Physical and numerical modelling of novel spudcans for easing footprint-spudcan interaction issues

Modélisation physique et numérique de nouvelles formes de fondation spudcan afin de réduire les intéractions avec des empreintes de spudcan existantes.

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ABSTRACT: The reinstallation of jack-up rigs nearby existing footprint is one of the key challenges in the offshore oil and gas field, especially in the surface clay layer. This paper reports the results from a series of model tests undertaken to validate the efficiency of a novel spudcan shape to mitigate footprint-spudcan interaction issues. The model tests were carried out at 1 g, allowing comparison of a variety of spudcan shapes. This paper also reports the results from finite element (FE) analyses simulating spudcan installation nearby the footprint. The 3D large deformation FE (3D LDFE) analyses were carried out using the Coupled Eulerian-Lagrangian (CEL) approach in the commercial finite element package ABAQUS. The critical reinstallation scenario of repenetration 0.55D (D = spudcan diameter) and into an existing footprint of depth 0.33D was investigated. The results from this study indicate that the new adjusted spudcan shape has the potential to ease spudcan-footprint interaction issues without any additional mechanical operations.

RÉSUMÉ : La réinstallation des plateformes autoélévatrices à proximité d'empreintes formé par d'ancienne pénétration de fondation de type spudcanest un des défis majeurs dans le secteur pétrolier et gazier offshore, et plus particulièrement lorsqu'il s'agit d'une couche argileuse. Le présent article présente les résultats de plusieurs séries de tests, réalisés afin de valider l'efficacité de différentes formes de fondation spudcan ayant pour but de réduire les problèmes d'interaction avec les empreintes existantes. Les essais furent réalisés à la gravité terrestre de 1g en faisant varier la forme de la fondation spudcan. Cet article présente également les résultats des analyses par éléments finis modélisant l'installation de la fondation spudcan à proximité d'une empreinte existante. Les analyses des grandes déformations par éléments finis en 3 dimensions utilisèrent l'analyse couplée Eulerian-Lagrange (CEL) dans Abaqus. Des emplacements de réinstallation critique de l'ordre de 0.55 fois le diamètre (D) de la fondation spudcan et une profondeur d'empreinte de 0.33 fois le diamètre furent étudiés. Les résultats de ces analyses indiquent que les nouvelles formes de spudcan étudiés ont le potentiel de réduire les problèmes d'interactions avec les anciennes empreintes de spudcan sans aucune autre mesure mécanique supplémentaire.

KEYWORDS: Footprint, spudcans, 1g test, and large deformation finite element analysis (LDFE)

1 INTRODUCTION

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 (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 jack-up operations, the legs are retracted from the seabed, leaving depressions (referred to as a crater or 'footprint') at the site.

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, wind turbines (InSafeJIP 2011). When a spudcan is located on or nearby an adjacent footprint slope, there is a tendency for the spudcan to slide towards the centre of the footprint, inducing excessive lateral forces and bending moments to the rig (see Figure 1). 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 1996~2006 (Osborne 2005) and at an even higher rate over 2005~2012 (Jack et al. 2013), with examples of offshore incidents also documented (Handidjaja et al. 2009).

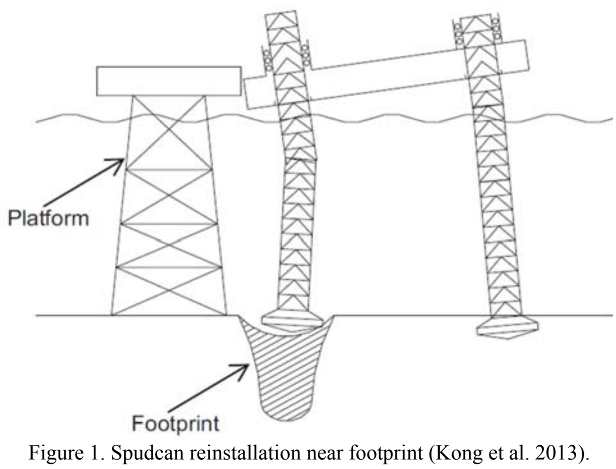

Figure 1. Spudcan reinstallation near footprint (Kong et al. 2013).

This study focuses on whether spudcan shape itself can be modified to ease the spudcan-footprint interaction issues. This is in contrast to the conventional additional mechanical approaches such as stomping, infilling crater, capping the infilled crater with gravel loading platforms, with the last two approaches being confirmed as unsatisfactory (Jardine et al. 2002). Combining 1 g model tests and 3D large deformation FE analyses, this paper provides insight into the behavior of spudcans nearby existing footprints. The results are the preliminary findings of ongoing research at UWA and DSME.

2 1G MODEL TEST

2.1 *Experimental programme*

The experimental programme comprised 1g modelling of penetration of spudcans in moderate clay deposits. The soil samples were confined within a rectangular strongbox, which has internal dimensions of 650 (length) × 390 (width) × 325 (depth) mm. An actuator was mounted on the strongbox allowing installation of the spudcan (and penetrometer) at a pre-determined rate. A highly instrumented shaft on the actuator measured vertical load and moments. The experimental arrangement is shown in Figure 2. A layer of free water was maintained at the sample surface.

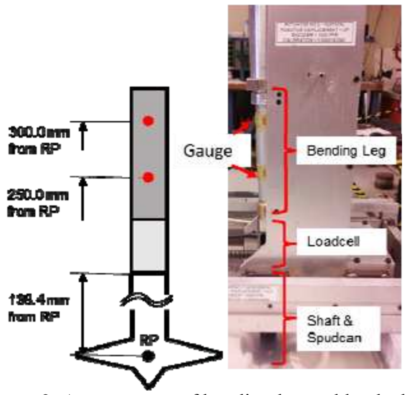

Figure 2. Arrangement of bending leg and loadcell.

2.2 *Sample preparation and spudcan*

A homogeneous slurry was prepared by mixing commercially available kaolin clay powder with water at 120% water content. Clay samples with a uniform strength profiles were prepared by consolidating the slurry at 1g. The consolidation pressure was adopted as 150 kPa and soil characterisation tests were carried out using a T-bar penetrometer of diameter 5 mm and length 20 mm. The T-bar and spudcans were penetrated at a rate of 1 mm/s and 0.19 mm/s respectively, chosen to balance viscous effects against ensuring undrained behaviour in clay. A typical shear strength (s_u) profile is plotted in Figure 3, based on a T-bar deep bearing capacity factor of $N_{T\text{-}bar}$ =10.5, where z is the penetration depth of the T-bar mid-diameter and D is the spudcan diameter.

A typical footprint geometry of diameter (D_F) = 120 mm (2.0D, D = spudcan diameter = 60 mm), depth (z_F) = 19.8 mm (0.33D), and spudcan installation offset distance from the footprint centre (β) = 60.0 mm (1.0D) was considered. Footprints were created manually on the surface of the consolidated sample. A cutting tool comprised of a mounting frame and cutting blades was used to create a footprint cavity (see Figure 4a). The frame was mounted on the strongbox and the blades were rotated and cut into the soil, forming a cavity of ideal conical shape.

The tests were performed using a model conventional spudcan (spudcan A) and a model novel spudcan (spudcan H). The shape of spudcan A (see Figure 4b) was chosen similar to the spudcans of the 'Marathon LeTourneau Design, Class 82-SDC' jack-up rig (Menzies & Roper 2008). The shape of spudcan H (see Figure 4c) is innovative featuring six evenly spaced holes (of diameter d_h = 8.4 mm) with slopes at the base and a skirt (of length, L_s = 7.6 mm) around the periphery (Lee et al. 2015).

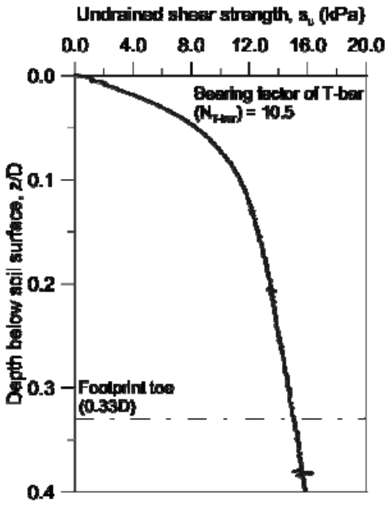

Figure 3. Undrained shear strength deduced from T-bar test.

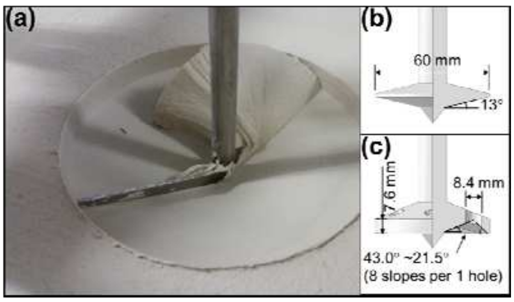

Figure 4. Footprint and model footings: (a) cutting tool and artificial footprint; (b) conventional footing, spudcan A; (c) novel footing, spudcan H.

2.3 *Performance of novel spudcan in mitigating footprint interaction*

The top of the spudcan leg was rigidly fixed with the actuator allowing no sliding of the spudcan during penetration. Figure 5 shows the test results of the spudcan A and spudcan H in terms of horizontal (H), vertical (V) and moment (M) response distribution along the penetration depth. It is seen that vertical forces (V) and maximum moments (M_{max}) for all the spudcans are similar. By using spudcan H, a reduction can be noticed in terms of induced horizontal force (H). The maximum horizontal force (H_{max}) for spudcan H is around 7.62 N, which is about 34% lower than that for spudcan A (H_{max} = 11.48 N).

3 NUMERICAL ANALYSIS

3D large deformation finite element (3D LDFE) analyses were carried out using the Coupled Eulerian-Lagrangian (CEL) approach in the commercial finite element package ABAQUS/Explicit (Dassault Systèmes). Various geotechnical problems using the CEL approach have been investigated and its applicability to solve problems involving large deformations confirmed (Tho et al. 2013, Hu et al. 2014, Zheng et al. 2015).

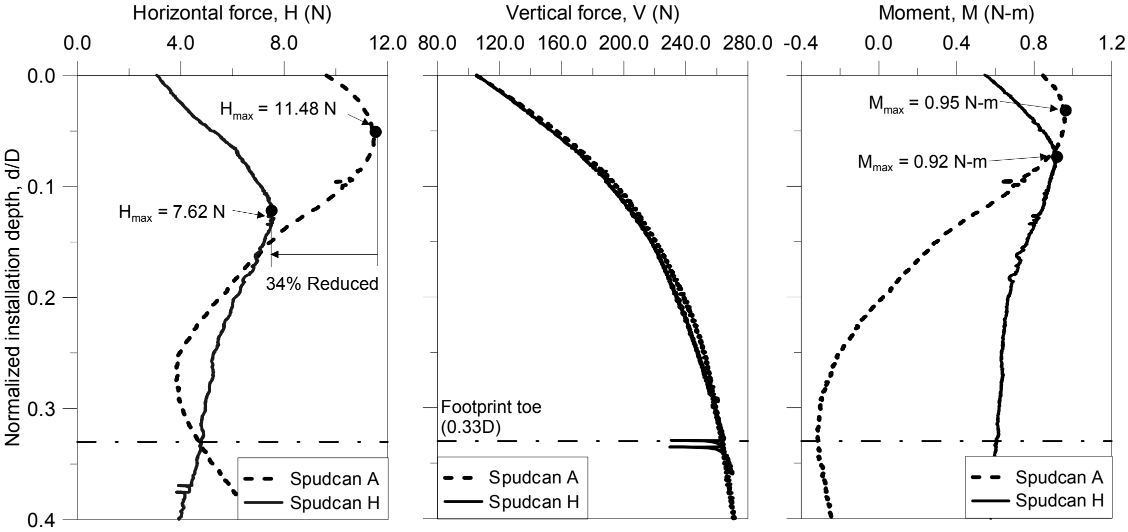

Figure 5. 1g model test results.

3.1 *Geometry and parameters*

This study has considered a circular spudcan of diameter D, penetrating adjacent to a footprint in a clay deposit. The soil undrained shear strength, s_u, was considered to mimic the profile produced by Kong et al. (2013) in their centrifuge tests. The soil undrained shear strength profile can be described by the following expressions

$$
s_u = \begin{cases} 7.5 + 0.92z \text{ (kPa)} & \text{for } z < 3.4 \text{ m} \\ 5.0 + 1.68z \text{ (kPa)} & \text{for } z \geq 3.4 \text{ m} \end{cases} \quad (1)
$$

where z is the depth below the mudline of the undisturbed zone of the deposit.

An idealized artificial footprint was considered (Kong et al. 2013). Figure 6 shows the footprint shape of a cone with D_F = 30.0 m (2D), z_F = 5 m (0.33D) and β = 8.25 m (0.55D).

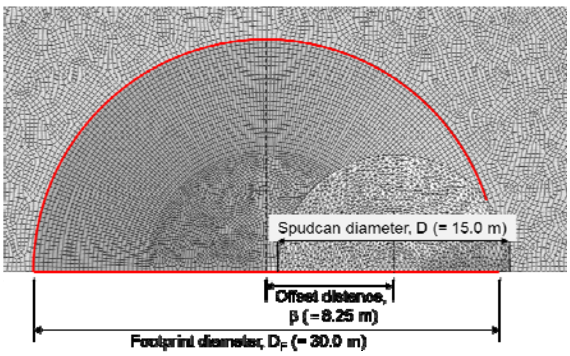

Figure 6. Footprint modeling.

Considering the symmetry of the problem, half spudcan and soil were modelled. The soil domain was constructed with dimensions of 100 m × 50 m × 80 m. The mesh comprised of 8-noded linear brick elements with reduced integration, and a fine mesh zone was generated to accommodate the spudcan trajectory during the entire penetration.

Based on the mesh convergence studies (Hu et al. 2014), the element size of the fine mesh zone was adopted 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 spudcan was assumed to be rigid with no horizontal or rotational movements allowed (fixed head condition). The penetration velocity of the spudcan was taken as 0.1 m/s.

The installations of spudcans in clay are completed under undrained conditions. The soil was therefore modelled as an elasto-perfectly plastic material obeying a Tresca yield criterion, but extending to capture strain-rate and strain-softening effects (Einav & Randolph 2005) according to

$$
s_{uc} = \left[1 + \mu \log\left(\frac{\text{Max}(|\dot{\gamma}|, \dot{\gamma}_{ref})}{\dot{\gamma}_{ref}}\right)\right]\left[\delta_{rem} + (1 - \delta_{rem})e^{-3\xi/\xi_{95}}\right]s_u \quad (2)
$$

where s_{uc} is the soil undrained strength combining strain-rate and strain-softening effects. The reference strain rate $\dot{\gamma}_{ref}$ = 0.015 h^{-1} (Lunne et al. 2007), rate parameter μ = 0.1 (Low et al. 2008), fully remoulded ratio $\delta_{rem} = 1/S_t = 1/3$, and ductility parameter ξ_{95} = 20 (i.e., 2,000% shear strain; Randolph 2004) were considered. 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 of 6.82 kN/m^3 over the soil depth.

The soil-spudcan interface was modelled as frictional contact, using a general contact algorithm and specifying a (total stress) Coulomb friction law together with a limiting shear stress along the soil-spudcan interface.

3.2 *Performance of novel spudcan in mitigating footprint interaction*

Figure 7 shows a comparison of performance of the conventional (spudcan A) and novel spudcan (spudcan H) in terms of horizontal, vertical and moment response distribution along the penetration depth.

It can be noted that the resistances from numerical analysis in Figure 7 are significantly higher than those from 1g test in Figure 5. This is mainly due to (i) the numerical results are for the prototype of spudcans (D = 15 m) and the test results are for the model spudcans (D = 60 mm); (ii) a full backflow above the penetrating spudcans is observed in numerical analysis and no soil backflow is observed in 1g test due to the lower stress level. However, there are remarkable similarities between the results from 1 g model tests and numerical analyses, such as the reduction of horizontal force by using spudcan H. The maximum horizontal force for spudcan H is around 1.17 MN, which is about 17% lower than that for spudcan A (H = 1.44

MN). The depth of appearing the maximum force also shifts down (0.05D for spudcan A to 0.25D for spudcan H).

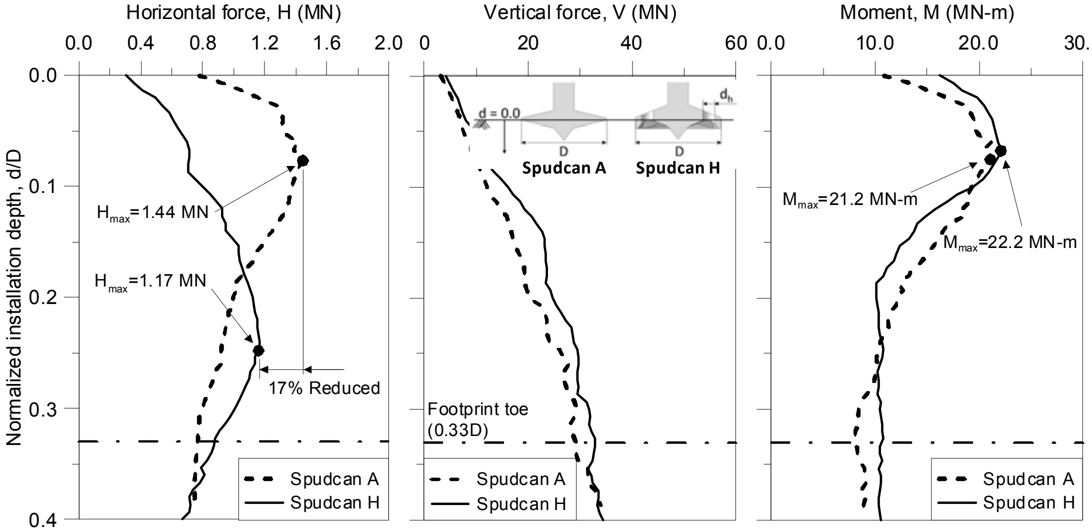

Figure 7. 3D LDFE analysis results.

4 CONCLUDING REMARKS

This paper has reported preliminary results from 1g model tests and 3D large deformation finite element (3D LDFE) analyses. The main aim was at assessing the potential of using a novel spudcan shape in mitigating or easing footprint-spudcan interaction issues. A novel spudcan along with a conventional one was considered, allowing a direct comparison in performance. The preliminary results presented in this paper showed that the novel spudcan with holes and underside profiles has a potential to ease the induced horizontal force. In the future, a series of centrifuge model tests and extensive LDFE analyses will be performed to optimise the novel spudcan shape with the confirmation of mitigating footprint-spudcan interaction issues.

5 ACKNOWLEDGMENTS

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