Examples of the influence of centrifuge modelling on offshore geotechnical engineering

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Abstract:Offshore geotechnical engineering is characterized by unusual soil and loading conditions, a continuously moving frontier resulting in the requirement for innovative geotechnical solutions, and the very high cost associated with in-situ soil characterization and field testing in remote and deep oceans. As a consequence, offshore engineering practices has probably benefitted more from centrifuge modelling than other domains of geotechnical engineering, since the first offshore projects performed in 1973. After a brief overview of the role, contribution and advantages of centrifuge modelling for offshore geotechnics, the paper illustrates the influence centrifuge modelling has had in recent years in improving the understanding of soil structure interaction and in the development of guidelines and recommendations in two particular areas via five examples; spudcan foundation and pipe-soil interaction.

Keywords: offshore geotechnics, centrifuge modelling, soil-structure interaction, spudcan, pipeline.

1 INTRODUCTION

1.1 A brief history of the impact of centrifuge modelling on offshore geotechnics

Centrifuge modelling was applied for the first time for offshore geotechnics problems in 1973 at Manchester University. The behaviour and performance of gravity platforms to be established in the Gulf of Mexico were investigated in a large beam centrifuge (Rowe & Craig, 1981). The work encompassed a wide range of soil and loading conditions and provided pivotal insights into the failure mechanism taking place (Craig & Al-Saoudi, 1981). In the early days of the centrifuge, it was understood and acknowledged that centrifuge modelling could significantly contribute to design when novel conditions, or those not fully understood, prevailed (Craig, 1984).

Since the pioneering work in 1973 centrifuge research has expanded worldwide, initially under the impulsion of Prof. Schofield in Europe and Prof. Kimura in Japan. Initially, research focused first on phenomenological and site specific studies before progressively developing towards more general studies, including the observation of failure mechanisms and the understanding of soil-structure interaction. Eventually it aided the development of predictive design methods.

As geotechnical centrifuge techniques developed technically and scientifically, and with an increased need for performance data and understanding of offshore soil-structure interaction, the acceptance of the offshore community to the benefits of the centrifuge grew significantly. An important step in this process was the keynote address given by Professor Murff to the wider offshore community, at the Offshore Technology Conference (Murff, 1996). It advocated the benefits of centrifuge methods by providing key examples, notably related to suction caissons, drag anchors and jack-up foundations. The latter example mainly discussed the research on jack-up foundations sponsored by Exxon and performed in the Cambridge University centrifuge, and also at Oxford University (final report: Noble Denton & Associates, 1987). The outcomes of this research were integrated in the original SNAME guidelines and are still influential on the draft ISO (2009) code of practice. Since then, the geotechnical offshore industry has continued to benefit from centrifuge methods, and both academic and industry users have

developed a strong expertise in analysing centrifuge method outcomes, incorporating them into the development of new design tools, and developing deeper understanding in offshore structure-soil interaction.

1.2 Role and contribution of centrifuge modelling

Offshore geotechnical engineering is characterized by unusual soil and loading conditions, a continuously moving frontier resulting in the requirement for innovative geotechnical solutions, and the very high cost associated with in-situ soil characterization and field testing in remote and deep oceans. As a consequence, offshore engineering practice has probably benefitted more from centrifuge modelling than other domains of geotechnical engineering. The role and contribution of centrifuge modelling to the design of offshore structures and the understanding of offshore structures-soil interaction has been addressed successively by Murff (1996), and more recently by Gaudin et al. (2010). A short summary of the roles of centrifuge modelling in offshore geotechnics practice is presented here, with a particular emphasis on spudcan installation and extraction and pipe soil interaction:

- 1. Provide performance data to calibrate analytical or numerical models. Centrifuge modelling provides homogeneous and well characterized soil conditions, known boundary conditions, accurate measurements of parameters and repeatable testing conditions, offering reliable performance data for a given idealized problem which can be used to calibrate analytical and numerical models. Pipeline lateral buckling models have been established for a fairly narrow range of soil condition. The use of the models for different soil conditions requires calibration data that can be easily and economically provided by centrifuge modelling.
- 2. Providing qualitative insights into soil-structure interaction and mechanisms. This aspect is particularly important when novel concepts or unusual conditions are encountered. Understanding the structure behaviour, observing the failure mechanism taking place, is a pivotal step into the development of sound design methodology. This is particularly relevant for spudcan installation and pipe-soil interaction were large deformations and specific soil flow dominate the soil-structure interaction.
- 3. Validate the structure design for a particular site or a specific design approach. By allowing the use of natural soils, sampled in-situ, by applying complex loading sequences directly relevant to design and by using a models replicating precisely prototypes, centrifuge modelling offers a valuable tool to validate or justify specific offshore structures. Pipeline design is still at an early development, where normalised recommendations have not been formulated yet. The totality of the pipeline development in the North West Shelf of Australia is supported by site-specific centrifuge data.
- 4. *Investigating the feasibility of developing new foundation concept.* The very good control of the testing conditions, the possibility of measuring a significant number of parameters and the relatively low cost of centrifuge testing compared to field testing make the centrifuge an ideal tool to develop new concepts and investigate the feasibility of particular foundations. New spudcan design, featuring skirts, jetting system and preloading systems are currently investigated using centrifuge modelling.
- 5. *Characterising in-situ soils*. The improvement of soils reconstitution methods allows the replication of complex soil stratigraphy using natural soils exhibiting the same properties as found in the field. The centrifuge offers the possibility of performing a large number of tests at a reduced cost, using characterization tools identical to the ones used in-situ.

1.3 Advantages of centrifuge methods to investigate spudcan and pipeline performance

The contributions listed in the previous section are the direct results of the advantages centrifuge methods provides when investigating offshore geotechnical issues. These advantages are intrinsic and are not limited to offshore geotechnics, but they are augmented in offshore geotechnical engineering, where guidelines and design rules play a lesser role than onshore, and where engineers' judgement is paramount in establishing the most technically sound and economically efficient design. Basing judgment on reliable and quality data from a range of modelling methods may make a significant difference between a

satisfactory and an optimal design. While there are several examples to illustrate the advantages of centrifuge methods, including notably suction caissons and other anchoring systems, the paper focuses on two of the most recent examples.

Some particular aspects of these advantages, when associated to spudcan installation and extraction and pipe-soil interaction are:

- Accelerated time frame. Centrifuge modelling and testing require a limited volume of soil, accelerating sample preparation. For soft soil, the process may be further accelerated by in-flight self-weight consolidation. Similarly, testing sequences are considerably shortened still ensuring the correct drainage conditions. This allows data to be collected in a short time frame and at cost orders of magnitude lower than those associated with field testing. More particularly, for pipe testing, this enables the investigation of the pipe-soil interaction over a significant number of cycles, throughout the whole operating life of the field. For spudcan testing, series of six to ten tests in the centrifuge can be undertaken within 2 to 3 weeks, including soil sample preparation. With an ability to cover a wide variety of loading and/or soil conditions, the centrifuge also provides the ability to conduct parametric studies
- Accurate loading sequences. New motion control techniques permit users to replicate accurately complex loading sequences, including cyclic vertical and/or horizontal motion under either load or displacement control. This is particularly relevant to replicate the complex motion of the pipe at the touchdown zone during laying, the large deformations resulting from lateral buckling, the combined loading conditions generated by environmental loading during jack-up operation, or during re-installation events near existing footprints.
- Use of natural soils. By requiring a limited volume of soil, it is possible to use in-situ soil with reasonable supply cost. The use of natural soils for model tests is maybe more important for pipelines than for other geotechnical structures, because of the heavy remoulding and the large deformations experienced by the soil. This may trigger specific behaviour which would not be captured by common artificial laboratory soils.
- Accurate seabed characterization. The good control of the soil reconstitution process results in a homogeneous sample with known boundary conditions and stress history. By using standard soil characterisation tools in controlled conditions (such as cone penetrometer tests, shear vane tests and more recently T-bar penetrometer tests for soft soils (see Randolph, 2004)), and post-testing soil classification methods (such as particle size distribution or Atterberg limits performed on core samples taken from centrifuge samples), it is possible to determine the soil characteristics accurately. Since boundary conditions, material properties and soil stress history are well controlled in centrifuge models, quantitative results of the penetration resistance and patterns of soil flow may be used to validate numerical or analytical models rigorously.
- *Enhanced instrumentation*. New insights into spudcan behaviour have been derived by improved instrumentation developed for centrifuge modelling. For instance, by using visual image acquisition systems (such as digital camera) and associated image processing systems (such as Particle Image Velocimetry (PIV), and photogrammetry, described for application to geotechnics by White et al., 2003), soil flow mechanisms evolving with spudcan penetration have provided the basis for a number of new predictive models. Accurate and detailed miniature pore pressure and total pressure measurements have also provided insights into mechanisms generating excess or negative pore pressures at the spudcan surface. By using similar image acquisition systems and pore pressure measurements, in addition to the measurements of load and displacements, one gains access to particular features of the pipe-soil interaction, such as the development of lateral berms during buckling, the creation of a trench during dynamic laying and the drainage conditions around the pipe during the pipe motion.
- *Case-specific study*. Centrifuge testing can be used to provide insight in some particular issues related to spudcan and pipeline design. This includes particular storm loading conditions or geometric conditions, such as sloped seabed for spudcan or scarp crossing for pipeline.

1.4 Centrifuge modelling for spudcan performance and pipe-soil interaction

Buckling and axial walking (due to changes in internal pressure and temperature in the pipeline) have only emerged recently as a major research topic. Significant advances have been made over the last 5 years, using data from 1g model tests (performed notably at Cambridge University, Cheuk et al., 2007, and at the Norwegian Geotechnical Institute (NGI), Dendani&Jaeck, 2007), in-situ tests (notably using the SMARTPIPE device developed by Fugro and BP, Jacob &Looijen, 2008, White et al. 2010) and also centrifuge tests. While each method has its own advantages and disadvantages (see Hill & Jacob, 2008 for a comparison of each method for pipelines), centrifuge tests have certainly boosted knowledge of pipeline-soil interaction and generated significant breakthroughs.

Example	Problem	Centrifuge	Insights / Outcomes	Application in	Future Requirements
	Addressed	Technology Used		Industry	
1	Installation in clays: - Deep penetration - Back flow	- PIV and photogrammetry - Accurate load- displacement measurements	 Definition of transition from shallow to deep mechanisms Method for predicting the depth at which flow around mechanism occurs New bearing capacity formulae that account for deep penetration, as well as rate and sensitivity 	New design charts and formula for predicting preferential flow mechanism, as implemented in draft ISO (2009)	 Tests with varying soil sensitivity Application into soils with intermediate drainage conditions Assessing capacity increase and settlement due to dissipation of pore- pressures during and after preloading
2	Spudcan punch- through: Stiff-over-soft clay and-over- clay	 PIV and photogrammetry Accurate load- displacement measurements Miniature ball penetrometers 	 Definition of punch- through mechanisms Underpinning of analytical prediction methods 	New methods being trialled in industry, such as in InSafeJIP (Osborne et al., 2009)	 Testing in more complex multi-layered soils Direct predictive methods based on in-situ penetrometer data Application in unconventional soils, such as cemented hard layers
3	Spudcan extraction	 PIV and photogrammetry Pore-pressure and total stress transducers Water jetting using a syringe pump 	 Mechanisms governing extraction, incl. additional capacity due to consolidation during long operations New methodology for predicting extraction resistance whilst using water jetting 	InSafeJIP (2009, 2010)	 Extend current methodology for deep embedment Investigating performance of top jetting Investigating performance of cyclic extraction
4	Pipe dynamic laying	- Accurate load- displacement measurements	 Increase embedment compared to static laying due to soil remoulding and water entrainment Dominance of lateral sweeping amplitude over cyclic vertical loading in embedment development 		 Integrate water entrainment in embedment prediction Investigate SCR soil interaction at the touchdown zone
5	Pipe thermal buckling	PIV and photogrammetryAccurate load-	- Mechanism governing lateral resistance including berm formation	Friction factor formulations and embedment	- Extend friction factor formulation to drained and partially drained conditions

Table 1. Examples of contribution o	of centrifuge modelling in offshore	geotechnics
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displacement measurements - Pore pressure measurements	- Development of friction factors including pipe soil friction and berm resistance as a function of the number of cycles	prediction (SAFEBUCK JIP)	- Develop VH yield envelope to predict breakout friction factors

In contrast, all aspects of spudcan development and design has greatly benefited from centrifuge modelling. This is notably evident for the research establishing spudcan yield surface approaches on the Cambridge centrifuge (see Dean et al., 1993, Wong et al., 1993 amongst others), the bearing capacity of spudcans in silica and calcareous sands (e.g. Finnie & Randolph, 1994; Dean et al., 1993; Teh et al., 2006), the interaction between an installing spudcan and the nearby piles of a fixed jacket platform (e.g. Siciliano et al., 1990; Leung et al., 2006; 2008; Xie et al., 2006; 2010), the contributions of Ng & Lee (2002) to predicting spudcan settlements under cyclic loading, the problematic of spudcan installation near existing footprint (Gaudin et al., 2012) and the combined VHM capacity of spudcan via the development of force-resultant models calibrated with centrifuge data (see Bienen et al., 2007 among many others).

The paper aims at illustrating some of these advances and breakthrough via five typical examples presented in Table 1 and developed in details in the following sections.

2 SPUDCAN INSTALLATION AND EXTRACTION

In the offshore oil and gas industry most drilling operations in water depths up to around 120 m are performed from self-elevating mobile jack-up units. These offshore platforms typically have a buoyant triangular hull, three independent truss-work legs, and foundations, commonly known as 'spudcans', that approximate large inverted cones. Roughly circular in plan, spudcans typically have a shallow conical underside, some with a sharp protruding spigot and can be in excess of 20 m in diameter, with shapes varying with manufacturer and rig.

Jack-up rigs are self-installing. They are towed to site with their legs elevated out of the water. On location, their legs are lowered to rest on the seabed. Once the jack-up has been positioned the spudcans are jacked until adequate bearing capacity exists for the hull to be lifted clear of the water. The spudcan foundations are then preloaded by pumping sea-water into ballast tanks in the hull. This 'proof tests' the foundations by exposing them to a larger vertical load than would be expected during service (usually by a factor of 1.3 to 2). The ballast tanks are emptied before drilling operations begin.

During the preloading process, challenges faced by the geotechnical engineer include accurate prediction of the penetration depth and ensuring the stability of the jack-up during penetration. Instabilities can notably occur due a rapid leg penetration during a 'punch-through' failure. In the latter the spudcan temporarily loses vertical capacity as it punches through a layer of stronger soil into underlaying softer conditions.

After the jack-up has been installed, it typically operates at the site for as little as days or as long as a number of years. When the jack-up is to be finally moved from the site the spudcan footings must be removed from the ground. Deep penetrations can make this operation difficult, with the time to pull the spudcans clear being reported to exceed one month in extreme circumstances. There is an industry need for better understanding of the extraction mechanisms and the development of a more efficient extraction procedure.

The following three examples present insights and outcomes provided by centrifuge modelling of spudcan installation and extraction on soft clay. On a modern jack-up the maximum vertical leg load during installation can exceed 140 MN and produce average vertical bearing pressures on the spudcan in excess of 400 kPa. In soft soils, this fully embeds the spudcan and can even cause penetration of over 30 m resulting in large deformation and significant soil flow. During extraction, undrained behaviour is expected resulting in suction developed at the spudcan invert increasing significantly the extraction resistance.

2.1 Example 1: Prediction of back-flow and bearing capacity in homogenous clay

In model tests in clay at 1g, the ratio of shear strength, s_u , to the effective overburden stress, σ'_{v0} is higher than for an offshore spudcan. However, producing correct stresses due to soil self-weight in experimental testing is particularly important for the continuous penetration of spudcans, where the soil flow mechanisms evolve with penetration depth and are affected by the strength ratio, s_u/σ'_{v0} . This is because the ratio directly controls the triggering of soil to flow around the footing from underneath to above (defined as backflow). This ratio can be correctly simulated in model tests in the centrifuge.

Spudcan penetration mechanisms were initially investigated in the centrifuge by installing dry spaghetti markers vertically across the centreline of the foundation in the undisturbed clay bed (Craig & Chua, 1990, 1991), or by inserting lead threads through a soil sample prior to testing (Murff, 1996). After completion of the test, the soil sample was dissected along the centreline, permitting the final deformation pattern to be observed. This only allowed the final mechanism to be considered and did not provide information on the ongoing mechanism changes, including when soil backflow occurred. Predictions of this were attempted by Springman & Schofield (1998). In the centrifuge, they used a mini video camera fixed to the model jack-up platform leg to capture the clay infill into the lattice leg. Although this provided good images of the surface soil deformation, mechanisms occurring within the soil could not be revealed.

By utilising new visualisation techniques for capturing soil flow mechanisms in the centrifuge, Hossain et al. (2005) provided a breakthrough in understanding the deep penetration mechanisms of a spudcan into soft clay. The system, which combines digital still photography, PIV and close range photogrammetry (GeoPIV, White et al., 2003), allows accurate resolution of the flow pattern around a 'half-object' penetrated adjacent to a transparent window (necessary due to the opacity of natural soils). The soil was confined within a purpose designed strongbox with a plexiglass window to allow observation of the soil deformations, with the box mounted within the drum centrifuge channel. Halfspudcan penetration tests were conducted at elevated gravity (50~200g) tight against the window of the strongbox. Images were captured continuously by a high resolution digital still camera sitting at right angles on a cradle within the channel. The experimental arrangement is shown in Figure 1.



Figure 1. Set-up within the drum centrifuge channel for a half-spudcan test (after Hossain and Randolph, 2010)

In single layer clay, the soil flow patterns observed from centrifuge model tests and continuous penetration finite element analyses revealed three distinct mechanisms of soil flow around the advancing spudcan, as presented in Figure 2 (Hossain et al., 2005, 2006). At a certain stage of penetration, soil backflow is initiated and, in contrast to the recommendation in the current offshore design guidelines (SNAME, 2008), Figure 2 shows that this occurs not because of instability of the open cavity, but because of a preferential flow mechanism of soil from below the spudcan to above it. A new design chart was proposed (see Figure 3) along with a robust formula to estimate the limiting cavity depth, H, above the penetrating spudcan as:

$$\frac{\mathrm{H}}{\mathrm{D}} = \left(\frac{\mathrm{s}_{\mathrm{uH}}}{\gamma'\mathrm{D}}\right)^{0.55} - \frac{1}{4} \left(\frac{\mathrm{s}_{\mathrm{uH}}}{\gamma'\mathrm{D}}\right) \tag{1}$$

where D is the spudcan diameter, γ' is the submerged unit weight of the clay and s_{uH} is the undrained shear strength at the backflow depth, H. Equation 1 has already replaced expressions that were based on hole collapse in offshore design guidelines (such as in the draft ISO, 2009).

It is significant as it modifies the bearing capacity calculation of a penetrating spudcan. Any soil backflow into the cavity created by spudcan penetration affects the bearing response in two ways: (a) by (partially) negating the surcharge contribution, γ' d, and (b) by increasing the shear resistance (and hence N_c) as the failure mechanism now must pass through the backfilled soil. Since backflow provides a seal over the top of the spudcan, the above relationship also provides guidance on conditions where transient suctions may be sustainable beneath the spudcan, with a consequential increase in uplift resistance and moment capacity at low vertical loads. These were also shown to exist in centrifuge experiments of deeply embedded spudcans by Cassidy et al. (2004a), amongst others.



Figure 2.Soil flow mechanisms of spudcan penetration in single layer clay. (a) heave mechanism, (b) onset of backflow mechanism, and (c) deep flow mechanism (after Hossain et al., 2006)



Figure 3.New design chart for estimating cavity depth after spudcan installation in clay (after Hossain et al., 2006)

2.2 Example 2: Installation in strong-over-soft clays

Jack-up installation and preloading in stratified deposits, where a strong layer overlays weaker soil, has always been a challenge to offshore engineers due to the potential for catastrophic 'punch-through' failure. Centrifuge testing has helped understand the problem, as the higher stress due to enhanced soil self-weight at elevated gravity has allowed researchers to more easily reconstitute stratified soil deposits. In 1g tests on the laboratory floor, it is arduous to achieve proper bonding (similar to field sediments) at the interface between two layers. However, this can be established more easily by simply testing under elevated gravity (Hossain & Randolph, 2010a), or by allowing for significant consolidation prior to testing (Teh et al., 2008; 2010; Lee, 2009). Homogeneous sand layers can be laid through sand raining techniques, including those developed for spraying sand in-flight (see Lee, 2009, for an example technique in a drum centrifuge). The development of such capabilities has focused research onto understanding spudcan punch-through mechanisms (Hossain & Randolph, 2010a; Teh et al., 2008; 2010; Lee, 2009).

In stiff-over-soft clays, the failure mechanisms reported by Kim (1978) from 1g model tests on a surface circular footing are inconsistent compared to the recent centrifuge visualisation on penetrating spudcan. Once again, half-spudcan penetration tests (at 100~200g) permitted the soil flow mechanisms to be captured with a digital camera (Hossain & Randolph, 2010a). The experimental evidence provided failure patterns at different spudcan penetration depths. The quantified soil flow vectors showed that punch-through was associated with the formation of distinct shear planes in the top layer (see Figure 4), and consequently a soil plug with the shape of an inverted truncated cone was forced down into the underlying soft layer.



Figure 4. Spudcan punch-through on stiff-over-soft clay (from PIV analysis: axes in mm and in model scale) (after Hossain & Randolph, 2010a)

For a spudcan penetrating sand-over-clay the situation is even more complex. Spudcan behaviour in the sand layer is governed by confining stress, q_{clay}/q_{sand} ratio and relative thickness of the sand layer (t/D; where t is the thickness of the strong layer) and they are a function of stress level and operative friction and dilation angles. These vary with stress level and footing diameter, even on sand layers with similar relative density (Lee et al., 2009). Revealing this has taken centrifuge developments over a couple of decades. Initially, Craig & Chua (1990; 1991) depicted post-test snapshots of sand-over-clay punch-through behaviour through use of spaghetti in the sample. Following this Okamura et al. (1997) reported mechanisms for surface flat footings by employing a radiography technique. More recently and again employing the image-based analysis technique of half-spudcan penetration tests against a transparent window, the detailed progressive failure mechanisms at a sand-over-clay site were illustrated by Teh et al. (2008). The mechanism at the time of punch-through is shown in Figure 5. The key finding is the dilatancy characteristics play a key role in the form of the projected area beneath the advancing spudcan. They are suppressed with the increase of t/D and the strength s_u of the lower clay layer.

In order to develop a calculation method, the image results discussed above require augmentation with full load displacement profiles and numerical finite-element analysis. In both stiff-over-soft clay and sand-over-clay sites, the load-penetration response was also measured experimentally through full-

spudcan penetration tests. In stiff-over-soft clay, centrifuge test data were also used to validate large deformation finite element (LDFE) analyses, before undertaking parametric analyses (Hossain & Randolph, 2010b). The combination of half-spudcan visual evidence, full spudcan load-displacement profiles and LDFE results provided the basis for the development of a more rational mechanism-based design approach reported by Hossain & Randolph (2009). In sand-over-clay, Lee et al. (2009) and Teh et al. (2009) have reported new analytical design approaches accounting for the failure patterns, the stress level and dilatant response of the sand. All these approaches have seen evaluation against field case studies in the recently completed InSafeJIP (Osborne et al., 2008; 2009; InSafeJIP, 2009; 2010).



Figure 5. Observed mechanism of spudcan punch-through in sand-over-clay soils (from PIV analysis: axes in mm and in model scale) (after Teh et al., 2008)

2.3 Example 3: Extraction with water jetting

Spudcan extraction often proves difficult and time-consuming in the field, especially in soft soils where deep penetrations are experienced. As no guidelines are currently available for spudcan extraction, various strategies to free the leg are usually employed through a trial and error process (InSafeJIP, 2009). Therefore, the key contributing factors to a successful extraction have remained uncertain to the jack-up industry. Aspects that increase the level of complexity in understanding spudcan extraction in the field include highly stratified soil conditions, difficulties in quantifying the changes in soil strength due to disturbance and reconsolidation, sometimes unquantifiable wave excitations, as well as difficulties in measuring the loading exerted during the extraction process on the jack-up. In order to develop sound predictive methods for the expected resistance and to devise successful extraction procedures, the governing soil failure mechanisms must first be established.

As detailed in the following example, centrifuge modelling has recently provided evidence of these extraction mechanisms and analytical models have been developed based on these results.

As was shown in examples 1 and 2, soil failure mechanisms can be visualised by testing half models against a transparent window in combination with PIV and photogrammetry. Purwana et al. (2006; 2008; 2009) employed this technique to gain insight into soil failure mechanisms during spudcan extraction, an example of which is shown in Figure 6.

In the left half of the figure the photo taken during the extraction test is presented, showing the spudcan and the clay to which coloured flock was added to allow for better visualisation of the soil movement. The right half of the figure depicts the corresponding vectors of soil displacement as obtained from PIV analysis. The results have proven valuable in determining the soil displacement pattern and understanding the mobilisation of soil resistance during spudcan extraction. Importantly, the effect on extraction of soil remoulding and consolidation during installation, preloading and holding of self-weight during operation could all be modelled in a timely manner in the centrifuge.

The centrifuge data can also be used as a basis for the development of predictive methods. Such a model for spudcan extraction resistance was proposed by Purwana et al. (2009). It was developed based on centrifuge extraction data from spudcan embedments of up to 1.5 diameters, and utilised experimental recordings of resistance at both the spudcan top and base, as well as pore pressures. A similar formulation for calculating extraction resistance was adopted in the InSafeJIP (2010) guidelines, also calibrated against centrifuge data.



Figure 6. Visualisation of soil failure mechanism during spudcan extraction (after Purwana et al., 2008)

When insufficient uplift load is available through jack-up hull buoyancy, water jetting may ease spudcan extraction. Jetting with nozzles located at the spudcan top face aims at reducing resistance to extraction through fracturing and remoulding the soil. Jetting with nozzles at the spudcan invert (i.e. the base of the spudcan), on the other hand, aims at decreasing the negative pore pressures mobilised by the uplifting spudcan. This can extend to creating positive excess pore pressures at the spudcan invert, applying additional active uplift force.

Insight into this has been provided by a series of centrifuge tests, investigating various parameters including the extraction rate, the jetting flow rate and the jetting pressure (Bienen et al., 2009; Gaudin et al., 2011). A model spudcan with the ability to jet water at different flow rates during a centrifuge test was used, as shown in Figure 7. The model represents a 17.11 m diameter spudcan currently being used offshore. The spudcan invert featured three concentric circles of twelve jetting nozzles each. Only one nozzle ring was used at a time, the other two were blocked. The prototype spudcan jetting nozzles are 38 mm in diameter. As direct scaling of the nozzle diameter for testing at 200g was technically not feasible, the model jetting nozzles were 2 mm in diameter initially. This was reduced to 0.5 mm after the first testing series. Dimensional analysis, as developed in Gaudin et al. (2011), was used to determine the prototype flow rate according to the model pump flow rate, accounting notably for the nozzle diameter. A semi-circular outlet guard above each nozzle redirected the jetting flow along the bottom face of the spudcan, which is consistent with offshore practice.

Results demonstrated that the jetting efficiency relates to the ratio of the jetting volume flow to the volume of the void theoretically created at the invert due to uplift of the spudcan (defined as the filling ratio). The experimental data suggest optimum jetting performance not to coincide with vented extraction (i.e. a filling ratio of 1), but to a mechanism where localised flow-around the spudcan edge still occurs in addition to the uplift mechanism of the soil above the spudcan (Bienen et al. 2009; Gaudin et al. 2011). Jetting flow appears to be a dominant factor over jetting pressure, in contrast to general belief.

From the understanding of mechanism gained from the centrifuge tests, a conceptual framework for spudcan extraction with water jetting was established based on (i) the pullout force resulting from the buoyancy of the jack-up hull, and (ii) the filling ratio f. A relationship between the ratio of applied extraction force (Q_{direct}) to the expected extraction resistance without jetting (Q_{ult}) and the filling ratio f was developed (Bienen et al. 2009; Gaudin et al. 2011), which is shown in Figure 8 (centrifuge test

results are represented by the open circles). The filling ratio can be related to the required parameter in the field, the jetting flow rate.







Figure 8. Conceptual chart of jetting extraction efficiency. The chart indicates, for a given extraction load, the required flow rate for a successful jetted extraction (after Gaudin et al., 2011)

3 PIPE-SOIL INTERACTION

Offshore pipelines are laid on the seabed and used as flow lines or trunk lines tied back to shore. They are becoming more and more common as the oil and gas extraction is taking place in deeper and more remote areas. Geotechnical design procedures for offshore pipeline and risers have not yet reached the maturity exhibited by design procedures for piles, foundations and anchoring systems. Reasons are multiple and relate mainly to the unknown geometry of the problem (the final embedment of the pipe is uncertain), the uncertainties of the soil conditions (both difficult to assess at very shallow depth and

significantly affected by the installation process) and the very large deformations (and associated postfailure behaviour) the pipeline may experience (notably during lateral buckling).

The following two examples aims to illustrate some of the insight and breakthrough, obtained from both centrifuge testing performed to gain insight into specific aspects of pipeline interaction, and from centrifuge modelling performed to assist in the design of specific pipeline projects. It is not a state-of-the-art report of pipeline behaviour and design. Such reports have been presented by Cathie et al. (2005) and White & Cathie (2010).

3.1 Example 4: Pipe dynamic laying

The knowledge of the pipe embedment is pivotal for subsequent on-bottom stability and lateral buckling design. The effect of dynamic laying on pipe embedment has been first observed by Lund (2000) who concluded on the necessity to account for pipeline laying history in subsequent on-bottom stability design, as it results in excessive embedment compared to a static laying process.

During the lay process, an element of pipe moves through the touchdown zone, from an initial contact with the seabed to a stationary position, where the pipe weight is supported by an equal up-wards seabed reaction force. The dynamic behaviour of the pipe through this process is complex and difficult to replicate. It is a function of the following parameters:

- The profile of stress concentration in the touch-down zone due to the catenary shape, resulting in a vertical load on the soil varying along the pipe and higher, at some specific location, than the as-laid pipeline weight. It can be estimated, based on a structural analysis of the hanging pipeline using the planned lay tension and hang-off angle.
- The horizontal and vertical oscillation due to the motion of the laying vessel, resulting in a sweeping and damping of the soil at the touchdown zone. It can be estimated from the analysis of the motion of the vessel under for the wave motion considered.
- The number of oscillations during the entire lay process. It can be assessed, based on the estimated pipeline laying rate, the touchdown zone length and the wave-induced oscillation frequency.

Figure 9 presents a typical pipeline setup used to model dynamic laying and lateral buckling. The pipe is modelled as a short section (with an aspect ratio of at least 6 to prevent any end effect) and may be sandblasted to achieve a particular roughness. It is connected to a VHM loading arm, use to measure the horizontal loads, via shear load cell, insensitive to bending moment. The purpose of this load cell is to provide a very accurate reading of the vertical load applied (permitting a resolution of 1 N model) which is essential for pipelines, which have a self-weight orders of magnitude lower than typical geotechnical structures. Additional instrumentation may include pore pressure transducers at the pipe invert, as shown in Figure 9.

A purposely developed motion control system (De Catania et al., 2010) is used to (i) apply a targeted vertical load depending on the stress concentration, via a feedback loop on the axial load cell and (ii) apply lateral oscillation of varying amplitude, linked via a second feedback loop to the pipe embedment. The following example presents centrifuge modelling performed recently to determine the final embedment of a flowline pipeline offshore Australia (Gaudin & White, 2009). In-situ soil was used and the dynamic motion applied replicated faithfully the one determined from the wave and vessel motion analysis.

The pipeline was divided into six sections, from the initial contact point to a far away position when the pipe was considered to be unaffected by the laying motion. The sic sections featured six different loading sequence. 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 10. 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 0.7Vlay before being lifted up until separation between the soil and the pipe occurred.

The resulting accumulation of pipe embedment is presented in Figure 11 for each sequence as a function of the number of imposed cycles. The key observation from Figure 10 and Figure 11 is the much larger pipe embedment (about 0.24 m) compared to a static embedment (about 44 mm using formulation presented by Randolph & White, 2008a), even accounting for the stress concentration.



Figure 9. Typical pipeline model setup



Figure 10. Dynamic lay simulation. Cyclic vertical loading and the associated pipe invert trajectory (after Gaudin & White, 2009)

Other important observations 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.

The results do stress the necessity to model accurately dynamic laying motion, in order to determine the pipe embedment, but also the remoulding of the soil resulting from the laying process, which are going to govern both on-bottom stability and lateral buckling. They demonstrate the capability of centrifuge modelling in replicating accurate laying motions and capturing particular soil behaviour features.



Figure 11. Accumulation of pipe embedment resulting from the dynamic lay simulation of Figure 32 (after Gaudin & White, 2009)

3.2 Example 5: Thermal buckling

3.2.1 Description of pipeline lateral buckling

To reduce the structural load resulting from thermal expansion, pipelines are permitted to buckle at targeted location, resulting in lateral displacements in order of 10-20 times the pipeline diameter (Bruton et al., 2006). In operation, as the pipeline experiences fluctuations in pressure and temperature, the pipe cycles back and forth across the same patch of seabed. Surface soil, swept ahead of the pipe on each cycle, then builds up into berms at the extremes of pipe displacement, as illustrated in Figure 12. Subsequent consolidation may increase the strength of the soil berms after disturbance. Pipe feeds axially into and out of the buckle with each cycle. On unloading, the pipeline attempts to return to the as-laid position but is prevented from doing so by both axial and lateral pipe-soil resistance generated by the berms.

Whilst lateral buckling reduces the axial load on the pipeline, it also generates bending moment in the buckling zone, which can ultimately lead to local bending failure. Design methods for buckling typically involve the definition of 'equivalent friction factors', which characterize the soil resistance to the lateral pipeline motion in the terminology of Coulomb friction. This simple approach is efficient to implement within the structural models of pipelines that are used to assess the in-service stresses and accumulating fatigue. However, it is important to note that the seabed is not a frictional surface and the soil resistance will not be proportional to the vertical pipe-soil load. Therefore, it is necessary to perform some form of geotechnical analysis – supported, if needed, by model testing – to estimate the limiting lateral and axial pipe-soil resistance. These values are then converted into 'equivalent' friction coefficients – which may vary with displacement or with cycle number – for implementation into the pipeline structural analysis.



Figure 12. Typical cross profile at crown of lateral buckle on an operated pipeline (After Bruton et al., 2007)

Unlike on-bottom stability design, overestimating the friction factor is not conservative as both high and low equivalent friction factors may be more onerous in design. The determination of an accurate range of design friction factors is therefore pivotal for a safe and sound design. This requires the understanding of the soil behaviour at large displacements and through many cycles of loading, well beyond the point of failure, all features that can be particularly well investigated by centrifuge methods.

3.2.2 Large amplitude lateral pipe-soil interaction

The general form of the pipe-soil interaction behaviour during lateral buckling in fine-grained soils has been investigated at UWA, through a series of project-specific industry studies and research projects using a test setup identical to the one presented in Figure 9. The modelling techniques developed have been presented in details in White & Gaudin (2008) and Gaudin & White (2009).

A typical lateral buckling pipe response on kaolin clay is presented in Figure 13, in terms of pipe trajectory and evolution of equivalent friction factor with lateral movement. The response is divided into an initial breakout, where the pipe moves away from the as-laid position, and a cyclic response as the pipe is swept back and forth under constant vertical load. The response presents key features that were subsequently incorporated into a schematic model used to describe pipe-soil interaction during lateral buckling (Cheuk et al., 2008).

- *Breakout response*: The response is characterized by a brittle peak (whose amplitude varies with initial embedment) followed by either a steady residual resistance for light pipes, or an increasing residual resistance for heavy pipes. The reason for this is the downward trajectory exhibited by heavy pipes, which results in the growth of the soil berm ahead of the pipe, leading to an increasing lateral resistance. For both pipes, the breakout peak partly from the loss of suction, and therefore tensile resistance, at the rear of the pipe, and also from the reducing embedment of the pipe as it rises towards the ground surface. This was directly observed in centrifuge tests reported by Dingle et al. (2008) and correlated to the pipe load displacement response.
- *Cyclic response*: The lateral response during the first sweep is characterized by a berm resistance and a cyclic residual resistance. For light pipes, as the pipe is swept across, it pushes forward a small berm of soil that has been scraped from the seabed mobilizing steady lateral resistance. Surface soil, swept ahead of the pipe on each cycle, builds into berm at the extremes of the pipe displacement, which are increasing in size after each cycle, providing increasing berm resistance. The response is slightly different for heavy pipes, where the pipe experiences increasing embedment and corresponding increase of the static berms.



Figure 13. A typical pipe-soil response normalized by the pipe diameter D during cyclic lateral movement under a constant vertical load (pipe weight) (Cheuk et al., 2008)

3.2.3 Development of design guidance and empirical correlations

The observations shown in Figure 13 formed the basis of a pipe-soil interaction model described in Figure 14 in terms of equivalent friction factors defined at key locations along the sweep and varying with the number of cycles, in order to account for the contribution of the soil berms. This soil-structure interaction is difficult to capture in design without a pipe-soil interaction model that simulates the trajectory of the pipe, as well as the varying equivalent friction. Current theoretical solutions are insufficient to parametise fully the form of model shown in Figure 14. The initial breakout resistance might be assessed theoretically from published failure envelopes (Randolph & White 2008b) but the residual resistance is more challenging. It is controlled by the size of the soil berm ahead of the pipe, the strength of the soil within it, and the trajectory of the pipe. Models for the cyclic large-amplitude lateral need to account for the accumulation and deposition of berm material (White & Cheuk, 2008), but also for re-consolidation of the soil that has been remoulded and transported ahead of the pipe.

The cyclic resistance is not only affected by the changing geometry. Depending on the soil type, pore pressure dissipation may occur during lateral sweeping, and is also likely to occur between start-up and shutdown events. This leads to reconsolidation of the disturbed soil within the berm, and also swelling of the unloaded seabed that is exposed by the scraping action of the pipe.



Figure 14. Idealized form of lateral pipe-soil interaction during buckling

Given these complications, current design guidance uses correlations derived from physical model tests and it also recommends that project-specific physical model tests be performed if tighter bounding of the behaviour is required. One such correlation developed to assess the lateral breakout resistance of pipelines laid on fine-grained soils has been developed within the SAFEBUCK JIP, who collated results from 28 large-scale tests and 39 small-scale centrifuge tests. Using these results for the breakout resistance of shallowly-embedded pipelines, a correlation was developed to link the normalized breakout resistance, H_{brk}/s_uD , to the key geotechnical properties (intact undrained shear strength, s_u , unit weight, γ' , and the vertical pipe-soil load, V), as well as the normalized pipe embedment, w/D. From dimensional analysis:

$$\frac{H_{brk}}{s_{u}D} = f\left(\frac{W}{D}, \frac{\gamma'D}{s_{u}}, \frac{V}{s_{u}D}\right)$$
(2)

A simple correlation was devised between these parameters, using theoretical solutions for guidance (e.g. Randolph & White 2008b). The correlation was calibrated to achieve the best agreement between the calculated and measured breakout resistance across all 67 measurements of breakout

resistance in the database. During the calibration process, skew was eliminated with respect to each of the dimensionless groups in the above expression.

The details of the calibrated expression are confidential to participants. Essentially, the three dimensionless terms above were combined as additive components, with each contributing non-linearly to H_{brk}/s_uD according to a power law. The calibration process ensured that the mean ratio between the calculated and measured resistance was 1.0. The standard deviation of the ratio calculated/measured is 0.25.

The performance of the empirical correlation was assessed by White & Cheuk (2010) on a database consisting of 8 different studies. Despite some scatter, the correlation provided on average a correct assessment of the breakout resistance. It is important to note the guidance is skewed to the average conditions explored in the model test database. For example, the correlation is influenced by the particular pipe-soil bonding condition observed in these tests, as well as the particular distribution of soil strength that exists after the pipe has been penetrated into the seabed, and been left to consolidate in place. Given these considerations, the correlations should be used with caution within the range of conditions over which is has been calibrated. These conditions include:

- The range of pipe weight, V/s_uD, soil strength/weight ratio, $\gamma'D/s_u$, and embedment, w/D spanned by the database.
- The secondary soil properties (not considered in the correlation) that control the operative soil strength during breakout (which is likely to differ from the intact s_u). These secondary properties include the sensitivity (and hence the softening during pipe 'laying') and the consolidation parameters.
- The pipeline properties adopted in the model test database including the pipe roughness (which is not considered in the correlation).
- The breakout processes simulated in the model test database including the rate of breakout (which is not considered in the correlation).

This list of limitations highlights the value in supporting model test observations by theoretical analyses that can set the results within a robust framework. Such a framework allows more confident extrapolation. However, soil behaviour, and lateral pipe-soil interaction, is controlled by further properties in addition to those given in the above Equation, such as sensitivity, the consolidation characteristics and so forth. As a result, correlations and analyses based on idealized theory can often be significantly refined through well-planned physical modelling studies using a geotechnical centrifuge. The 8 project-specific studies performed at UWA in recent years to support pipeline developments worldwide are testament to this.

4 CONCLUSIONS

Centrifuge modelling techniques have played an important role in developing new design and assessment methods for jack-up spudcan foundations and pipeline-soil interaction, many of which have been incorporated into industry guidelines and practices. This paper provides anoverview of recent contributions covering jack-up installation and extraction, and pipe dynamic laying and thermal buckling.

With the development of centrifuge technology, further opportunities will be created for solving the emerging issues faced by the offshore industry as they move into deeper water and more challenging seabed conditions. Some of the opportunities for the near future include amongst others: direct prediction of jack-up installations using penetrometer data, installation through footprints and sloped seabeds, spudcan behaviour in multi-layered and intermediate silty soils, pipeline behaviour through varying drainage conditions or steel catenary riser soil interaction.

The geotechnical centrifuge will continue to provide pivotal insights into spudcan and pipeline behaviour, as well as other offshore geotechnical issues. While the author advocates the use of centrifuge methods as a valuable and necessary tool to assist the offshore industry in developing and designing solutions for a wide range of geotechnical problems, it is also acknowledged that centrifuge modelling should not been considered as the unique tool to be used, but as a particular one which outcomes may be maximised if integrated into a global approach. It is believed that while technological and scientific developments will, without doubt, increase the utility of centrifuge methods, the most spectacular improvement will be in the understanding of the centrifuge methods contribution and their integration at key stages into a global design procedure, which will incorporate in-situ, numerical and analytical methods.

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REFERENCES

- Bienen B., Gaudin C., Cassidy M.J. (2007). Centrifuge tests of shallow footing behaviour on sand under combined vertical-torsional loading. *International Journal of Physical Modelling in Geotechnics*, 7(2), 1-21.
- Bienen B., Gaudin C., Cassidy M.J. (2009). The influence of pull-out load on the efficiency of jetting during spudcan extraction. *Applied Ocean Research*, 31(3), 202-211.
- Bruton D.A.S., White D.J., Cheuk C.Y., Bolton M.D., Carr M.C. (2006). Pipe-soil interaction behaviour during lateral buckling, including large amplitude cyclic displacement tests by the Safebuck JIP. *Proc. Offshore Technology Conference, Houston.* OTC17944.
- Cathie D.N., Jaeck C., Ballard, J-C., Wintgens J-F. (2005). Pipeline geotechnics State-of-the-art. Proc. Intern. Symp. on Frontiers in Offshore Geotechnics, Perth, Australia, 95-114.
- Cassidy M.J., Byrne B.W., Randolph M.F. (2004). A comparison of the combined load behaviour of spudcan and caisson foundations on soft normally consolidated clay. *Géotechnique*, 54(2), 91–106.
- Cheuk C.Y., White D.J., Bolton M.D. (2007). Large scale modelling of soil-pipe interaction during large amplitude movements of partially-embedded pipelines. *Canadian Geotechnical Journal*, 44(8):977-996.
- Cheuk C.Y., White D.J., Bolton M.D. (2008). Reply to Discussion by W.O. McCarron on "Large scale modelling of soil-pipe interaction during large amplitude movements of partially-embedded pipelines". *Canadian Geotechnical Journal*, 45(5):744-749. (Original paper 44(8):977-996.
- Craig W.H., Al-Saoudi N.K.S. (1981). The behaviour of some model offshore structures. Proc. 10th Intern. Conf. on Soil Mechanics and Foundation Engineeting, Stockholm, Sweden, (2), 541-556.
- Craig W.H. (1984). Preface. Proc. Intern. Symp. Application of Centrifuge Modellingto geotechnical Design, Manchester, UK, 1.
- Craig W.H., Chua K. (1990). Deep penetration of spudcan foundations on sand and clay. *Géotechnique*, 40(4), 541-556.
- Craig W.H., Chua K. (1991). Large displacement performance of jack-up spudcans. *Proc. Int. Conf. on Centrifuge* '91, *Rotterdam*: Balkema, 139-144.
- Dean E.T.R., James R.G., Schofield A.N., Tan F.S.C., Tsukamoto Y. (1993). The bearing capacity of conical footings on sand in relation to the behavior of spudcan footings of jack-ups. *Proc. Wroth Memorial Symp. Predictive Soil Mechanics, Oxford*, 230-253.
- De Catania S., Breen J., Gaudin C., White D.J. (2010). Development of a multiple axis actuator control system. *Proc.* 7th Intern. Conf. on Phy. Model. in Geotechnics, Zurich, Switzerland, 325-330.
- Dendani D., Jaeck C. (2007). Pipe-Soil Interaction in Highly Plastic Clays, Proc. 6th Intern. Offshore Site Investigation and Geotechnics Conf., London, 115-124.
- Dingle H.R.C., White D.J., Gaudin C. (2008). Mechanisms of pipe embedment and lateral breakout on soft clay *Canadian Geotechnical Journal*, 45(5):636-652.

- Finnie I.M.S., Randolph M.F. (1994). Bearing response of shallow foundations in uncemented calcareous soil. *Proc. Int. Conf. on Centrifuge '94, Rotterdam, Netherlands.*
- Gaudin C., White D.J. (2009). New centrifuge modelling techniques for investigating seabed pipeline behaviour. *Proc. of 17th Intern. Conf. of Soil Mech. and Geotech. Eng., Alexandria, Egypt,* 1, 448-451.
- Gaudin C., Cluckey, E.C., Garnier, J., Phillips, R. (2010). New frontiers for centrifuge modelling in offshore geotechnics. *Proc.* 2nd Intern. Symp. on Frontiers in Offshore Geotechnics, Perth, Australia, 155-188.
- Gaudin C., Bienen B., Cassidy M.J. (2011). Investigation of the potential of bottom water jetting to ease spudcan extraction in soft clay. *Géotechnique*, 61(12), 1043-1054.
- Gaudin C., Kong V., Cassidy M.J (2012). An overview of spudcan reinstallation near footprint. Offshore Technology Conference, Houston, USA.
- Hill A.J., Jacob H. (2008). In-situ measurements of pipe-soil interaction in deep water. *Proc. Offshore Technology Conf., Houston, OTC* 19528.
- Hossain M.S., Hu Y., Randolph M.F., White D.J. (2005). Limiting cavity depth for spudcan foundations penetrating clay. *Géotechnique*, 55(9), 679-690.
- Hossain M.S., Randolph M.F., Hu Y., White D.J. (2006). Cavity stability and bearing capacity of spudcan foundations on clay. *Proc. Offshore Technology Conf., Houston*, OTC 17770.
- Hossain M.S., Randolph M.F. (2009). New mechanism-based design approach for spudcan foundations on stiffover-soft clay. *Proc. Offshore Technology Conf., Houston*, OTC 19907.
- Hossain M.S., Randolph M.F. (2010a). Deep-penetrating spudcan foundations on layered clays: centrifuge tests. *Géotechnique*, 60(3), 157-170.
- Hossain M.S., Randolph M.F. (2010b). Deep-penetrating spudcan foundations on layered clays: numerical analysis. *Géotechnique* 60(3), 171-184.
- InSafeJIP (2009). Improved guidelines for the prediction of geotechnical performance of spudcan foundations during installation and removal of jack-up units. First year report. Authors: Osborne, J.J., Teh, K.L., Houlsby, G.T., Cassidy, M.J., Bienen, B., Leung, C.F.
- InSafeJIP (2010). Improved guidelines for the prediction of geotechnical performance of spudcan foundations during installation and removal of jack-up units. Proposed Industry Guidelines. Authors: Osborne, J.J., Teh, K.L., Houlsby, G.T., Cassidy, M.J., Bienen, B., Leung, C.F.
- ISO (2009). Petroleum and natural gas industries Site-specific assessment of mobile offshore units Part 1: Jack-ups. International Organization for Standardization, ISO 19905-1.
- Jacob H., Looijen P. (2008). Development of a deepwater tool for in-situ pipe-soil interaction measurement and its benefit in pipeline analysis. *Offshore Pipeline Technology Conference and Exhibition, Amsterdam, Netherlands.*
- Kim S.W. (1978). *Bearing capacity of footings on two-layered clays under inclined loads*. MEng Thesis, Nova Scotia Technical College.
- Lee K.K. (2009). *Investigation of potential punch-through failure on sands overlaying clay soils*. PhD Thesis, The 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. Offshore Technology Conference, Houston*, OTC-20012.
- Leung C.F., Xie Y., Chow Y.K. (2006). Centrifuge model study of spudcan-pile interaction. Proc. 16th Int. Offshore and Polar Engineering Conf. (ISOPE), San Francesco, 530-535.
- Leung C.F., Xie Y., Chow Y.K. (2008). Use of PIV to investigate spudcan-pile interaction. Proc. 18th Int. Offshore and Polar Engineering Conf. (ISOPE), Vancouver, 721-726.
- Lund K.M. (2000). Effect of increase in pipeline soil penetration from installation. Proc. Intern. Conf. Ocean Offshore Artic Eng. New Orleans, USA, OMAE2000/PIPE-5047
- Murff J.D. (1996). The geotechnical centrifuge in offshore engineering. Proc. Offshore Technology Conf., Houston, OTC 8265.
- Noble Denton & Associates (1987). Foundation fixity of jack-up units: a joint industry study. Noble & Denton Associates.
- Osborne J.J., Teh K.L., Leung C.F., Cassidy M.J., Houlsby G.T., Chan N., Devoy D., Handidjaja P., Wong P., Foo K.S. (2008). An introduction to the InSafe JIP. *Proc.* 2nd Jack-up Asia Conference. Singapore.
- Osborne J.J., Houlsby G.T., Teh K.L., Bienen B., Cassidy M.J., Randolph M.F., Leung C.F. (2009). Improved guidelines for the prediction of geotechnical performance of spudcan foundations during installation and removal of jack-up units. *Proc. Offshore Technology Conference, Houston, OTC* 20291.
- Okamura M., Takemura J., Kimura T. (1997). Centrifuge model test on bearing capacity and deformation of sand layer overlying clay. *Soils and Foundations* 37(1), 73-88.

- Purwana O.A., Leung C.F., Chow Y.K., Foo K.S. (2006). Breakout failure mechanism of jackup spudcan extraction. Proc. 6th Intern. Conf. of Physical Modelling in Geotechnics (ICPMG06), Hong-Kong, 1, 667-672.
- Purwana O.A., Quah M., Foo K.S., Leung C.F., Chow Y.K. (2008). Understanding spudcan extraction problem and mitigation devices. *Proc.* 2nd Jack-Up Asia Conference & Exhibition, Singapore.
- Purwana O.A., Quah M., Foo K.S., Nowak S., Handidjaja P. (2009). Leg Extraction / Pullout Resistance -Theoretical and Practical Perspectives. Proc. 12th International Conference The Jack-Up Platform Design, Construction & Operation, London.
- Randolph M.F. (2004). Characterisation of soft sediments for offshore applications. Proc. 2nd Int. Conf. on Site Characterisation, Porto, 1, 209-231.
- Randolph M.F., White D.J. (2008a). Pipeline embedment in deep water: processes and quantitative assessment. *Proc. Offshore Technology Conference, Houston, USA*. OTC19128-PP.
- Randolph M.F., White D.J. (2008b). Upper bound yield envelopes for pipelines at shallow embedment in clay *Géotechnique*, 58(4):297-301.
- Rowe P.W., Craig W.H. (1981). Applications of models to the prediction of offshore gravity platform foundation performance. *Proc. Intern. Conf. on Offshore Site Investigation, London*, 269-281.
- Siciliano R.J., Hamilton J.M., Murff J.D., Phillips R. (1990). Effect of jackup spudcans on piles. Offshore Technology Conference, Houston, OTC 6467.
- SNAME (2008). *Recommended practice for site specific assessment of mobile jack-up units*. T&R Bulletin 5-5A, 1st Edition Rev. 3, Society of Naval Architects and Marine Engineers, New Jersey.
- Springman S.M., Schofield A.N. (1998). Monotonic lateral load transfer from a jack-up platform lattice leg to a soft clay deposit. *Proc. Int. Conf. on Centrifuge '98, Rotterdam: Balkema*, 563-568.
- Teh K.L., Cassidy M.J., Chow Y.K., Leung C.F. (2006). Effects of scale and progressive failure on spudcan ultimate bearing capacity in sand. Proc. Int. Symp. On Ultimate States of Geotechnical Structures, Marne-la-Valèe, France, 1, 481-489.
- Teh K.L., Leung C.F., Chow Y.K., Handidjaja P. (2009). Prediction of punch-through for spudcan penetration in sand overlying clay. *Proc. Offshore Technology Conference, Houston*, OTC 20060.
- Teh K.L., Leung C.F., Chow Y.K., Cassidy M.J. (2010). Centrifuge model study of spudcan penetration in sand overlying clay. *Géotechnique*.
- Wong P.C., Chao J.C., Murff J.D., Dean E.T.R., James R.G., Schofield A.N., Tsukamoto Y. (1993). Jack up rig foundation modelling II. *Offshore Technology Conference, Houston*, OTC 7303.
- White D.J., Take W.A., Bolton M.D. (2003). Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry. *Géotechnique* 53(7), 619-631.
- White D.J. & Cheuk C.Y. (2008). Modelling the soil resistance on seabed pipelines during large cycles of lateral movement. *Marine Structures* 21(1):59-79.
- White D.J., Gaudin C. (2008). Simulation of seabed pipe-soil interaction using geotechnical centrifuge modelling. *Proc. 1st Asia-Pacific Deep Offshore Technology Conference, Perth, Australia.*
- White D.J. ,Cathie D.N. (2010). Geotechnics for Subsea pipeline and risers. Proc. 2nd Int. Symp. on Frontiers in Offshore Geotechnics. Perth, Australia.
- White D.J., Hill A.J., Westgate Z. & Ballard J-C (2010). Observations of pipe-soil response from the first deepwater deployment of the SMARTPIPE. Proc. 2nd Int. Symp. on Frontiers in Offshore Geotechnics, Perth, Australia, 851-85.
- White D.J., Cheuk C.Y. (2010). SAFEBUCK JIP: Pipe-soil interaction models for lateral buckling design: Phase IIA data review. Report to Boreas Consultants (SAFEBUCK JIP), UWA report GEO 09497r2. 185pp. (currently confidential to JIP participants).
- Xie Y., Leung C.F., Chow Y.K. (2006). Effects of spudcan penetration on adjacent piles. *Proc* 6th Int. Conf. on *Physical Modeling in Geotechnics, Hong Kong*, 2, 701-706.
- Xie Y., Leung C.F., Chow Y.K. (2010). Study of soil movements around a penetrating spudcan. Proc 7th Int. Conf. on Physical Modeling in Geotechnics, Zurich, 2, 1075-1080.