular floating platform hosting all of the facilities required for operation of the unit, which is supported on independently retractable, trussed legs. The retractable legs allow the jack-up platform to be installed at a chosen location for a given operating period, before extraction and re-deployment elsewhere. Quasi-circular or occasionally polygonal foundations, known as spudcans, are typically used to support the trussed legs.

Before commencement of drilling from the platform, the spudcan foundations are proof loaded with a preload typically 50–100% higher than the expected working loads. Under this preload the foundation penetrates into the seabed until vertical equilibrium is established. In stratigraphies with stiff layers of soil overlying soft layers, this preloading stage can lead to uncontrolled rapid leg penetration or severe punch-through if part of the penetration resistance involves a reduction in resistance with depth.

The soil stratigraphies which are typically responsible for such failure include: (i) sand overlying clay, (ii) stiff clay overlying soft clay and (iii) inter-bedded stiff layers of sand or clay within a bed of soft clay. Testing these stratigraphies in the laboratory inside a test chamber with a finite depth makes predicting the free boundary distance (F_{BD}) crucial (see Fig. 1). This distance must be sufficiently large for the punch through event

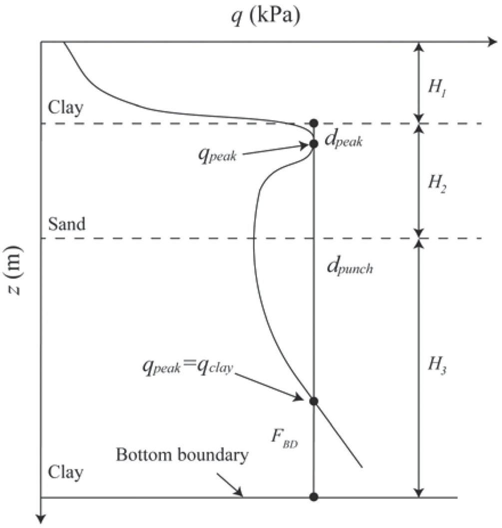

Figure 1. Schematic of expected punch-through behaviour in clay-sand-clay bed.

to be completed prior to the bottom boundary having a significant influence on the penetration resistance.

As a result, for a successful testing program using the aforementioned stratigraphies, accurate prediction of F_{BD} is vital.

Many experimental investigations into bearing capacity on two-layer models of sand overlying clay have been reported in the literature (e.g. Craig & Chua 1990, Teh et al. 2008, Teh et al. 2010, Lee et al. 2009, Stanier et al. 2012). In addition, to date, experimental investigations into multi-layer stratigraphies have also focussed upon interbedded stiff layers of clay in a bed of soft clay (e.g. Hossain et al. 2011).

However as discussed later, in terms of confirming a sufficiently high F_{BD} the tests were not always consistent. This suggests that, a careful planning of soil properties and the influence on the free boundary distance should be understood before any such test is attempted in the centrifuge. As offshore reports suggest, multi-layer soil profiles are common in emerging oil and gas fields (Kostelnik et al. 2007, Hossain et al. 2011). This has led to increased demand for testing such layered profiles in the limited working depth of the centrifuge.

Multi-layer profiles with interbedded sand layers often lead to greater d_{punch} since the additional layers will generate greater peak resistance. Accurately predicting the free boundary distance is of paramount importance to ensure that critical aspects of the tests are adequately captured within the limited depth of the centrifuge boxes. This paper describes how a series of centrifuge tests were designed using the 'step zero' approach, involving prediction of the results of the experiments as part of the planning phase. These predictions were used to maximise the likelihood of success of the experiments allowing refinement of the test plan before entering the laboratory.

3 EXISTING PREDICTION MODELS

When designing a series of centrifuge experiments the first steps of the 'step zero' approach are to (i) define the key aspects of the proposed experiments that must be captured and (ii) generate some initial predictions of the outcomes using simple 'back-of-the-envelope' calculations.

To have a sufficient free boundary distance (F_{BD}) It is critical that any experimental investigation captures both the initial punch-through and the point where the foundation regains vertical equilibrium, i.e. q_{peak} and $q_{peak} = q_{clay}$ (Fig. 1). In a clay-sand-clay scenario (as compared to the more studied sand-over-clay scenario), it is envisaged that punch-through will still begin during penetration of the stiff sand layer and finish in the underlying clay layer as illustrated in Figure 1. Therefore, simple calculation models are required to predict the magnitude and depth of q_{peak}, the depth at which $q_{peak} = q_{clay}$, and subsequently the magnitude of d_{punch}.

3.1 *Peak penetration resistance, q_{peak}*

The peak penetration resistance, q_{peak}, of a foundation on sand overlying clay is predicted here using the model of Lee et al. (2009). The model assumes that a frustum of sand with a projecting angle equal to the dilation angle, ψ, is pushed into the underlying clay layer. The model is adapted for the clay-sand-clay scenario of interest here, by approximating the pressure exerted by the overlying clay layer as a surcharge pressure of $q_0 = H_1 \cdot \gamma'_c$ acting on the surface of the sand layer, where γ'_c is the effective unit weight of the clay.

3.2 *Depth of peak resistance, d_{peak}*

Teh et al. (2008) observed through centrifuge tests that the peak resistance during punch-through occurred at a depth of typically 12% of the sand layer height, H_s. Stanier et al. (2012) confirmed experimentally, using further centrifuge tests, that this estimate was also valid for loose sand overlying clay. Hence, in these analyses the depth of peak resistance, d_{peak}, is taken at $0.12H_s$, which in reference to Figure 1 is equivalent to $0.12H_2$.

3.3 *Stability at depth, $q_{peak} = q_{clay}$*

The bearing capacity in the lower clay layer is generated by deformations around a composite foundation consisting of the foundation and an underlying trapped sand plug. Based upon observations of the sand plug geometry from samples extracted following centrifuge tests, Lee (2009) performed small strain Finite Element (FE) analyses to derive relationships for the bearing capacity factor, N_{c0}. These relationships were used to predict the bearing capacity of the composite spudcan-plug foundation when it penetrated into the lower clay layer.

3.4 *Depth of punch-through event, d_{punch}*

The depth of the punch-through event, d_{punch}, is estimated by solving the equations describing the bearing capacity in the lower clay layer for the depth at which $q_{peak} = q_{clay}$.

4 EXPERIMENTAL PLANNING

The stages of the experimental planning process are outlined in the flow chart shown in Figure 2. The following sections describe information relevant to the planning process with reference to the target problem of punch-through in a clay-sand-clay bed.

4.1 *Aims and apparatus constraints*

The primary aims of this investigation were to (i) capture the two key aspects of a punch-through event (q_{peak} and $q_{peak} = q_{clay}$) allowing the measurement of the depth of the event (d_{punch}) and (ii) observe the associated deformation mechanisms. The latter aim was achieved by performing the tests in a small strongbox with a transparent acrylic window on one side. This allowed a digital camera to be used to record images of the exposed plane of the model, which were later subjected to Particle Image Velocimetry (PIV) analysis to assess the deformation mechanisms (Stanier et al. 2013).

The strongbox had internal dimensions of 258 mm length, 180 mm height and 80 mm depth. The field of view through the transparent window was 258 mm by 160 mm. The foundation Diameter (D) was chosen as 30 mm, giving a minimum free lateral boundary distance of 2.67D from the centreline of the foundation. Although smaller D would lead to greater free boundary distance, it would also cause less details of the deformation mechanisms to be captured by the digital camera.

To maximise the data yielded from each sample, two offset tests were performed in each strongbox on opposite faces of the sample. This allowed a flat foundation and spudcan shaped (i.e. conical underside) foundation to be tested in the same stratigraphy, facilitating investigation of the effect of foundation shape on the associated deformation mechanisms. The general schematic of the tests is illustrated in Figure 3.

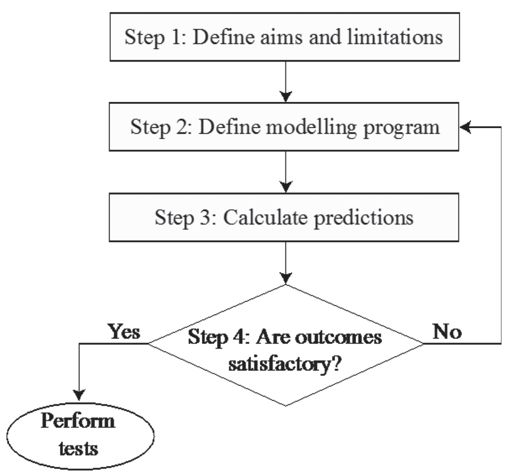

Figure 2. Flow chart of the experimental planning process.

4.2 *Target variables*

For sand overlying clay, punch-through is most prevalent for H_s/D ratios less than unity (Lee, 2009). In the absence of any evidence to the contrary, the same was assumed for the clay-sand-clay case investigated here. Given that the diameter of the foundations used in the investigation was fixed at 30 mm, the thicknesses of the first two soil layers, H_1 and H_2, became the most logical variables

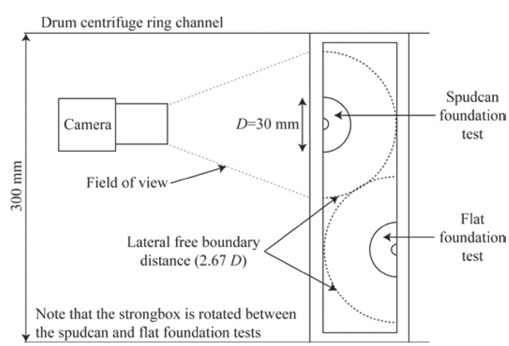

Figure 3. Schematic of test setup.

to modify to allow a range of realistic sand layer to diameter ratios to be modelled.

Given that a key aim of the investigation was to use PIV to assess deformation mechanisms, it was critical to ensure that subsets of the tests performed were comparable with each other. With this in mind, subsets of tests concerned with the effect of (i) varying clay layer height (H_1/D) with constant sand layer height (H_2/D) and (ii) varying sand layer height (H_2/D) with constant clay layer height (H_1/D) were planned as outlined in Figure 4. The exact layer height ratios to be tested were determined later as part of the iterative planning process summarised in Figure 2.

4.3 *Potential soil properties*

A range of sample properties including sand-clay intercept shear strength (s_{u0}), clay shear strength gradient (ρ), sand relative density (I_D) have been reported in centrifuge investigations of punch-through (e.g. Craig & Chua 1990, Teh et al. 2008, Lee 2009, Teh et al. 2010, Stanier et al. 2012). Of these only the tests reported by Lee (2009) and Stanier et al. (2012) were able to consistently model both the q_{peak} and $q_{peak} = q_{clay}$ events within the confines of the centrifuge strongbox. This was primarily because the underlying clay layer was consolidated at 300 g whilst the tests were performed at 200 g, giving an OCR of 1.5. This meant that the clay had a higher gradient of shear strength with depth and so $q_{peak} = q_{clay}$ was reached more rapidly. In contrast the other investigations had a normally consolidated underlying clay layer and correspondingly low shear strength gradient

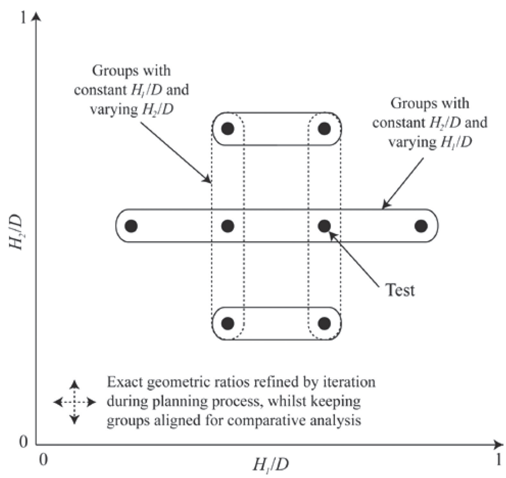

Figure 4. Groups of tests for comparative analysis with varying geometric ratios, H_1/D and H_2/D.

with depth. Based on this experience, an OCR of 1.5, and the associated gradient of shear strength was also used in this investigation.

Of these previous tests, many were performed at UWA, using the same apparatus as this investigation. Lee (2009) tested for punch-through on dense sand overlying soft clay, whereas Stanier et al. (2012) tested on loose sand overlying clay. The dense sand tests exhibited greater q_{peak} and correspondingly greater d_{punch}. Soil parameters from these investigations, which are summarised in Table 1, were used in the planning process to generate a range of potential outcomes.

Soil property set 'A' represents a worst case punch-through depth (dense sand over clay causing large d_{punch}), set 'B' represents a best case (loose sand overlying clay causing small d_{punch}) and set 'C' is the average of sets 'A' and 'B'. For all sets, the normalised sand plug height, H_{plug}/H_s, was taken as the average of the range given by Lee (2009).

4.4 *Free boundary distance (F_{BD})*

The free boundary is defined as the distance between the bottom of the strongbox and the point on the load resistance curve where $q_{peak} = q_{clay}$ (see Fig. 1). This distance can be estimated as follows:

$$F_{BD} = \left(H_2 + H_3\right) - \left(d_{peak} + d_{punch}\right) \tag{1}$$

To define acceptability of predictions, a minimum F_{BD}/D criterion was required. Ullah & Hu (2012) used LDFE (Large Deformation Finite Element) analyses to show that for $H_2/D = 0.75$ the boundary affected zone was 1D. To allow for sufficient margin for error, the minimum F_{BD}/D criterion was increased to 1.25. To predict q_{peak} and F_{BD} the layer heights for all tests were varied until the predictions were acceptable (i.e. the process outlined in Figure 2 was satisfied). The final layer heights resulting from this process are summarised in Table 2.

4.5 *Final predictions of q_{peak} and F_{BD}*

The final predictions are summarised in Figures 5 and 6, which show q_{peak} and F_{BD} plotted versus

Table 1. Soil property sets used in the planning process.

Set	I_D (%)	s_{u0} (kPa)	ρ (kPa/m)	H_{plug}/H_s (–)
A	92[1]	17.70[1]	2.0[1]	0.75[3]
B	43[2]	12.12[2]	1.54[2]	0.75[3]
C	67.5	14.91	1.77	0.75[3]

[1]Values from Lee (2009). [2]Values from Stanier et al. (2012). [3]Average of range given by Lee (2009).

Table 2. Dimensions adopted in tests.

Test	Dimension (mm, m) H_1	H_2	H_3	D
T01	10, 2	20, 4	80, 16	30, 6
T02	20, 4	20, 4	80, 16	30, 6
T03	30, 6	20, 4	80, 16	30, 6
T04	0, 0	20, 4	80, 16	30, 6
T05	20, 4	10, 2	80, 16	30, 6
T06	20, 4	30, 6	80, 16	30, 6
T07	10, 2	10, 2	80, 16	30, 6
T08	10, 2	30, 6	80, 16	30, 6

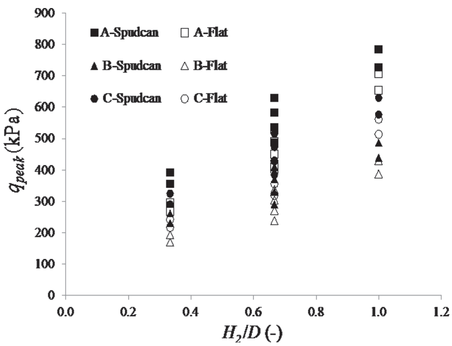

Figure 5. Predicted peak penetration resistance, q_{peak}, versus normalised sand height, for soil profiles A, B and C.

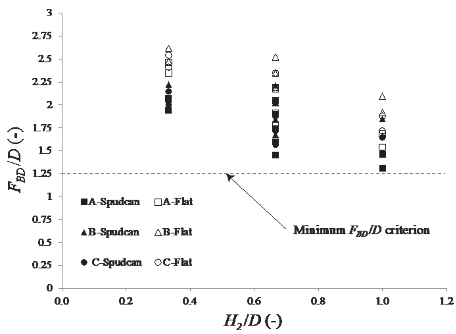

Figure 6. Predicted normalised free boundary distance versus normalised sand thickness, for soil profiles A, B and C.

the normalised sand layer height respectively. As expected soil property set 'A' exhibits the smallest remaining F_{BD}, while soil property set 'B' exhibits the largest remaining F_{BD}. The average soil set 'C' produced predictions that lie between the two extremes. In all cases the predictions show a remaining F_{BD}/D of >1.25 after the punch-through event.

5 EXPERIMENTAL PROCEDURE

The experiments were then performed using the geometries outlined in Table 2. The sample preparation procedures aimed to reproduce soil properties similar to set 'C', to raise the likely value of F_{BD} and reduce the potential impact of any unforeseen error in the estimate of F_{BD}.

Kaolin clay slurry was poured into the strongboxes in flight using a slurry placement tool, before consolidation at an acceleration of 300 g. Further slurry was added at intervals until a bed height of 140 mm was achieved. T-bar tests were then performed to measure the shear strength gradient with depth, ρ, which was on average ~1.66 kPa/m.

Following consolidation of the clay, the top 60 mm was cut from the top of the sample and the required sand depth was rained into the strongbox. From the T-bar tests, s_{u0} was ~16 kPa at a depth of 60 mm. The relative density produced by the sand rainer was found to be ~74% through volumetric measurement. After placement of the sand layer the removed layer of clay was replaced on top of the sand before scraping off the excess clay to form the target height of the top layer, H_1/D.

Coloured flock material was added to the exposed sample surface to facilitate precise PIV analysis. Due to problems during consolidation, two samples were unusable due to leakage and so tests T07 and T08 were discarded. Complementary tests, investigating the same variable change, still existed within the test plan (see Fig. 4).

Flat and spudcan foundation tests were performed in each strongbox at an acceleration of 200 g (i.e. OCR = 1.50) on opposite faces of the box. Digital images were captured at 5 Hz. Vertical load and displacement were measured using a load cell and the encoders on the actuator.

6 RESULTS

The sample properties were broadly similar to those used in the set 'C' predictions, with some properties closer to the worst case 'A' and some closer to the best case 'B'. Predictions of q_{peak} were updated to account for the actual soil parameters measured in the experiments. When compared to the experimentally measured q_{peak}, the majority of the comparisons fell outside of the 20% variation line as illustrated in Figure 7. Hence, in respect to the current model, where the top clay layer is approximated as an effective surcharge, the peak resistance is significantly underestimated.

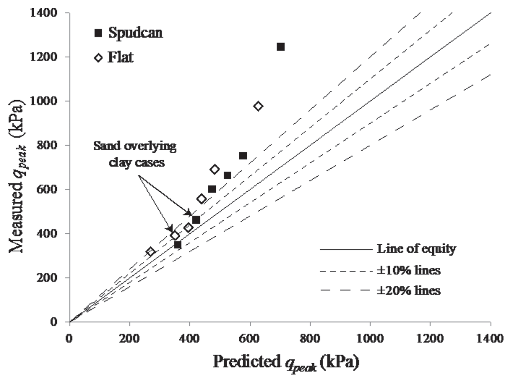

Figure 7. Predicted peak penetration resistance versus measured peak resistance in a clay-sand-clay bed.

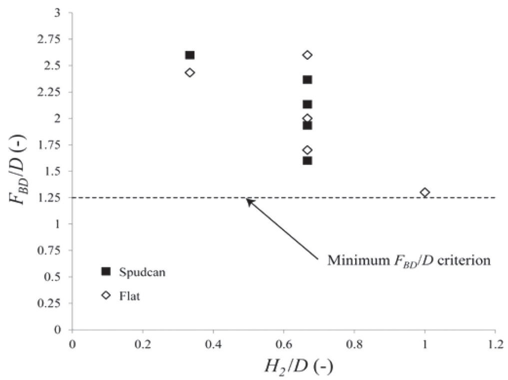

Figure 8. Measured normalised free boundary distance versus normalised sand thickness in a clay-sand-clay bed.

Current research is attempting to refine the prediction methods for q_{peak}.

Figure 8 shows the results in terms of the free boundary distance (F_{BD}) remaining after $q_{peak} = q_{clay}$ is reached in the lower clay layer. Apart from a single spudcan test (T06—see Tab. 2), which due to the thicker sand layer measured the highest peak of 1250 kPa (see Fig. 7), all the other tests lie above the minimum F_{BD}/D criterion. Therefore, d_{punch} was measurable in all tests performed except for the spudcan in T06.

The fact that q_{peak} was under predicted, yet all but one test were successful in respect to d_{punch} being measureable, would suggest that neither model (q_{peak} or q_{clay}) used in the planning process was accurate. In fact both models must be inaccurate, for this application to clay-sand-clay conditions, but in a complementary manner—one counteracted the other so that d_{punch} remained moderate and measureable. The images captured during the investigation will be used in future PIV analyses to explain the reasons for this.

7 CONCLUSIONS

This paper described the application and potential benefits of using the 'step zero' approach when planning a program of centrifuge modelling. From the process the following conclusions can be drawn:

i. Existing calculation methods for punch through bearing capacity could be adapted to the 3-layer conditions under investigation. This allowed predicted penetration resistance profiles to be used to assess the required sample and foundation dimensions to avoid unwanted boundary effects.
ii. The majority of the tests were successful in capturing the punch-through event prior to the boundary having an influence. In this respect the 'step zero' approach added significant value and provided confidence in the test program prior to commencement.
iii. The peak bearing capacity in most of the tests was higher than predicted by the current analytical model by more than 20% indicating scope for developing improved prediction models.
iv. The model used to describe the bearing capacity post-punch through (when there is effectively a composite foundation of the footing plus the sand plug) is also inappropriate for clay-sand-clay. Even though q_{peak} was higher than expected, the depth of the punch-through event was broadly similar to the predictions for all but one test, indicating that the predicted q_{clay} is probably also in error.
v. PIV analysis of the images recorded during the tests will provide insight that may help to tackle these last two points.

ACKNOWLEDGEMENTS

The work forms part of the activities of the Centre for Offshore Foundation Systems (COFS) at the University of Western Australia, which is supported by the Lloyd's Register Education Trust as a Centre of Excellence and is a node of the Australian Research Council (ARC) Centre of Excellence in Geotechnical Science and Engineering. The authors would also like to acknowledge the financial contribution of the Australian Research Council (ARC) through Discovery Project No. 1096764. The third author is supported by an ARC Future Fellowship and holds the Shell Energy and Minerals Institute (EMI) Chair in Offshore Engineering.

REFERENCES

Craig, W.H. & Chua, K. 1990. Deep penetration of spudcan foundation on sand and clay. *Géotechnique* 40(4): 541–556.

Hossain, M.S., Randolph, M.F. & Saunier, Y.N. 2011. Spudcan deep penetration in multi-layered fine-grained soils. *International Journal of Physical Modelling in Geotechnics* 11(3): 100–115.

Kostelnik, A., Guerra, M., Alford, J., Vazquez, J. & Zhong, J. 2007. Jackup mobilization in hazardous soils. *Society of Petroleum Engineering, Drilling & Completion,* 22: 4–15.

Lee, K.K. 2009. *Investigation of Potential Spudcan Punch Through Failure on Sand Overlying Clay Soils. PhD dissertation*, University of Western Australia.

Lee, K.K., Randolph, M.F. & Cassidy, M.J. 2009. New simplified conceptual model for spudcan foundations on sand overlying clay soils. *Proc.* 40*th Offshore Technology Conf.,* Houston.

Stanier, S.A., Hu, P. & Cassidy, M.J. 2012. Calibration of a model to predict the peak punch-through penetration resistance of a spudcan on sand overlying clay. *Proceedings of the 2nd European Conference on Physical Modelling in Geotechnics (Eurofuge 2012)*, Delft, The Netherlands.

Stanier, S.A., Breen, J. & White, D.J. 2013. A compact high-speed image capture system for the drum centrifuge. Manuscript submitted for publication in the *Proceedings of the 8th International Conference on Physical Modelling in Geotechnics*.

Teh, K.L., Cassidy, M.J., Leung, C.F., Chow, Y.K., Randolph, M.F. & Quah, M. 2008. Revealing the bearing capacity mechanisms of a penetrating spudcan through sand overlying clay. *Géotechnique* 58(10): 793–804.

Teh, K.L., Leung, C.F., Chow, Y.K. & Cassidy, M.J. 2010. Centrifuge model study of spudcan penetration in sand overlying clay. *Géotechnique* 60: 825–842.

Ullah, S.N. & Hu, Y. 2012. A Numerical investigation into the bottom boundary effect for spudcan penetration on sand overlying clay in centrifuge test. *31st International Conference on Ocean, Offshore and Arctic Engineering*, Rio de Janeiro, Brazil.