Numerical Investigation of Novel Spudcan Shapes for Easing Spudcan-Footprint Interactions

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- Number of Words: 5178 (text only)

- Number of Tables: 02

- Number of Figures: 14

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ABSTRACT

This paper reports a measure for easing spudcan-footprint interactions when a jack-up rig needs to be installed near existing jack-up footprints. Two novel spudcan shapes, skirted spudcan with four rectangular holes and skirted spudcan with six circular holes and sloped bottom profile, were investigated using 3D large deformation finite element (LDFE) analyses. The LDFE analyses were performed using the Coupled Eulerian-Lagrangian (CEL) approach in the commercial finite element package ABAQUS. After displaying the validity of the analyses against existing LDFE results and centrifuge test data, the efficiencies of the novel spudcans were studied against a generic spudcan shape, including the effects of spudcan offset distance from the footprint and the footprint depth. Both soft and stiff seabed strength profiles were considered with the undrained shear strength increasing with depth. The potential of spudcan sliding towards the footprint center during installation was evaluated based on the resultant maximum horizontal force ($H_{\max}$) and moment ($M_{\max}$) acting on the different spudcans. It is found that, between the two novel spudcans, the spudcan with six holes and sloped bottom profile is more effective at reducing $H_{\max}$ and $M_{\max}$. Any reduction in the resultant horizontal force on the spudcan can generate a large reduction of the moment at the top of a long jack-up leg. The results from this study indicate that the novel spudcan with circular holes and sloped bottom profile has potential to ease spudcan-footprint interactions without any additional mechanical operations.

Keywords: Clays; Spudcan-footprint interaction, Large deformation finite element, Coupled Eulerian-Lagrangian

49 Nomenclature

50	A_{hole}	total hole area
51	A_{net}	net spudcan plan area at largest section
52	A_{total}	total spudcan plan area at largest section
53	D	spudcan diameter at largest section
54	D_F	footprint diameter
55	d	penetration depth of spudcan base (lowest point of largest section) from mudline
56	d_h	hole diameter
57	H	horizontal force at spudcan base level
58	H_{max}	maximum horizontal force at spudcan base level
59	h_{min}	minimum element size
60	k	shear strength gradient with depth
61	L_h	jack-up leg height
62	L_s	skirt length
63	M	moment at spudcan base level
64	M_a	additional moment induced by horizontal force and jack-up leg height
65	M_{max}	maximum moment at spudcan base level
66	M_t	moment at given jack-up leg height
67	$M_{t,\text{max}}$	maximum moment at given jack-up leg height

68	RP	reference point at spudcan
69	RP1	reference point at top of leg
70	S_t	soil sensitivity
71	s_u	undrained shear strength
72	$s_{u,ref}$	reference undrained shear strength
73	$s_{um,ref}$	reference undrained shear strength at the seabed
74	$s_{u,ave}$	average undrained shear strength along the frictional surface
75	V	vertical force
76	v	spudcan penetration velocity
77	z	depth below soil surface
78	z_F	footprint depth
79	α	interface friction ratio
80	α_b	spudcan base angle
81	β	offset distance
82	δ_{rem}	remoulded strength ratio
83	$\dot{\gamma}$	shear strain rate
84	$\dot{\gamma}_{ref}$	reference shear strain rate
85	μ	rate parameter for logarithmic expression
86	μ_C	Coulomb friction coefficient

87	θ_F	footprint slope angle
88	$\tau_{\max}$	limiting shear strength at soil-spudcan interface
89	ξ	cumulative plastic shear strain
90	ξ_{95}	cumulative plastic shear strain required for 95% remoulding

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1 INTRODUCTION

1.1 'Mobile' Jack-Up Rig and Spudcan-Footprint Interactions

Most offshore drilling in shallow to moderate water depths (< 150 m) is performed from self-elevating jack-up rigs due to their proven flexibility, mobility and cost-effectiveness (CLAROM 1993; Randolph et al. 2005). Today's jack-ups typically consist of a buoyant triangular platform supported by three independent truss legs, each attached to a large 10 to 20 m diameter spudcan. After the completion of the task, the legs are retracted from the seabed, leaving depressions, referred to as a crater or 'footprint', at the site (see Figure 1a).

Jack-ups often return to sites where previous operations have left footprints in the seabed. This is, for example, to drill additional wells or service existing wells; installing structures such as jackets or wind turbines (Killalea 2002; Osborne and Paisley 2002; InSafeJIP 2011). When a spudcan is located on or near a footprint slope, there is a tendency for the spudcan to slide towards the center of the footprint, inducing excessive lateral forces and bending moments to the rig (see Figure 1b). Adverse spudcan displacement could result in an inability to install the jack-up in the required position, leg splay, structural damage to the leg, and at worst, bumping or collapsing into the neighbouring operating platform. The frequency of offshore incidents during installation near footprints has increased by a factor of four between the period 1979~88 and 1996~06 (Osborne 2005) and at an even higher rate over 2005~2012 (Jack et al. 2013), with examples of offshore incidents also documented by Hunt and Marsh (2004), Brennan et al. (2006) and Handidjaja et al. (2009).

1.2 Spudcan Footprint Geometry

In general, the soil strength profile, the depth of detaching the spudcan base from the underlying soil during extraction, and the degree of soil reverse backflow around the extracting spudcan dominate the formation of the footprint. From the results of a series of

half-spudcan centrifuge tests, Hossain and Dong (2014) concluded that a conical footprint of depth $z_F = 0.22\sim 0.33D$ was formed in soft clay whilst a cylindrical footprint of depth $z_F = 0.5\sim 0.66D$ was formed in stiff clay. In addition, the combined effects of soil heaving during initial penetration of the spudcan and reverse backflow during extraction resulted in a soil bulge extending laterally over $1.92\sim 1.96D$ particularly in soft clay. These findings are consistent with footprints measured in Gan et al. (2008), Teh et al. (2010), and Erbrich et al. (2015). Critical footprint depth (z_F) of $0.33D$ and $0.66D$ and width of $2D$ were considered in this study.

Natural fine grained soils experience remoulding during the spudcan penetration and extraction event. This disturbance is healed gradually with the passing of time through dissipation of excess pore pressure. Centrifuge tests in Kaolin clay showed full recovery of the original strength taking 1~1.5 years in the vicinity of the footprint, though of course this is a function of the soil's permeability (Leung et al. 2007). Further disturbance and strength's greater than the original intact strength were measured at greater depths below the depth to which the spudcan was originally penetrated and after the passing of many years (see contours of Gan et al. 2012). Because of the complexity and variety of possible strength gradients around the footprint, in this study, an artificial footprint with the soil strength along and adjacent to the footprint identical to the intact strength profile was considered. This allows a consistent evaluation of the benefits of the spudcan shape (and allows comparisons with the testing programs of Kong et al., 2013, 2015a, 2015b). Further numerical study and experiments in more complex soil profiles are recommended.

1.3 Previous Work

Penetration of spudcan foundations next to footprints has been addressed by a number of researchers, with of particular interest being on spudcan-footprint interactions and consequent

influence on jack-up legs with various fixity conditions. Gaudin et al. (2007), Leung et al. (2007), Cassidy et al. (2009), Gan et al. (2012), Kong et al. (2013) reported data from centrifuge tests. Tho et al. (2013) and Zhang et al. (2015) performed 3D LDFE simulations using the remeshing and interpolation technique with small strain-analysis (RITSS) technique and coupled Eulerian-Lagrangian (CEL) approach, respectively, in the commercial finite element package ABAQUS. From all investigations, as summarized in Figure 10 of Kong et al. (2013), the critical offset distance β (defined as the distance between the footprint center and spudcan center) was identified as $0.5D \sim 1.0D$. From case histories, Handidjaja et al. (2009) found that if $\beta > 1.5D \sim 1.7D$, the effect of interaction can be neglected, while Teh et al. (2010) reported a minor slip for $\beta = 1.0D$.

1.4 Existing methods for mitigating spudcan-footprint interactions

For mitigating spudcan-footprint interactions, only a minimum attention was paid. In the field, stomping, successive leg repositioning (Brennan et al. 2006), use of an identical or very similar spudcan diameter and exactly on the existing footprint (Erbrich et al. 2015), and water jetting along with the spudcan preloading (Handidjaja et al. 2009) have been used. Perforation drilling was also identified as a potential means for mitigating spudcan-footprint interactions (Maung and Ahmad 2000; Hossain and Stainforth 2016). Additional works involved with these methods incur additional cost and time to be applied in the field.

1.5 Objectives of present study

This study focuses on tweaking spudcan shapes to ease the spudcan-footprint interactions. The investigation was carried out through 3D large deformation finite element (LDFE) analyses. Firstly, for ensuring the accuracy of the numerical model, vertical (V), horizontal (H) and moment (M) loads acting on a spudcan were validated against the results from centrifuge test result performed by Kong et al. (2013) and from LDFE using RITSS

conducted by Zhang et al. (2015). Secondly, the effect of the previously developed novel spudcan shapes (Lee et al. 2015) at mitigating spudcan-footprint interactions has been evaluated through comparison with the performance of a generic spudcan shape. An extensive parametric investigation was then undertaken, encompassing the relevant range of various parameters related to the footprint geometry, reinstallation location and soil strength.

2 NUMERICAL ANALYSIS

2.1 CEL method for large deformation problem

3D LDFE analyses were carried out using the coupled Eulerian-Lagrangian (CEL) approach in the commercial FE package ABAQUS/Explicit (Dassault, 2012). Qiu et al. (2011), Chen et al. (2013), Tho et al. (2013), Hu et al. (2014), Hamann et al. (2015), Kim and Hossain (2015) and Zheng et al. (2015) investigated various geotechnical problems using the CEL approach and provided confidence to its applicability to solve problems involving large deformations.

The CEL approach is identified as advantageous in circumventing mesh distortion in large deformation problems. The soil is tracked as it flows through an Eulerian mesh, fixed in space, by computing the material volume fraction in each element. The Eulerian element can be materially void or occupied partially or fully by more than one material, with the volume fraction representing the portion of that element filled with a specified material. The structural element, such as a spudcan, is discretized with Lagrangian elements, which can move through the Eulerian mesh without resistance until they encounter Eulerian elements containing soil. The interaction between the structure and the soil is represented using a contact algorithm named 'general contact' in ABAQUS (Dassault 2012).

2.2 Mesh and boundary conditions

Considering the symmetry of the problem, half spudcan and soil were modelled. The lateral extensions of the soil domain from the center of the footprint were $2.5D$ (D is the spudcan diameter) on the left hand side and $4.5D$ on the opposite side, and the depth of the soil domain was $\sim 5.5D$ to avoid boundary effect during the installation process (as obtained from preliminary convergence studies and also considered by e.g. Hu et al. 2015; Zheng et al. 2015). An idealized artificial footprint was considered following Kong et al. (2013). Figure 2 shows the footprint shape of a cone with $D_F = 2D$ and $z_F = 0.33D$ and $0.66D$. Similar to the Kong's experimental setup, the spudcan was assumed to be rigid with no horizontal or rotational movements allowed (fixed head condition). A typical mesh is shown in Figure 3. A very fine soil mesh was necessary to capture the spudcan-soil interaction accurately. Therefore, mesh convergence studies were first performed to ensure that the mesh was sufficiently fine to give accurate results. As shown in Figure 4, four different mesh densities were considered (in the 'very fine mesh zone' in Figure 3) for a spudcan reinstallation near an existing footprint. The numerical results based on mesh 1 and mesh 2, with minimum element sizes ($h_{\min}$) $0.019D$ and $0.025D$ respectively, are essentially identical, indicating that mesh convergence was achieved with the density of mesh 2 ($h_{\min} = 0.025D$). As such, for subsequent parametric analyses, the typical minimum soil element size in the very fine mesh zone was selected as $0.025D$. A 3 m (i.e. $0.2D$) thick void (i.e. material free) layer was set above the intact soil surface, allowing the soil to heave by flowing into the empty Eulerian elements during the penetration process. The penetration velocity of the spudcan (v) was taken as 0.1 m/s .

2.3 Constitutive law and material parameters

The soil was modelled as a linear elastic–perfectly plastic material obeying a Tresca yield criterion, but extended as described later to capture strain-rate and strain-softening effects. A user subroutine was implemented to track the evolving soil strength profile. The elastic behaviour was defined by a Poisson’s ratio of 0.49 and Young’s modulus of $500s_u$ throughout the soil profile. Total stress analyses were carried out adopting a uniform effective unit weight over the soil depth, representing a typical average value for field conditions.

The interaction between (e.g. spudcan) and Eulerian (e.g. soil) materials is enforced by a general contact algorithm that is based on a penalty contact method in ABAQUS (Dassault, 2012). Therefore, the spudcan-soil interface was modelled as frictional contact using this algorithm and specifying a (total stress) Coulomb friction law with a limiting shear stress ($\tau_{\max}$). Two different contact properties were applied for the side and bottom of spudcan, respectively. For the side friction of spudcan shoulder, skirt and holes, the Coulomb friction coefficient was set to a high value of $\mu_c = 50$, in order to allow the value of $\tau_{\max}$ ($= \alpha s_{u,ave}$; where α is the frictional ratio taken as the inverse of the soil sensitivity, $1/S_t$; $s_{u,ave}$ is the average undrained shear strength along the frictional surface) to govern failure (Ma et al. 2014; Kim et al. 2015). For the friction between the bottom profile of spudcan and footprint slope, μ_c was taken as 0.1, without specifying a $\tau_{\max}$. It allows the frictional behaviour to be governed by the contact pressure beneath the spudcan (Wang et al. 2012; Wang et al. 2015; Mao et al. 2015).

2.4 Incorporation of combined effects of strain rate and strain softening

The Tresca soil model was extended in order to take the combined effects of rate dependency and gradual softening into account following the Einav & Randolph model (Einav & Randolph 2005). The undrained shear strength at individual Gauss points was

modified at the beginning of each time step, $\dot{\gamma}$, according to the average rate of maximum shear strain in the previous increments and the current accumulated absolute plastic shear strain, ξ , expressed as

$$s_u = \left[1 + \mu \log \left(\frac{\text{Max}(|\dot{\gamma}|, \dot{\gamma}_{\text{ref}})}{\dot{\gamma}_{\text{ref}}} \right) \right] \left[\delta_{\text{rem}} + (1 - \delta_{\text{rem}}) e^{-3\xi/\xi_{95}} \right] s_{u,\text{ref}} \quad (1)$$

The first bracketed term augments the strength according to the maximum strain rate relative to a reference value, $\dot{\gamma}_{\text{ref}}$, which was considered as 1.5%/h as consistent with triaxial tests (Lunne et al. 2006), following a logarithmic law with rate parameter μ taken as 0.1 for ‘circular’ spudcan foundations (Low et al. 2008). The second part of Equation 1 models the degradation of strength according to an exponential function of cumulative shear strain, ξ , from the intact condition to a fully remoulded ratio, $\delta_{\text{rem}} (= 1/S_t = \alpha)$. The relative ductility is controlled by the parameter, ξ_{95} , which represents the cumulative shear strain required for 95% remoulding. A typical value of $\xi_{95} = 15$ (i.e. 1500% shear strain; Randolph 2004) was considered. Further details can be found in Hossain & Randolph (2009) and Zheng et al. (2015).

3 VALIDATION AGAINST CENTRIFUGE TESTING AND PREVIOUS LDFE ANALYSIS

The LDFE results were validated against previously published centrifuge test data and LDFE results using the alternative RITSS method. Kong et al. (2013) presented data from a centrifuge test carried out at 250 g in kaolin clay. A model flat base circular footing ($D = 15$ m) was adopted, instead of real spudcans to eliminate any effects of spudcan base profile, and an idealized artificial footprint ($D_F = 2D$ and $z_F = 0.33D$; footprint A in Figure 2) were used in that testing. The slope angle of the footprint (θ_F) was 18.5°. The soil undrained

shear strength of $s_{u,ref}$ was deduced from T-bar penetration tests as $s_{u,ref} = 7.5$ kPa at the ground surface with a linearly increasing gradient of $k = 0.92$ kPa/m down to 3.4 m; and $s_{u,ref} = 5$ kPa and gradient of $k = 1.68$ kPa/m for the soil below 3.4 m. The footing was penetrated at an offset of $\beta = 0.55D$ from the footprint center. In the LDFE simulation, these parameters and $\mu = 0.1$; $\delta_{rem} = 1/S_t = 1/3$; $\xi_{95} = 15$; and $\dot{\gamma}_{ref} = 1.5\% \text{ h}^{-1}$ were used. For the same case, Zhang et al. (2015) performed a 3D LDFE simulation using the RITSS technique. The soil was modelled as an elasto-plastic material obeying a Tresca yield criterion, with strain softening and rate dependency of the undrained shear strength not incorporated.

Figure 5 shows penetration resistance profiles, in terms of horizontal force (H), vertical force (V) and bending moment (M) distribution along the normalized penetration depth, d/D (where d is the penetration depth of spudcan base i.e. lowest point of largest section from mudline). The results from Zhang et al.'s (2015) LDFE/RITSS simulation are also included for comparison. By comparing with the measured data, the horizontal and vertical load responses from this study are in reasonable agreement, while the moment response is slightly higher. The horizontal load response from the LDFE/RITSS analysis is significantly higher. It can be explained as the LDFE/RITSS analysis adopted a 'tie restrained condition' between the soil and the footing, and an ideal Tresca soil material (without any softening effect). This may have led to a larger horizontal force. In order to highlight the individual effect of strain rate dependency and softening, two additional analyses have been performed considering (i) rate dependent, non-softening soil ($\mu = 0.1$; $\delta_{rem} = 1$), and (ii) rate independent, softening soil ($\mu = 0$; $\delta_{rem} = 1/3$; $\xi_{95} = 15$). The results are also plotted in Figure 5. As expected, for this spudcan penetration problem, the curves for rate-dependent softening soil is somewhat bounded by the curves for rate dependent, non-softening soil and rate independent, softening soil (see Figure 5); with H_{max} for these three cases being 0.84, 0.92 and 0.77 MN, respectively (see Figure 5a). The influences will be more profound for deeper penetration depths with soil flow around the

embedded spudcan (Hossain and Randolph, 2009). In practice, the undrained shear strength of clay is assessed through e.g. triaxial tests. During a spudcan penetration in the field, the operational shear strength of the adjacent soil is affected by the strain rate induced by the spudcan penetration rate and accumulated plastic shear strain simultaneously. As such, the rate dependent, strain softening soil ($\mu = 0.1$; $\delta_{rem} = 1/S_t = 1/3$; $\xi_{95} = 15$) was chosen for the further parametric analyses. As the moment about the load reference point (RP) at the center of a footing is mainly governed by the resultant vertical force and its eccentricity from RP (see Figure 5c), the difference in moment response between the LDFE simulations are not very obvious (will discuss later). Overall, this validation analysis has reasonably confirmed the capability and accuracy of the CEL approach in assessing responses during penetration of a footing adjacent to an existing footprint.

4 RESULTS AND DISCUSSION: PARAMETRIC STUDY

To examine whether by changing spudcan shape spudcan-footprint interactions can be mitigated, an extensive parametric study was carried out varying (a) the spudcan shape (conventional or generic spudcan – referred to as spudcan A, novel spudcan with 4 rectangular holes – referred to as spudcan S, and novel spudcan with 6 circular holes and sloped bottom profile – referred to as spudcan H; Table 1 and Figure 6); (b) the reinstallation location ($\beta = 0.55D \sim 1.5D$); (c) the footprint geometry ($z_F = 0.33D$ and $0.66D$); and (d) the soil undrained shear strength (soft to stiff clay deposit). The results from this parametric study, as assembled in Table 2, are discussed below. Parameters in terms of rate dependency and strain-softening were taken as $\mu = 0.1$; $\delta_{rem} = 1/S_t = 1/3$; $\xi_{95} = 15$; and $\dot{\gamma}_{ref} = 1.5\% \text{ h}^{-1}$, as they typically provided good match in the validation exercise.

4.1 Effect of novel spudcan geometry

Numerical analyses were performed using 3 spudcans (spudcan A, spudcan S and spudcan H) of 15 m diameter (Group I; Table 2). The shape of spudcan A (Figure 6a) was chosen similar to the spudcans of the ‘Marathon LeTourneau Design, Class 82-SDC’ jack-up rig, as illustrated by Menzies & Roper (2008). The basic shape of spudcan S (Figure 6b) is similar to spudcan A. A skirt of height 2 m was added around the periphery, and four evenly spaced rectangular holes (2 m $\times$ 4.95 m) were made at the base close to the skirt. The ratio of skirt length to diameter (L/D) was 0.13. The shape of spudcan H (Figure 6c) is innovative and featuring six evenly spaced circular holes (of diameter $d_h = 2.1$ m) with slopes at the base. More details can be found in Lee et al. (2015). The spudcans were penetrated at an offset of $\beta = 0.55D$ from the footprint center ($z_F = 0.33D$, $D_f = 2D$ and $\theta_F = 18.5^\circ$; footprint A in Figure 2).

Performance of novel spudcans

Figure 7 shows a comparison of performance of the generic and two novel spudcans in terms of horizontal (H), vertical (V) and moment distribution (M) along the normalized penetration depth d/D . The corresponding failure mechanisms at different stages of penetration are illustrated in Figure 8.

It is seen that vertical forces (V) and maximum moments (M_{max}) for all the spudcans are similar. Note, at the shallow penetration stage prior to the footprint toe level ($d/D < 0.33$), the vertical forces (V) for spudcans H and S are larger than that for spudcan A although the net area (A_{net}) is smaller ($A_{net} = 155.9 \text{ m}^2$ and 136.5 m^2 for spudcans H & S vs 176.7 m^2 for spudcan A; Table 1). This indicates that the effect of the increased initial bottom contact area by trapped soil (see Fig. 8b) and the frictional resistance mobilized between the trapped soil flowed through the holes and the holes peripheral surface (as was modelled as frictional

contact; see Figs. 8a~8e) outweigh the effect of less net area. After the footprint toe level ($d/D > 0.33$), the gap gradually diminishes and the curves merge together. This is because the soil flowed back around the spudcan and the flowed through the holes gradually seal the holes (see Fig. 8e) with negligible or no further effect of the holes.

By using spudcan H, a reduction in induced horizontal force was measured. The maximum horizontal force ($H_{\max}$) for spudcan H is around 1.17 MN, which is about 18.8 % lower than that for spudcan A ($H_{\max} = 1.44\text{MN}$). As discussed later, this is because the holes of the advancing spudcan and underside profiles (e.g. slopes) provide a preferential soil flow path, forcing the spudcan to remain vertical. The depth of the peak also shifts down (0.05D for spudcan A to 0.2D for spudcan H) due to the skirt. The deeper mobilisation of $H_{\max}$ of spudcans S and H provides more potential for the spudcan to reach its vertical capacity before reaching its horizontal capacity $H_{\max}$. For instance, for spudcan A, $V = 10.0\text{ MN}$ at $H_{\max} = 1.44\text{ MN}$; while for spudcan H, $V = 29.5\text{ MN}$ at $H_{\max} = 1.17\text{ MN}$.

Soil failure mechanisms

Figure 8 depicts the instantaneous (resultant) velocity vectors during reinstallation of the spudcans in soft clay (note, the instantaneous velocity vector plots are not the same as for the real Lagrangian material, but the representation of the deformed soil flow in Eulerian element; e.g. Tho et al. 2013; Kim et al. 2015). The soil failure mechanisms show that the asymmetric soil (and hence the tendency of horizontal force towards the footprint toe) has been reduced by the novel spudcan owing to soil flowing through the holes.

For the generic spudcan, once the footprint toe level is reached, the localized soil backflow on the left hand side begins to collapse back on the spudcan ($d/D = 0.38$ in Figure 8). Generally, after passing this depth, soil begins to flow back on both sides of the spudcan

(Zhang et al. 2015); the influence on the failure mechanism caused by the presence of the footprint geometry therefore diminishes.

For the novel spudcans in Figures 8b and 8c, the holes on the spudcans make this process occur earlier, easing the footprint interactions. Interestingly, spudcan H shows more efficiency compared to spudcan S, even though the net area of spudcan H is larger ($A_{\text{net}} = 155.9 \text{ m}^2$ for spudcan H vs 136.5 m^2 for spudcan S; see Table 1). It can be explained that the underside profile (e.g. various slopes at the base) of spudcan H reduces the horizontal force to some extent by trapping more soil volume underneath. Based on these results, only spudcan H was used as a novel spudcan for further parametric studies described below.

4.2 Effect of offset distance

Spudcan reinstallation processes near the idealized footprint ($z_F = 0.33D$, $D_f = 2D$ and $\theta_F = 18.5^\circ$) were investigated with different offset distances (e.g. $\beta = 0.55D$, $1.00D$ and $1.50D$; Group II; Table 2). This parametric study aims at investigating the combination effect between the spudcan shape and offset distance during reinstallation processes. The results of this analysis are plotted in Figure 9. Deviations in the vertical penetration resistances are shown in the initial penetration stage (see Figure 9b). As expected, the magnitude of the vertical force (V) increases with the offset distance β as a result of increasing initial contact area. For all cases, as the penetration continues, the contact area increases rapidly and thus leads to increase the vertical forces. The effect of offset distance becomes less influential on the vertical penetration resistance as the penetration depth increases, which results in the merging of the six vertical force curves at a depth of about $d/D = 0.4$ after the spudcans pass the toe of the footprint.

The horizontal and moment distribution for each offset distance β are presented in Figure 9a and Figure 9c. Peak H_{max} and M_{max} are observed at an offset value of $0.55D$; these findings

confirm the physical modelling results of previous publications, such as Cassidy et al. (2009) and Gan et al. (2012), in which a critical offset distance range of $0.5D$ to $1.0D$ was suggested.

The horizontal force and moment reduce with increasing β . The reduction in $H_{\max}$ with increasing β for spudcan A is more pronounced than that for spudcan H. Eventually the horizontal force for spudcan A becomes lower than that for spudcan H for $\beta = 1.50D$. This could be attributed to the skirt on spudcan H. As β increases and particularly for $\beta = 1.50D$, the left skirt of spudcan H touches the soil surface and buries earlier than the shoulder of spudcan A (see Figure 11). The buried section of the left skirt is still close to the footprint slope. This leads to increase the resulting imbalance in earth pressure, compared to the generic spudcan.

The corresponding soil flow mechanisms can be seen in Figures 10 and 11. As the reinstallation location moves away from the center of the footprint (i.e. increasing β), the localized soil backflow is initiated earlier on the left hand side of the spudcan, which significantly reduces the asymmetry of the soil failure mechanism of the spudcan. As a consequence, the horizontal force and moment dramatically reduce with increasing the offset value up to $\beta = 1.50D$. The reduction in $H_{\max}$ with increasing β for spudcan A is more pronounced than that for spudcan H. This could be attributed to the skirt and holes on spudcan H that initiate the symmetry of soil failure mechanisms earlier than spudcan A (see Figure 11).

4.3 Effect of footprint depth and soil strength

So far, as discussed in section 4.2, a conical crater of dimensions $2D$ wide ($D_F = 2.0D$) and $0.33D$ depth ($z_F = 0.33D$) and slope angle $\theta_F = 18.5^\circ$ was considered for soft clay deposits ($s_{u,ref} = 7.5 + 0.92z$ kPa (for $z < 3.4$ m) and $5.0 + 1.68z$ kPa (for $z \geq 3.4$); footprint A in Figure 2). The effect of footprint depth and soil strength were explored considering both a shallow

($D_F = 2D$, $z_F = 0.33D$) as well as a deeper conical crater ($D_F = 2D$, $z_F = 0.66D$ depth; footprint B in Figure 2) with a stiff clay strength more representative of that found in the field the Gulf of Mexico ($s_{u,ref} = 19 + 1.46z$ kPa; Menzies and Roper, 2008) for spudcan A and spudcan H (Groups III and IV; Table 2). An analysis was also carried out on a uniform clay deposit with $s_{u,ref} = 19$ kPa (Group V; Table 2) for comparison. Note, the deeper conical crater was shifted down by a cylindrical cavity of depth $0.33D$ (hence slope angle θ_F is the same of 18.5°) as shown in Figure 2.

The effects of footprint geometry and soil strength are shown in Figure 12 for both spudcans A and H. With a deeper footprint depth ($z_F = 0.66D$; Group III; Table 2), the maximum horizontal force increases significantly (185% for spudcan A; 261% for spudcan H). The corresponding moments was also nearly 50% higher compared to that for a shallow footprint crater on the clay deposit with identical strength ($z_F = 0.33D$; Group IV; Table 2). This is because of the asymmetric soil flow, which is more critical for the deeper footprint depth. As expected, spudcan H shows a mitigation effect regardless of footprint depths. For instance, for the shallow footprint depth (i.e. $z_F = 0.33D$) with stiff clay, H_{max} of spudcan H is 1.54 MN, which is about 42.3% lower than that of spudcan A ($H_{max} = 2.67$ MN). For the deeper footprint depth (i.e. $z_F = 0.66D$) this difference is 19% on the soil deposit with $s_{u,ref} = 19 + 1.46z$ kPa and 13% on the clay with $s_{u,ref} = 19$ kPa.

As shown in Figure 13, in general, the failure mechanisms in the stiff clay are consistent to those in the soft clay (Figure 8 and Group I; Table 2), but the amount of soil flowing through the holes is different. Due to the higher soil strength, the effect of hole is of course more pronounced and it leads to an increase in the reduction of H_{max} (reduction $H_{max} = 42.3\%$ for the stiff clay in Figure 12a vs 18.8% for the soft clay in Figure 9a).

4.4 Effect of horizontal force on jack-up leg bending moment

The horizontal force induced by spudcan-footprint interactions generates additional bending moment (M_a) along a jack-up leg and the largest one occurs at the top level (or just below the hull). If the moment is over the structural capacity, the leg can be damaged. Therefore, the reduction in horizontal force on the spudcan has a significant effect on the structural integrity of the jack-up leg.

All the results in the thus far discussed parametric studies are obtained using the reference point at the center of spudcans (see RP in Figure 2). With this reference point, the bending moment (M) on the spudcan is induced only by the resultant vertical force and its eccentricity as the resultant horizontal force H passes nearly through RP. If the reference point is located at the top of the leg (see RP1 in Figure 14a), an additional moment (M_a) will be mobilized by H and its eccentricity (= the leg length). The horizontal and vertical forces are not affected by this change of RP.

The analyses of Group IV (Table 2) were carried out to examine the effect of this shifting of the reference point. The leg length was setup as $L_h = 150$ m, which is similar to the practical maximum length (submerged in water i.e. = maximum operable water depth) in the field (e.g. GustoMSC CJ-80, KFELS N-Class; Koole and van der Kraan 2015). The top head of the leg was fully fixed and the spudcan was considered as a rigid body. Thus, the additional bending moment (M_a) at RP1 due to the horizontal force acting on the spudcan can be calculated as $M_a = H \times L_h$ (Figure 14a). The total moment about RP1 can therefore be calculated as $M_t = M + M_a$. The M_t profiles are shown in Figure 14b and the values of the maximum moment, $M_{t,max}$, about RP1 are summarized in Table 2. With the reference point being shifted from RP to RP1, the novel spudcan H shows more benefit in reducing $M_{t,max}$ about the fixed leg head. For instance, for the shallow footprint with stiff clay (Group IV; Table 2), the reduction in $M_{t,max}$

is as high as 38.3% by replacing the generic spudcan A with the novel spudcan H (see Figure 14b). This means that the use of the novel spudcan can significantly reduce the damage potential at the leg top level induced by spudcan-footprint interactions.

5 CONCLUDING REMARKS

To ease spudcan-footprint interactions during a jack-up installation near exiting footprints, the performances of two novel spudcan shapes, skirted spudcan with four rectangular holes (spudcan S) and skirted spudcan with six circular holes and sloped bottom profile (spudcan H), were investigated against a conventional/generic spudcan (spudcan A). The potential of spudcan sliding towards to the existing footprint center was evaluated by the maximum horizontal force and moment acting on the spudcan during installation. The computed LDFE results presented in this paper have confirmed that the novel spudcan H is more effective at mitigating spudcan-footprint interactions than the novel spudcan S and the generic spudcan A. It is attributed to the holes and various slopes at the base of spudcan H, allowing more soil volume to be trapped underneath the spudcan and forcing the soil to flow through the holes. With the footprint geometries setup in the current study in both soft and stiff clays, spudcan H can reduce the maximum horizontal force by up to 42.3% and the maximum moment up to 38.3% at the top of the jack-up leg, when comparing with the generic spudcan A. It should be noted that the novel spudcan H shows comparable vertical resistance to the generic spudcan A. In this study, the analyses were performed on previously developed novel spudcan shapes aiming at assessing their performance in easing spudcan-footprint interactions, and the viability of the numerical technique in analysing novel spudcan penetration adjacent to a footprint. Further systematic analyses are being carried out varying skirt length, bottom profile, and number of holes to propose an optimum spudcan shape at mitigating spudcan-footprint interactions. The results will be published in the future.

6 ACKNOWLEDGEMENTS

The third author is an ARC Discovery Early Career Researcher Award (DECRA) Fellow and is supported by the ARC Project DE140100903. The work forms part of the activities of the Centre for Offshore Foundation Systems (COFS), currently supported as a node of the Australian Research Council Centre of Excellence for Geotechnical Science and Engineering and as a Centre of Excellence by the Lloyd's Register Foundation. This support is gratefully acknowledged, as is the benefit of discussion with Dr. Dong Wang.

REFERENCES

- Brennan, R., Diana, H., Stonor, R.W.P., Hoyle, M.J.R., Cheng, C.-P., Martin, D., and Roper, R., (2006). "Installing jackups in punch-through-sensitive clays." In Proceedings of the Offshore Technology Conference, Houston, OTC 18268.
- Cassidy, M.J., Quah, C.K., and Foo, K.S., (2009). "Experimental investigation of the reinstallation of spudcan footings close to exiting footprints." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 135(4), 474–486.
- Chen, Z., Tho, K.K., Leung, C.F., and Chow, Y.K., (2013). "Influence of overburden pressure and soil rigidity on uplift behavior of square plate anchor in uniform clay." *Computers and Geotechnics*, 52, 71-81.
- CLAROM, (1993). "Design guides for offshore structures." Club des Actions de Recherche sur les Ouvrages en Mer, Eds: Le Tirant, P. & Pérol, C., Paris.
- Dassault Systemes, (2012). "ABAQUS, Version 6.11 EF Documentation." Rhode Island: Hibbitt, Karlsson and Sorensen, Inc.
- Einav, I., and Randolph, M., (2005). "Combining upper bound and strain path methods for evaluating penetration resistance." *International Journal for Numerical Methods in Engineering*, 63 (14), 1991-2016.
- Erbrich, C.T., Amodio A., Krisdani H., Lam S.Y., Xu X., and Tho, K. K., (2015). "Revisiting Yolla- new insight on spudcan penetration." In Proceedings of the 15th International Conference on the Jack-up Platform Design, Construction and Operation, London.
- Gan, C.T., Leung, C.F. and Chow, Y.K., (2008). "A study on spudcan footprint interaction." In Proceedings of 2nd BGA International Conference on Foundations, Dundee, 861-872.
- Gan, C.T., Leung, C.F., Cassidy, M.J., Gaudin, C., and Chow, Y.K., (2012). "Effect of time on spudcan-footprint interaction in clay." *Géotechnique*, 62(5), 401–413.
- Gaudin, C., Cassidy, M.J., and Donovan, T., (2007). "Spudcan reinstallation near existing footprints." In Proceedings of the 6th International Offshore Site Investigation and Geotechnics Conference, London, 285-292.

- 516 Hamann, T., Qiu, G., and Grabe, J., (2015). "Application of a Coupled Eulerian-Lagrangian
517 approach on pile installation problems under partially drained conditions." *Computers*
518 *and Geotechnics*, 63, 279-290.
- 519 Handidjaja, P., Gan, C.T., Leung, C.F., and Chow, Y.K., (2009). "Jack-up foundation
520 performance over spudcan footprints analysis of a case history." In *Proceedings of the*
521 *12th International Conference on the Jack-up Platform Design, Construction and*
522 *Operation*, London.
- 523 Hossain, M.S., and Dong, X., (2014). "Extraction of spudcan foundations in single and
524 multilayer soils." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE,
525 140(1), 170-184.
- 526 Hossain, M. S., and Randolph, M. F., (2009). "Effect of strain rate and strain softening on the
527 penetration resistance of spudcan foundations on clay." *International Journal of*
528 *Geomechanics*, ASCE, 9(3), 122-132.
- 529 Hossain, M.S., and Stainforth, R., (2016). "Perforation drilling for easing spudcan-footprint
530 interaction issues." *Ocean Engineering*, 113, 308-318.
- 531 Hu, P., Wang, D., Cassidy, M.J., and Stanier, S.A., (2014). "Predicting the resistance profile
532 of a spudcan penetrating sand overlying clay." *Canadian Geotechnical Journal*, 51(10),
533 1151- 1164.
- 534 Hu, P., Wang, D., Stainer, S.A., and Cassdy, M.J., (2015). "Assessing the punch-through
535 hazard of a spudcan on sand overlying clay." *Géotechnique*, 65(11), 883-896.
- 536 Hunt, R.J., and Marsh, P.D., (2004). "Opportunities to improve the operational and technical
537 management of jack-up deployments." *Marine Structures*, 17(3-4), 261-273.
- 538 InSafeJIP, (2011). "Improved guidelines for the prediction of geotechnical performance of
539 spudcan foundations during installation and removal of jack-up units." *Joint Industry*
540 *Funded Project*.
- 541 Jack, R.L., Hoyle, M.J.R., Smith, N.P., and Hunt, R.J., (2013). "Jack-up accident statistics –
542 A further update." In *Proceedings of the 14th International Conference on the Jack-up*
543 *Platform Design, Construction and Operation*, London.

- 544 Killalea, M., (2002). "Jackup footprint, punch through studies underway." Drilling
545 Contractor, 43.
- 546 Kim, Y.H., and Hossain, M.S., (2015). "Dynamic installation of OMNI-Max anchors in clay:
547 Numerical Analysis." *Géotechnique*, 65(12), 1029-1037.
- 548 Kim, Y.H., Hossain, M.S., Wang, D., and Randolph, M.F., (2015). "Numerical investigation
549 of dynamic installation of torpedo anchors in clay." *Ocean Engineering*, 108, 820-832.
- 550 Kong, V.W., Cassidy, M.J., and Gaudin, C., (2013). "Experimental study of the effect of
551 geometry on reinstallation of jack-up next to footprint." *Canadian Geotechnical*
552 *Journal*, 50(5), 557-573.
- 553 Kong, V., Cassidy, M.J., Gaudin, C., (2015^a). "Investigating the failure mechanisms of a
554 spudcan penetrating next to an existing footprint." *Theoretical and Applied Mechanics*
555 *Letters, Special Edition on Offshore Structure-Soil Interaction*, 5, 64–68.
- 556 Kong, V., Cassidy, M.J., Gaudin, C., (2015^b). "Development of a real-time hybrid testing
557 method in a geotechnical centrifuge." *International Journal of Physical Modelling in*
558 *Geotechnics*, 15(4), 169-190.
- 559 Koole, T., and van der Kraan, M., (2015). "Modern jack-ups and their dynamic behaviour." In
560 *Proceedings of the 15th International Conference on the Jack-up Platform Design,*
561 *Construction and Operation*, London.
- 562 Lee, J.M., Kim, Y.H., Hossain, M.S., Cassidy, M.J., Hu, Y., Won, J.H., Park, J.S., and Jun,
563 M.J., (2015). "Use of novel spudcan shapes for mitigating punch-through hazards." In
564 *Proceedings of the 15th International Conference on the Jack-up Platform Design,*
565 *Construction and Operation*, London.
- 566 Leung, C.F., Gan, C.T., and Chow, Y.K., (2007). "Shear strength changes within jack-up
567 spudcan footprint." In *Proceedings of the 17th International Offshore and Polar*
568 *Engineering Conference*, Lisbon, 1504-1509.
- 569 Low, H.E., Randolph, M.F., DeJong, J.T., and Yafrate, N.J., (2008). "Variable rate full-flow
570 penetration tests in intact and remoulded soil." In *Proceedings of the 3rd International*
571 *Conference on Geotechnical and Geophysical Site Characterisation*, Taipei, 1087-
572 1092.

- 573 Lunne, T., Berre, T., Andersen, K.H., Strandvik, S., and Sjursen, M., (2006). "Effects of
574 sample disturbance and consolidation procedures on measured shear strength of soft
575 marine Norwegian clays." *Canadian Geotechnical Journal*, 43(7), 726-750.
- 576 Ma, J., Wang, D., and Randolph, M.F., (2014). "A new contact algorithm in the material point
577 method for geotechnical simulation." *International Journal for Numerical and*
578 *Analytical Methods in Geomechanics*, 38, 1197-1210.
- 579 Mao, D.F., Zhang, M.H., Yu, Y., Duan, M.L., and Zhao, J., (2015). "Analysis of spudcan-
580 footprint interaction in a single soil with nonlinear FEM." *Petroleum Science*, 12(1),
581 148-156.
- 582 Maung, U.M., and Ahmad, C.K.M., (2000). "Swiss cheesing to bring in a jack-up rig at
583 Anding location." In *Proceedings of the IADC/SPE Asia Pacific Drilling Technology*
584 *Conference*, Kuala Lumpur, Malaysia. Asia Pacific Drilling Technology, Richardson,
585 Tex. Paper IADC/SPE 62755.
- 586 Menzies, D., and Roper, R., (2008). "Comparison of jackup rig spudcan penetration methods
587 in clay." In *Proceedings of the 40th Offshore Technology Conference*, Houston, OTC
588 19545.
- 589 Osborne, J.J., (2005). "Are we good or are we lucky?" OGP/CORE Workshop, Singapore.
- 590 Osborne, J.J., and Paisley, J.M., (2002). "S E Asia jack-up punch- throughs: the way
591 forward?" In *Proceedings of the Offshore Site Investigation and Geotechnics –*
592 *Diversity and Sustainability*, London, 301-306.
- 593 Pollock, N., Moyle, I., Hayward, M., and Rahman, Z., (2015). "Tools for mitigating and
594 managing VDL limitations in challenging Australia soil and environmental
595 conditions." In *Proceedings of the 15th International Conference on the Jack-up*
596 *Platform Design, Construction and Operation*, London.
- 597 Qiu, G., Henke, S., and Grabe, J., (2011). "Application of a coupled Eulerian–Lagrangian
598 approach on geomechanical problems involving large deformations." *Computers and*
599 *Geotechnics*, 38, 30-39.
- 600 Randolph, M. F., (2004). "Characterisation of soft sediments for offshore applications."
601 Keynote Lecture. In *Proceedings of the 2nd International Conference on Site*
602 *Characterisation*, Porto, 209–231.

- Randolph, M.F., Cassidy, M.J., Gourvenec, S., and Erbrich, C.J., (2005). "Challenges of offshore geotechnical engineering." State of the Art paper, In Proceedings of the International Conference on Soil Mech. and Found. Eng., Osaka, 1, 123–176.
- Teh, K.L., Handidjaja, P., Leung, C.F., and Chow, Y.K., (2010). "Leg penetration analysis of jack-up rig installation over existing footprints." In Proceedings of the 20th International Offshore and Polar Engineering Conference, Beijing, 2, 427–433.
- Tho, K.K., Leung C.F., Chow, Y.K., and Swaddiwudhipong, S., (2013). "Eulerian finite-element simulation of spudcan-pile interaction." Canadian Geotechnical Journal, 50, 595-608.
- Wang, D., Bienen, B., Nazem, M., Tian, Y., Zheng, J., Pucker, T., and Randolph, M.F., (2015). "Large deformation finite element analyses in geotechnical engineering." Computers and Geotechnics, 65, 104-114.
- Wang, N., Wu, J., Xu, Y., Huang, Z., and Zhu, L., (2012). "Research on soil failure modes and spudcan penetration depths in a single layer." In Proceedings of the 22nd International Offshore and Polar Engineering Conference, Rhodes, 2, 700-704.
- Zhang, W., Cassidy, M.J., and Tian, Y., (2015). "3D large deformation finite element analyses o jack-up reinstallations near idealised footprints." In Proceedings of the 15th International Conference on the Jack-up Platform Design, Construction and Operation, London.
- Zheng, J., Hossain, M.S., and Wang, D., (2015). "New design approach for spudcan penetration in nonuniform clay with an interbedded stiff layer." Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 141(4), 04015003.

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Table 1. Details of spudcans

Description	Symbol (unit)	Spudcan A (conventional type)	Spudcan H (6 circular holes)	Spudcan S (4 rectangular holes)
Spudcan diameter	D (m)	15	15	15
Skirt length	L_s (m)	-	1.9	2.0
Spudcan base angle (underside profile)	α_b (°)	13.0	-43.0 ~ 21.5 (8 slopes per 1 hole)	13.0
Number of holes	-	-	6	4
Hole size	m	-	$d_h = 2.1$	2 x 4.95
Total spudcan plan area (at largest section)	A_{total} (m ²)	176.7	176.7	176.7
Total hole area	A_{hole} (m ²)	-	20.8	40.2
Net spudcan plan area ($A_{total} - A_{hole}$)	A_{net} (m ²)	176.7	155.9	136.5
A_{net} / A_{total}	(%)	100	88.2	77.2

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Table 2. Summary of 3D LDFE analyses performed

Group	Spudcan shape (see Figure 6)	S _{u,ref} (kPa)	Footprint depth, z _F (m)	Offset distance, β (m)	Spudcan responses			Note
					H _{max} (MN)	M _{max} (MN-m)	M _{t,max} [^] (MN-m)	
I	Spudcan A	Soft clay*	0.33D (footprint A; see Figure 2)	0.55D	1.44	21.3	-194.4	Effect of spudcan shape
	1.17 (18.8%) ⁺				22.0 (-3.3%)	-167.5 (13.8%)		
	1.32 (8.3%)				21.8 (-2.3%)	-188.0 (3.3%)		
II	Spudcan A	Soft clay	0.33D (footprint A)	1.0D	1.06	11.14	-155.7	Effect of offset distance
	1.5D			-	-	-		
	Spudcan H			1.0D	0.99 (6.6%)	11.64 (-4.5%)	-143.4 (7.9%)	
				1.5D	-	-	-	
III	Spudcan A	Stiff clay [#]	0.66D (footprint B; see Figure 2)	0.55D	4.96	68.01	-676.5	Effect of combined footprint depth and soil strength
	Spudcan H				4.02 (19.0%)	59.4 (12.7%)	-581.2 (14.1%)	
IV	Spudcan A	Stiff clay	0.33D (footprint A)	0.55D	2.67	43.3	-358.4	Effect of soil strength
	Spudcan H				1.54 (42.3%)	45.1 (-4.2%)	-221.2 (38.3%)	
V	Spudcan A	Homogeneous stiff clay ^{\$}	0.66D	0.55D	3.22	39.24	-445.2	Effect of homogeneous soil strength
	Spudcan H				2.79 (13.3%)	36.67 (6.6%)	-410.6 (7.8%)	

* Soft clay: $s_{u,ref} = 7.5 + 0.92z$ kPa (for $z < 3.4$ m) and $5.0 + 1.68z$ kPa (for $z \geq 3.4$) (Kong et al. 2013)

Stiff clay: $s_{u,ref} = 19.0 + 1.46z$ kPa (Menzies & Roper 2008)

\$ Homogeneous clay: $s_{u,ref} = 19.0$ kPa

[^] Jack-up leg height = 150 m

+ Reduction percentage compared to spudcan A

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642 **No of Figure: 14**

643 **Figure 1.** Jack-up installation near a footprint: (a) Bathymetry plot showing footprints (after
644 Pollock et al. 2015); (b) Section view (A-A')

645 **Figure 2.** Schematic diagram of spudcan-footprint interaction

646 **Figure 3.** Typical mesh used in 3D LDFE analysis: (a) Typical 3D mesh; (b) Detail plan
647 view; (c) Side view

648 **Figure 4.** Effect of FE mesh density on spudcan penetration response near an existing
649 footprint: (a) Horizontal force; (b) Vertical force; (c) Moment distribution

650 **Figure 5.** Validation of current LDFE results : (a) Horizontal force; (b) Vertical force; (c)
651 Moment distribution

652 **Figure 6.** Generic and novel spudcan shapes: (a) Spudcan A (generic); (b) Spudcan S (4
653 rectangular holes); (c) Spudcan H (6 circular holes with base slopes)

654 **Figure 7.** Effect of spudcan shape (Group I; Table 2): (a) Horizontal force; (b) Vertical force;
655 (c) Moment distribution

656 **Figure 8.** Effect of spudcan shapes: soil failure mechanisms (Group I; Table 2): (a) $d/D = 0.1$;
657 (b) $d/D = 0.12$; (c) $d/D = 0.2$; (d) $d/D = 0.3$; (e) $d/D = 0.38$

658 **Figure 9.** Effect of spudcan offset distance (Groups I and II; Table 2): (a) Horizontal force;
659 (b) Vertical force; (c) Moment distribution

660 **Figure 10.** Effect of offset distance: failure mechanisms of spudcan A (Groups I and II; Table
661 2): (a) $d/D = 0.1$; (b) $d/D = 0.2$; (c) $d/D = 0.3$; (d) $d/D = 0.38$

662 **Figure 11.** Effect of offset distance: failure mechanisms of spudcan H (Groups I and II; Table
663 2): (a) $d/D = 0.1$; (b) $d/D = 0.2$; (c) $d/D = 0.3$; (d) $d/D = 0.38$

Figure 12. Effect of footprint depth and soil strength (Groups III, IV and V; Table 2): (a) Horizontal force; (b) Vertical force; (c) Moment distribution

Figure 13. Effect of footprint geometry and soil strength: failure mechanisms (Groups III and IV; Table 2): (a) $d/D = 0.1$ & $d/D = 0.2$; (b) $d/D = 0.2$ & $d/D = 0.4$; (c) $d/D = 0.3$ & $d/D = 0.6$; (d) $d/D = 0.38$ & $d/D = 0.78$

Figure 14. Effect of horizontal force on total moment (Group IV; Table 2): (a) Shift load reference point; (b) Moment distribution

(a) Bathymetry plot showing footprints (after Pollock et al. 2015)

(b) Section view (A-A')

Figure 1. Jack-up installation near a footprint

Figure 2. Schematic diagram of spudcan-footprint interaction

Figure 3. Typical mesh used in 3D LDFE analysis

Figure 4. Effect of FE mesh density on spudcan penetration response near an existing footprint

Figure 5. Validation of current LDFE results

Figure 6. Generic and novel spudcan shapes

Figure 7. Effect of spudcan shape (Group I; Table 2)

Figure 8. Effect of spudcan shapes: soil failure mechanisms (Group I; Table 2)

Figure 9. Effect of spudcan offset distance (Groups I and II; Table 2)

Figure 10. Effect of offset distance: failure mechanisms of spudcan A (Groups I and II; Table 2)

Figure 11. Effect of offset distance: failure mechanisms of spudcan H (Groups I and II; Table 2)

Figure 12. Effect of footprint depth and soil strength (Groups III, IV and V; Table 2)

Figure 13. Effect of footprint geometry and soil strength: failure mechanisms (stiff clay; Groups III and IV; Table 2)

(a) Shift of load reference point

(b) Moment distribution

Figure 14. Effect of horizontal force on total moment (Group IV; Table 2)