Optimising Spudcan Shape for Mitigating Horizontal and Moment Loads induced on a Spudcan Penetrating near a Conical Footprint

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- Number of Words: 3517 (text only)
- Number of Tables: 1
- Number of Figures: 17
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ABSTRACT

The horizontal force and moment induced on a spudcan as it penetrates next to an existing seabed footprint have been identified as one of the key challenges in the offshore oil and gas industry. This paper assesses the potential of changing and then optimising the spudcan foundation shape to mitigate the spudcan-footprint interaction. Large-deformation finite-element (LDFE) analyses are performed using the Coupled Eulerian-Lagrangian (CEL) approach with the simple elastic-perfectly plastic Tresca soil model modified to enable strain softening and to incorporate strain-rate dependency of the shear strength. The spudcan shape was optimised by parametric analyses varying the spudcan’s skirt length, underside profile, and number of holes through the spudcan periphery. A spudcan with a flatter (or even concave) underside profile and with holes was shown to significantly reduce the induced horizontal force and moment during reinstallation next to an existing footprint. However, use of skirts has an adverse influence. Based on the results, an optimised spudcan shape is proposed.

Keywords: jack-up; spudcan-footprint interaction; foundation shape; numerical modelling; offshore engineering
1 INTRODUCTION

Mobile jack-up platforms often return to sites where previous jack-up installation, operation and extraction has left craters, commonly referred to as footprints, in the seabed. The reinstallation of jack-up rigs near an existing footprint has been identified as the second major geotechnical failure concern in jack-up industry [1,2] because (i) during this reinstallation, the spudcan tends to slide towards the centre of the footprint and it induces excessive lateral forces and bending moments to the leg (see Fig. 1), and (ii) the frequency of offshore incidents during installation near footprints has increased by a factor of four between the periods 1979–88 and 1996–06 [2] and at an even higher rate during 2005–2012 [3].

This issue has received significant attention from researchers, with most measuring the induced loads on a generic shaped spudcan (or flat plate) and analysing the consequent effects on the jack-up legs [4-9]. Systematic investigations on how to mitigate spudcan-footprint interaction issues are notably limited with industry restricted to conducting trials, such as stomping [10,11], reaming [11-13], infilling [10,14,15] and successive leg repositioning [16] and water jetting with the spudcan preloading [17], under field conditions. The effect of the stomping method was reported by Jardine et al. [10] and Hartono [11]. It shows a significant effectiveness in mitigating the spudcan-footprint interactions. The reaming method was also investigated as effective way with small amplitude of leg up-and-down movement [11-13]. However, both methods on improving the seabed condition require additional mechanical operations, which can increase the installation cost of the jack-up rig. The potential of using the infilling measures was addressed by Jardine et al. [10,14] and Grammatikopoulou et al. [15]. However, the pattern of soil movement became markedly asymmetrical, which led to intolerable forces and moments developing in the jack-up leg before reaching the target preload level.
The effect of a skirt around the footing periphery at mitigating the interaction was also evaluated through model tests [4, 8, 18-20]. The results have consistently indicated that the skirt has induced higher horizontal and moment forces, but minimised lateral displacement. More recently, Hartono [11] carried out a total of 7 centrifuge tests (4 in soft normally consolidated clay and 3 in stiff over consolidated clay) on a flat-based skirted footing of diameter $D = 10\, \text{m}$ and skirt length $0.25D$. The footprints were created by spudcan penetration followed by immediate extraction, and a generic spudcan and the flat-based skirted footing were then installed at offset distances of $\beta = 0.25D, 0.75D$ and $1D$ from the footprint centre. The results indicated that the skirted flat-based footing is ineffective at mitigating spudcan-footprint interaction in soft clay, but is moderately effective in stiff clay provided that the re-penetration depth is shallow [note, it was also warned that the skirt increased the extraction resistance as like installation resistance]. Nonetheless, the effects of skirt and flat base cannot be decoupled. A more systemic investigation exploring the effect of each spudcan shape component was therefore necessary.

This study aims at providing optimal spudcan shape at mitigating spudcan-footprint interaction issues during jack-up reinstallation by adjusting the spudcan shape. The investigation was carried out through 3D large deformation finite element (LDFE) analyses. To optimise the shape of the spudcan, an extensive parametric investigation was performed by varying the skirt length, underside profile of a spudcan and number of holes.

2 NUMERICAL ANALYSIS DETAILS

3D LDFE analyses were carried out using the coupled Eulerian-Lagrangian (CEL) approach in the commercial FE package ABAQUS/Explicit [21]. Qiu et al. [22-24], Tho et al. [25, 27], Hu et al. [26, 28], Zheng et al. [29] and Jun et al [30] investigated various spudcan penetrating...
behaviours using the CEL approach and provided confidence to its applicability to solve problems involving large deformations.

Considering the symmetry of the problem, half spudcan and soil were modelled. As obtained from preliminary convergence studies [26, 28-30], the lateral extension of the soil domain was 2.5D and 4.5D from the centre of the footprint on the left and right sides, respectively. The height of the soil domain was 5.5D with a void layer above of 0.2D for soil heaving. The soil element size along the trajectory of the spudcan was 0.025D. A typical mesh and the footprint shape are shown in Fig. 2.

In this study, a conical footprint (D_F = 2D and z_F = 0.33D) with the soil strength along and adjacent to the footprint identical to the intact strength profile (s_{sum,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_{sum,ref} = 5 kPa and gradient of k = 1.68 kPa/m for the soil below 3.4 m.) was considered. From the results of a series of half-spudcan centrifuge tests, Hossain and Dong [31] concluded that a conical footprint of depth z_F = 0.22~0.33D was formed in soft 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 1.92~1.96D particularly in soft clay. These findings are consistent with footprints measured in other centrifuge tests and in the field, as typically shown in Fig. 2 [6,31-33]. This justifies the selection of the footprint shape.

Further, natural fine grained soils experience remoulding during a spudcan penetration and extraction event. This disturbance is healed gradually with the passing of time through dissipation of excess pore pressure [5, 7]. The changes of strength in kaolin clay were presented by Gan et al. [7] plotting strength contour as a function of the jack-up operational period (0 and 2 years) and the intervening period before reinstallation (1 and 100 years). Leung et al. [5] showed a full recovery of the original strength in kaolin takes 1~1.5 years in

4
the vicinity of the footprint. In this study, the soil strength along and adjacent to the footprint identical to the intact strength profile was considered because of two main reasons: (i) removing the variety of possible strength gradients around the footprint allowed a consistent evaluation of the benefits of the spudcan shape (and allows comparisons with the testing programs of Kong et al. [8]), (ii) due to the limitation of the current CEL approach, it is difficult to capture the effect of the jack-up operational period and the intervening period before reinstallation, and to maintain suction at the base of the extracting spudcan [34,35].

The spudcan was simplified as a rigid body with the fixed head condition. As obtained from previous convergence studies on spudcan and cone penetrations [26, 36], the penetration velocity (v) of 0.1 m/s was adopted in this study.

Typically the reinstallation of spudcans in clay is completed under undrained conditions. Thus, the soil was modelled as an elasto-perfectly plastic material that obeys a Tresca yield criterion but extended to capture the strain rate and strain-softening effects following [37]:

\[ s_u = \left( 1 + \mu \log \left( \frac{\text{Max}(\xi, \xi_{\text{ref}})}{\xi_{\text{ref}}} \right) \right) \left[ \delta_{\text{rem}} + (1 - \delta_{\text{rem}}) e^{-3\xi_{\text{ref}} \xi_{\text{rem}}} \right] s_{u, \text{ref}} \] (1)

The first bracketed term augments the strength according to the maximum strain rate relative to a reference value, \( \xi_{\text{ref}} \), which was considered as 1.5% h\(^{-1}\) as consistent with triaxial tests [38], following a logarithmic law with rate parameter \( \mu \) taken as 0.1 for ‘circular’ spudcan foundations [39]. The second part of Equation 1 models the degradation of strength according to an exponential function of cumulative shear strain, \( \xi \), from the intact condition to a fully remoulded ratio, \( \delta_{\text{rem}} (= 1/S_t = \alpha) \). The relative ductility is controlled by the parameter, \( \xi_{95} \), which represents the cumulative shear strain required for 95% remoulding. The definitions are given under notation list. Further details can be found in Zheng et al.[29] and Hossain and
Randolph [40]. 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 $\tau_{\text{max}} (= \alpha s_u,\text{ave};$ where $\alpha$ is the frictional ratio taken as the inverse of the soil sensitivity, $1/S_t$; $s_u,\text{ave}$ is the average undrained shear strength along the frictional surface) to govern failure [41,42]. For the friction between the bottom profile of spudcan and footprint slope, $\mu_C$ was taken as 0.1, without specifying a $\tau_{\text{max}}$. It allows the frictional behaviour will be governed by the contact pressure beneath the spudcan [36,43,44].

3 VALIDATION ANALYSIS AGAINST CENTRIFUGE TEST AND LDFE ANALYSIS

The LDFE results were validated against previously published centrifuge test data. Kong et al. [8] presented data from a centrifuge test carried out at 250 g in kaolin clay. The footing diameter in prototype was $D = 15$ m and the footprint geometry and soil strength are the same as those described in Section 2. In the LDFE simulation, these parameters and $\mu = 0.1; \delta_{\text{rem}} = 1/3; \xi_{95} = 15; \text{and } \dot{\gamma}_{\text{ref}} = 1.5\%h^{-1}$ were used. The footing was penetrated at an offset of $\beta = 0.55D$ from the footprint centre.

Fig. 3 shows penetration resistance profiles, in terms of horizontal force (H), vertical force (V) and bending moment (M) distribution along the normalised penetration depth, $d/D$ (where $d$ is the penetration depth of spudcan base i.e. lowest point of largest section from the mudline). 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. Additionally, to show the effects of strain rate and softening, the results from (i) rate dependent, non-softening soil ($\mu = 0.1; \delta_{\text{rem}} = 1$) and (ii) rate independent, softening soil ($\mu = 0; \delta_{\text{rem}} = 1/3; \xi_{95} = 15$) are also presented in Fig. 3. As expected, for the rate dependent, non-softening soil, the...
horizontal (H) and vertical force profiles (V) lie slightly above the results from the combined strain rate and softening soil, due to the only enhancement of the local undrained shear strength. The reverse trend is evident with the rate independent, softening soil. During penetration of the spudcan, the mobilised soil strength was affected by strain rate and accumulated strain softening simultaneously. Therefore, the rate dependent, strain softening soil ($\mu = 0.1; \delta_{\text{rem}} = 1/S_t = 1/3; \xi_{95} = 15$) was chosen for the further parametric analyses.

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

A systematic parametric study of spudcan geometry was performed by varying the (a) skirt length ($L_s$); (b) underside profile ($\alpha_b$); and (c) configuration of holes on the spudcan: number of holes ($N_{\text{h}}$). For the comparison of various spudcan shapes, the undrained soil strength ($s_{\text{u,ref}}$), outer diameter of the spudcan ($D = 15$ m), and the distance of installation from the centre of the footprint ($\beta = 0.55D$; critical offset distance from Kong et al. [8], Zhang et al. [9] and Jun et al. [30]) were fixed. Parameters in terms of rate dependency and strain-softening were taken as $\mu = 0.1; \dot{\gamma}_{\text{ref}} = 1.5\% \text{ h}^{-1}; \xi_{95} = 20$, as they provided good match in the validation exercise. The results from this parametric study, as assembled in Table 1, are discussed below.

4.1 Effect of skirt length ($L_s$)

The effect of the skirt length ($L_s$) was investigated varying $L_s$ from 0 m to 3.9 m (Fig. 4; Groups I and II, Table 1). Fig. 5 shows a comparison of performance of the generic (spudcan A: $L_s = 0$ m) and two skirted spudcans (spudcans $S_1$: $L_s = 1.9$ m and $S_2$: $L_s = 3.9$ m) in terms
of the horizontal (H), vertical (V) and moment (M) response distributions along the normalised penetration depth d/D, where d is the penetration depth of spudcan base. The corresponding schematic diagrams of the responses of each spudcan and the failure mechanisms at different stages of penetration are illustrated in Fig. 6a and 7, respectively. Overall, the horizontal force (H) and vertical force (V) increase with increasing skirt length (L_s). For example, the maximum horizontal force (H_max) for spudcans A, S_1 (L_s = 1.9 m) and S_2 (L_s = 3.9 m) is 1.44 MN, 1.77 MN and 2.72 MN (+23% and +89% increase of that of spudcan A), respectively. The horizontal force is governed by the result of earth pressures on the inner and outer surfaces of the skirt. The resulting imbalance in earth pressure (left vs. right and inner vs. outer) causes higher H_max for longer skirt length (see Fig. 6a). This difference in H diminishes when the spudcan base approaches the footprint toe level (d/D = 0.33).

The maximum moment (M_max) is not proportional to the skirt length. The maximum moment of spudcan S_1 is 26.1 MN-m (+23% of spudcan A), whereas spudcan S_2 has a slightly smaller maximum moment than spudcan A (-3% of spudcan A). The moment at the reference point (RP) is induced by the vertical forces (V) and its eccentricity (e) (see Fig. 6a), and by the imbalance horizontal force (that is relatively negligible and hence not discussed further). Fig. 6b plots the eccentricity (e = M/V), as a function of normalised penetration depth, indicating an identical value of e_{M_max} = 2.1 m for spudcans A and S_1 at the depths of mobilising the maximum moment (M_max). However, as V is higher for spudcan S_1, the corresponding moment is higher. For spudcan S_2, by contrast, e_{M_max} is significantly lower of 1.6 m, and as such, although V is higher, compared to spudcans A and S_1, the induced M_max is lower. This can be explained illustrating the corresponding soil failure mechanisms, as shown in Fig. 7. As the skirt length L_s increases, the more lateral soil flow is restrained by the skirt, which is more on the left hand side as the soil tends to direct towards the footprint toe. This results in
an increase in the vertical force of the trapped soil in the skirt on the left side, and reduces the eccentricity shifting the line of action of $V$ towards left. However, at the depths of mobilising $M_{\text{max}}$, which are very shallow (<0.1D), spudcan $S_1$ with a short $L_s$ was unable to restrain the soil.

In the field, spudcan-footprint interactions generally result in buckling of the leg at just below the hull (see Fig. 1). If the reference point is located at the top of the leg (see RP1 in Fig. 8a), an additional moment ($M_a$) will be mobilised by $H$ and the leg length, $L_1$. Therefore, the total moment at RP1 is $M_t = M + M_a$. Note, the horizontal ($H$) and vertical forces ($V$) are not affected by this change of RP. The total moment ($M_t$) distributions are shown in Fig. 8b. The leg length was setup as $L_1 = 150$ m, which is similar to the practical maximum length in the field (e.g. GustoMSC CJ-80, KFELS N-Class). With the reference point being shifted from RP to RP1, the longest skirted spudcan $S_2$ clearly shows the highest maximum total moment ($M_{t,\text{max}}$), which is more than double the generic spudcan $A$ about the fixed leg head.

In summary, the skirt length has a negative effect at reducing the horizontal responses of spudcan, and hence mitigating spudcan-footprint interaction issues. As such, non-skirted spudcans have been selected for subsequent explorations.

### 4.2 Effect of underside profile ($\alpha_b$)

To investigate the effect of the underside profile, numerical analyses were performed varying the bottom surface slope angle: $\alpha_b = 13^\circ$ (conventional one or spudcan $A$), $0^\circ$ (spudcan $U_1$) and $-15^\circ$ (spudcan $U_2$). The dimensions of the protruding spigot were maintained constant (see Fig. 9; Groups I and III, Table 1). Note, for spudcan $U_2$, the little skirt through the spudcan periphery was needed to produce a negative bottom surface angle. The results and corresponding soil failure mechanisms are shown in Fig. 10 and Fig. 11, respectively. The vertical forces ($V$) for all tested spudcans are similar. Interestingly, with the lower base slope
angles ($\alpha_b = 0^\circ$ and $-15^\circ$), a significant reduction in induced horizontal force is obtained. The maximum horizontal force ($H_{\text{max}}$) for spudcans $U_1$ and $U_2$ are approximately 0.98 MN and 1.11 MN, respectively, which are approximately 23~32% lower than that for spudcan A ($H_{\text{max}} = 1.44$ MN). The main reason is the correlation effect between the underside profiles and the resistance force vectors. Generally, the resistance force vectors are mobilised in a perpendicular direction on the bottom surface. As shown in Fig. 12, for the spudcan with a generic underside profile (spudcan A), all resistance force vectors are arranged in the left-upper diagonal direction, which generates the additional horizontal force. However, the resistance force vector on the flat surface (spudcan $U_1$) only has the vertical directional force component, i.e., there is no horizontal force. Spudcan $U_2$ with a negative base slope angle ($\alpha_b = -15^\circ$) has the smallest horizontal force at shallow penetration depths because of the opposite direction of the horizontal force component. However, $H_{\text{max}}$ is slightly larger (11.7%) than that of spudcan $U_1$, which is mobilised at a deeper depth of 0.26 $d/D$ (see Fig. 10a), because the outward horizontal force component on the right side (including earth pressure on the skirt) is counterbalanced by that on the left side of the spudcan after the full spudcan bottom profile penetrates into the ground (see Fig. 11). The two moments at RP (spudcan location) and RP1 (the leg at just below the hull), $M$ and $M_t$, are plotted together in Fig. 10c. The moment at RP1 is much larger than that of RP (-194.4 vs 24.4 MN-m in the generic spudcan) and shows a similar tendency to the horizontal force because the additional moment, $M_a (= H \times L_t)$ governs the moment at the top level of the leg. The maximum $M_t$ of $U_1$ is also reduced with the similar ratio of $H_{\text{max}}$.

In essence, flat-based (apart from the spigot) spudcans are better than the conventional one at mitigating spudcan-footprint interaction issues at the surface due to geometry in the conical footprint, which is considered for the following investigation.
4.3 Effect of hole configuration

To examine the effect of the hole configuration, numerical analyses were performed for 4-hole (spudcan H1), 6-hole (spudcan H2) and 8-hole (spudcan H3) flat-based spudcans, where the total hole area was maintained constant at 20% (or the net or effective spudcan base area was at 80%) of the total spudcan plan area (see Fig. 13; Group IV, Table 1). The results of these spudcans, the generic spudcan (spudcan A) and a no-hole flat-based spudcan are shown in Fig. 14 and 15. Overall, the holes on the spudcan show a positive effect on reducing the horizontal force (approximately 10% smaller than that of spudcan U1) because the holes on the advancing spudcan provide a preferential soil flow path and force the spudcan to penetrate vertically (see Fig. 16). However, the comparison results with spudcan A show that the underside profile has a much larger effect (32% reduction of $H_{\text{max}}$) than the holes (10% reduction of $H_{\text{max}}$). In addition, Fig. 15 shows that the effect of the number of holes ($N_h$) is minimal. Thus, the net spudcan area ($A_{\text{net}}$) is more critical at mitigating spudcan-footprint interaction issues than the hole diameter ($D_h$) if $D_h$ is sufficient to enable the soil to flow through the holes.

5 OPTIMISED SPUDCAN SHAPE TO REDUCE FOOTPRINT-SPUDCAN INTERACTION

From the parametric study results, the effectiveness of each shape factor is summarised in Fig. 17. Overall, the skirt has a negative effect, whereas the flat base, negative-sloped base, and holes have positive effects on reducing both horizontal force and moment. The diameter and number of holes have minimal effects if the soil can flow through the holes.

Based on all findings, the flat-based spudcan with minimum number of holes (spudcan H1; Group IV, Table 1) is selected as the optimum spudcan at mitigating spudcan-footprint interaction issues. As shown in Table 1 and Fig. 17, using spudcan H1, both $H_{\text{max}}$ and $M_{t,\text{max}}$
can be reduced by 42% and 46%, respectively, compared to the generic spudcan. The change of $M_{\text{max}}$ is small because of the selection of RP at the centre of the spudcan base, making the H-induced moment negligible.

6 CONCLUDING REMARKS

In an attempt to mitigate spudcan-footprint interaction issues, 3D large-deformation finite-element analyses have been performed with varying spudcan shapes. Systematic parametric analyses were performed: (i) first, varying the skirt length, which caused a worsening effect (i.e., increased induced horizontal force and moment) with increasing skirt length; (ii) second, varying the spudcan base slope angle, and a flat-based (apart from the spigot) spudcan provided positive effect for full penetration depths; and (iii) finally, varying the number and diameter of holes on the spudcan, which directed that a 4-hole flat-based spudcan is the optimal shape. In comparison with the performance of the generic spudcan shape, this optimal shape reduced the maximum horizontal force by 42% and the maximum total moment by up to 46%, which confirm the potential to ease spudcan-footprint interactions without any additional mechanical operations.

In this study, the analyses were performed considering a fixed head boundary condition at the spudcan, a single strength profile of clay deposit, and a conical footprint geometry. Further analyses are being carried out considering a three-legged jack-up rig, and simulating the footprints with strength contour presented by Gan et al. [7] as a function of the jack-up operational period and the intervening period before reinstallation. The results will be published in the future.

7 ACKNOWLEDGEMENTS

The research presented here was undertaken with support from the Australian Research Council (ARC) through the ARC Linkage Project LP140100066. 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.
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Submitted March 2018


NOMENCLATURE

\(A_{net}\)  net spudcan plan area at largest section

\(A_{total}\)  total spudcan plan area at largest section

\(D\)  spudcan diameter at largest section

\(D_F\)  footprint diameter

\(D_h\)  hole diameter

\(d\)  penetration depth of spudcan base

\(e\)  eccentricity between centres of spudcan and vertical reaction force

\(e_{M_{max}}\)  eccentricity at maximum moment

\(H\)  horizontal force at spudcan base level

\(H_{max}\)  maximum horizontal force at spudcan base level

\(k\)  shear strength gradient with depth

\(L_l\)  leg length

\(L_s\)  skirt length

\(M\)  moment at spudcan base level

\(M_a\)  additional moment at RP1

\(M_{max}\)  maximum moment at RP1

\(M_t\)  total moment at RP1

\(M_{t,max}\)  maximum total moment at RP1

\(N_h\)  number of hole

\(RP\)  reference point

\(RP1\)  shifted reference point to leg top

\(S_t\)  soil sensitivity

\(s_u\)  undrained shear strength

\(s_{u,ave}\)  average undrained shear strength
452 \( s_{u, \text{ref}} \) reference undrained shear strength

453 \( s_{u, \text{ref}} \) reference undrained shear strength at the seabed

454 \( V \) vertical force

455 \( v \) spudcan penetration velocity

456 \( z \) depth below soil surface

457 \( z_F \) footprint depth

458 \( \alpha \) interface friction ratio

459 \( \alpha_b \) spudcan base angle

460 \( \beta \) offset distance

461 \( \delta_{\text{rem}} \) remoulded strength ratio

462 \( \gamma \) shear strain rate

463 \( \gamma_{\text{ref}} \) reference shear strain rate

464 \( \mu \) rate parameter for logarithmic expression

465 \( \mu_C \) Coulomb friction coefficient

466 \( \tau_{\text{max}} \) limiting shear strength at soil-spudcan interface

467 \( \xi \) cumulative plastic shear strain

468 \( \xi_{95} \) cumulative plastic shear strain required for 95% remoulding

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Table 1. Details of the spudcans

<table>
<thead>
<tr>
<th>Group</th>
<th>Spudcan type</th>
<th>D (m)</th>
<th>Ls (m)</th>
<th>αb (°)</th>
<th>Hole</th>
<th>Nh</th>
<th>Db (m)</th>
<th>A_total (m²)</th>
<th>A_net (m²)</th>
<th>s_u,ref (kPa)</th>
<th>zF (m)</th>
<th>β (m)</th>
<th>Hmax (MN)</th>
<th>Mmax (MN-m)</th>
<th>Mt,max (MN-m)</th>
<th>Note</th>
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<tbody>
<tr>
<td>I</td>
<td>Spudcan A</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.33D</td>
<td>0.55D</td>
<td>-</td>
<td>1.44</td>
<td>21.3</td>
<td>-194.4</td>
<td>Generic</td>
</tr>
<tr>
<td>II</td>
<td>Spudcan S1</td>
<td>1.9</td>
<td>13</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>1.44</td>
<td>26.1</td>
<td>2.72</td>
<td>0.98</td>
<td>1.77 (-23%) +</td>
<td>26.1 (-23%)</td>
<td>-257.0 (-32%)</td>
<td>Skirt Effect</td>
</tr>
<tr>
<td></td>
<td>Spudcan S2</td>
<td>3.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.77</td>
<td>20.6</td>
<td>2.72</td>
<td>1.11</td>
<td>0.98 (-89%) +</td>
<td>22.3 (+3%)</td>
<td>-401.8 (+107%)</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>Spudcan U1</td>
<td>1.9</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.98</td>
<td>1.11</td>
<td>0.98</td>
<td>1.11</td>
<td>0.98 (+32%) +</td>
<td>23.4 (+5%)</td>
<td>-159.6 (+18%)</td>
<td>Underside Profile Effect</td>
</tr>
<tr>
<td></td>
<td>Spudcan U2</td>
<td>1.9</td>
<td>-</td>
<td>15</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.98</td>
<td>1.11</td>
<td>0.98</td>
<td>1.11</td>
<td>0.98 (+23%) +</td>
<td>23.4 (-10%)</td>
<td>-159.6 (+18%)</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>Spudcan H1</td>
<td>-</td>
<td>4</td>
<td>3.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.84</td>
<td>-</td>
<td>0.84</td>
<td>0.84</td>
<td>0.84 (+42%) +</td>
<td>22.7 (+7%)</td>
<td>-105.4 (+46%)</td>
<td>Hole Effect</td>
</tr>
<tr>
<td></td>
<td>Spudcan H2</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>6</td>
<td>-</td>
<td>2.7</td>
<td>176.7</td>
<td>141.4</td>
<td>0.85</td>
<td>-</td>
<td>0.85 (+41%) +</td>
<td>22.5 (-6%)</td>
<td>-109.3 (+44%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spudcan H3</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>8</td>
<td>-</td>
<td>2.4</td>
<td>176.7</td>
<td>141.4</td>
<td>0.86</td>
<td>-</td>
<td>0.86 (+40%) +</td>
<td>22.8 (-7%)</td>
<td>-110.6 (+43%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

\(^\wedge\) Jack-up leg length \( L_l = 150 \) m

+ Reduction percentage compared to Spudcan A: “+ve” – reduction; “-ve” – increase
No of Fig.: 17

Fig. 1. Jack-up reinstallation on a nearby footprint

Fig. 2. Typical mesh in 3D LDFE analysis: (a) 3D mesh; (b) Detailed plan view; (c) Side view

Fig. 3. Validation analysis against centrifuge test and other LDFE analysis

Fig. 4. Spudcan shapes to evaluate skirt length effect (Groups I and II; Table 1): (a) Spudcan A (generic); (b) Spudcan S1; (c) Spudcan S2

Fig. 5. Comparison results for skirt length effect (Groups I and II; Table 1): (a) Horizontal force; (b) Vertical force; (c) Moment distribution

Fig. 6. Horizontal force and moment with changing skirt length Ls (Groups I and II; Table 1): (a) Effect of skirt length Ls on horizontal force and moment (resultant horizontal, vertical force and eccentricity); (b) Eccentricity distribution

Fig. 7. Effect of skirt length on failure mechanisms (Groups I and II; Table 1): (a) d/D = 0.05; (b) d/D = 0.1; (c) d/D = 0.3; (d) d/D = 0.38

Fig. 8. Effect of horizontal force on induced moment: (a) Shift load reference point; (b) Moment distribution at RP1

Fig. 9. Spudcan shapes to evaluate underside profile effect (Group III; Table 1): (a) Spudcan U1; (b) Spudcan U2

Fig. 10. Comparison results for underside profile effect (Groups I and III; Table 1): (a) Horizontal force; (b) Vertical force; (c) Moment distribution at RP and RP1

Fig. 11. Effect of underside profile on failure mechanisms (Groups I and III; Table 1): (a) d/D = 0.1; (b) d/D = 0.2; (c) d/D = 0.3; (d) d/D = 0.38

Fig. 12. Effect of underside profile on horizontal force (Groups I and III; Table 1)

Fig. 13. Spudcan shapes to evaluate hole and number of hole effect (Group IV; Table 1): (a) Spudcan H1; (b) Spudcan H2; (c) Spudcan H3
Fig. 14. Comparison results of hole effect (Groups I, III and IV; Table 1): (a) Horizontal force; (b) Vertical force; (c) Moment distribution at RP and RP1

Fig. 15. Comparison results of effect of number of holes (Group IV; Table 1): (a) Horizontal force; (b) Vertical force; (c) Moment distribution at RP and RP1

Fig. 16. Effect of hole and number of holes on failure mechanisms (Group IV; Table 1): (a) d/D = 0.1; (b) d/D = 0.2; (c) d/D = 0.3; (d) d/D = 0.38

Fig. 17. Mitigation efficiency of tested spudcans
Fig. 1. Jack-up reinstallation on a nearby footprint
Fig. 2. Typical mesh in 3D LDFE analysis
Fig. 3. Validation analysis against centrifuge test and other LDFE analysis.
Fig. 4. Spudcan shapes to evaluate skirt length effect (Groups I and II; Table 1)
Fig. 5. Comparison results for skirt length effect (Groups I and II; Table 1): (a) Horizontal force; (b) Vertical force; (c) Moment distribution.

Horizontal force, $H$ (MN)

- Spudcan A ($L_s = 0.0$ m)
- Spudcan $S_1$ ($L_s = 1.9$ m)
- Spudcan $S_2$ ($L_s = 3.9$ m)

$H_{max}$ = 1.44 MN (a)
$H_{max}$ = 2.72 MN
$H_{max}$ = 1.77 MN

Vertical force, $V$ (MN)

- Spudcan A ($L_s = 0.0$ m)
- Spudcan $S_1$ ($L_s = 1.9$ m)
- Spudcan $S_2$ ($L_s = 3.9$ m)

Footprint toe level (0.33D)

$V_{max} = 20.6$ MN-m (b)
$V_{max} = 26.1$ MN-m
$V_{max} = 21.3$ MN-m

Moments, $M$ (MN-m)

- Spudcan A ($L_s = 0.0$ m)
- Spudcan $S_1$ ($L_s = 1.9$ m)
- Spudcan $S_2$ ($L_s = 3.9$ m)

$M_{max} = 21.3$ MN-m (c)
(a) Effect of skirt length $L_s$ on horizontal force and moment (resultant horizontal, vertical force and eccentricity)

(b) Eccentricity distribution

Fig. 6. Horizontal force and moment with changing skirt length $L_s$ (Groups I and II; Table 1)
Fig. 7. Effect of skirt length on failure mechanisms (Groups I and II; Table 1)
Fig. 8. Effect of horizontal force on induced moment: (a) Shift load reference point; (b) Moment distribution at RP1

\[ M_t = M + M_a \]

\[ M_a = L_l \times H \]

(a) RP1 (leg top)

(b) Moment at RP1, \( M_t (\text{MN-m}) \)

- \( M_{t,\text{max}} = -194.4 \text{ MN-m} \)
- \( M_{t,\text{max}} = -257.0 \text{ MN-m} \)
- \( M_{t,\text{max}} = -401.8 \text{ MN-m} \)

Spudcan A \((L_s = 0.0 \text{ m})\)
Spudcan S1 \((L_s = 1.9 \text{ m})\)
Spudcan S2 \((L_s = 3.9 \text{ m})\)
Fig. 9. Spudcan shapes to evaluate underside profile effect (Group III; Table 1)
Fig. 10. Comparison results for underside profile effect (Groups I and III; Table 1): (a) Horizontal force; (b) Vertical force; (c) Moment distribution at RP and RP1

- Spudcan A ($\alpha_b = 13^\circ$)
- Spudcan U$_1$ ($\alpha_b = 0^\circ$)
- Spudcan U$_2$ ($\alpha_b = -15^\circ$)

- $H_{max} = 0.98$ MN
- $H_{max} = 1.44$ MN
- $H_{max} = 1.11$ MN

- $M_{t,max} = -194.4$ MN-m
- $M_{t,max} = -125.4$ MN-m
- $M_{t,max} = -159.6$ MN-m

Horizontal force, $H$ (MN)
Vertical force, $V$ (MN)
Moment at RP, $M$ (MN-m)
Moment at RP1, $M_t$ (MN-m)

Footprint toe level (0.33D)
Fig. 11. Effect of underside profile on failure mechanisms (Groups I and III; Table 1)
Fig. 12. Effect of underside profile on horizontal force (Groups I and III; Table 1)
Fig. 13. Spudcan shapes to evaluate hole and number of hole effect (Group IV; Table 1)
Fig. 34. Comparison results of hole effect (Groups I, III and IV; Table 1): (a) Horizontal force; (b) Vertical force; (c) Moment distribution at RP and RP1

- Spudcan A (generic)
- Spudcan U1 (αb = 0°)
- Spudcan H1 (Nh = 4)

- Moment at RP1, $M_t$ (MN-m)
- Moment at RP, $M_t$ (MN-m)

- $M_{t,\text{max}} = -125.4$ MN-m
- $M_{t,\text{max}} = -194.4$ MN-m
- $M_{t,\text{max}} = -105.4$ MN-m

- $H_{\text{max}} = 1.44$ MN
- $H_{\text{max}} = 0.84$ MN
- $H_{\text{max}} = 0.84$ MN

- 32% Reduction
- 10% Reduction
- 35% Reduced
- 11% Reduced
Fig. 45. Comparison results of effect of number of holes (Group IV; Table 1): (a) Horizontal force; (b) Vertical force; (c) Moment distribution at RP and RP1
Fig. 56. Effect of hole and number of holes on failure mechanisms (Group IV; Table 1)
Fig. 67. Mitigation efficiency of tested spudcans