BEARING CAPACITIES OF SPUDCAN FOUNDATIONS IN CLAY AFTER PENETRATING THROUGH A SAND LAYER

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ABSTRACT

Layered seabeds are prevalent in many emerging provinces and sand-over-clay soil stratigraphy is particularly problematic. However, the behaviour of spudcans under combined vertical (*V*), horizontal (*H*) and moment (*M*) loading in such layered soil stratigraphy is not well understood and *VHM* yield surfaces are not defined. Centrifuge model tests in the literature have shown that a sand plug trapped underneath the spudcan increases the vertical capacity, but its effect on the horizontal and moment capacity has not yet been investigated. A set of geotechnical centrifuge test has been reported to establish the *VHM* yield surface of a spudcan that has been installed through a layer of sand into underlying clay. This paper is a follow-up analysis of the centrifuge testing result. Numerical simulations are presented to derive the bearing capacity factors, investigating the effect of the trapped sand plug underneath the spudcan and the backfill soil. Findings from the testing and numerical simulations are discussed.

KEY WORDS: bearing capacity; offshore engineering; spudcan; sand; clay

INTRODUCTION

The vast majority of present day jack-up rigs are of the independent leg type and they typically stay on location for only a few weeks or months. The jack-ups are subjected to self-weight of the structure and environmental loads. Environmental loads mainly consist of wind, wave and current, which act laterally producing horizontal and moment loads at the foundation. Before every installation at a new location, a site specific assessment must demonstrate its stability in large storms (ISO [1]). This requires understanding of the bearing capacity of each spudcan under combined vertical (*V*), horizontal (*H*) and moment (*M*) loading, as well as their interaction with the jack-up structure.

For soil conditions of single layer sand or single layer clay, several experimental studies on combined loading of footings have shown that the capacity envelope can be written directly as a *VHM* surface (e.g. Gottardi et al. [2]; Martin & Houlsby [3]; Bienen et al. [4]; Zhang et al. [5]). However, no guidance is available for sand-over-clay soils, although the combined load capacity of the foundations in such soil stratigraphy is important to the overall stability of the platform during large storms and thus affects the outcome of a site-specific assessment (a jack-up must be assessed to be stable under a 100-year storm at each new site, see ISO [1]). As an alternative, the guideline conservatively recommends to rely on the capacity of the clay layer only. In addition, when a spudcan penetrates through the top sand layer into the underlying clay, a sand plug will be trapped underneath the spudcan, mobilising higher bearing capacity of the soil and have great effect on the *VHM* bearing capacity. The backfill soil on top of the spudcan would also have a beneficial effect on the horizontal and moment capacities. All these perceived benefits need to be investigated and quantified for an accurate site-specific assessment. This paper further discusses the findings from a set of combined loading tests in sand-over-clay soils and accompanied numerical simulations.

FURTHER ANALYSIS ON THE TESTING RESULT

A programme of geotechnical centrifuge model tests, involving combined loading of circular footings to establish the *VHM* yield surface of a spudcan that has been installed through a layer of sand into underlying clay, was reported in Hu et al. [6]. A summary of the testing programme is shown in Table 1. In total 10 swipe tests were conducted immediately after the spudcan vertical penetrated to the prescribed depths of either 0.45*D* or 0.7*D*, where *D* is the diameter of the spudcan, as shown in Fig. 1. When the spudcan penetrated through the top sand into the underlying clay, a sand plug with height of ~0.9H_s, where H_s is the sand thickness, was found beneath the moving spudcan. This is consistent with the findings reported in Teh [7] and Hu et al. [8]. The spudcan together with the sand plug were then subjected to an excursion at a fixed ratio of horizontal displacement (u) and rotation (θ) while maintaining the vertical penetration depth.

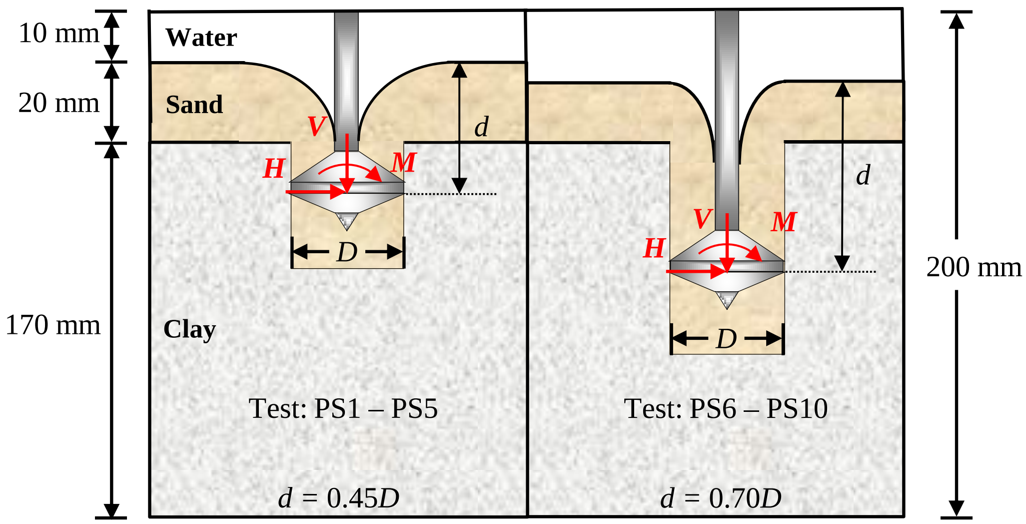


Fig. 1 Schematic diagram of spudcan *VHM* loading tests in sand-over-clay soils

Table 1 Summary of centrifuge swipe tests

Type	Test name	Test depth w	Swipe movement			Bearing pressure
			u (mm)	θ (°)	$u/D\theta$	V_0/A (kPa)
Vertical penetration test*	SP1	1.15*D*	N/A	N/A	N/A	390.4
Swipe tests	PS1	0.45*D*	10	0	∞	205.5
	PS2		8	8	0.95	204.6
	PS3		-1	8	-0.12	193.5
	PS4		-5	8	-0.6	211.9
	PS5		-10	6	-1.59	195.9
	PS6	0.70*D*	8	0	∞	270.2
	PS7		8	8	0.95	294.2
	PS8		-1	8	-0.12	281.0
	PS9		-5	8	-0.6	241.8
	PS10		-10	6	-1.59	214.5

* note: a database of 71 centrifuge tests of a vertically penetrating spudcan and flat circular footing in sand-over-clay can be found summarised in Hu et al. [10].

The testing results on sand-over-clay are interpreted to give empirical expressions for the combined loading yield surface in *VHM* space. A three-dimensional yield surface expression with parabolic cross-sections in the *VH* and *VM* planes and a rotated elliptical cross-section in the *HM* plane (Vlahos et al. [9]) was used to fit the testing result:

$$f=\left(\frac{H}{h_0V_0}\right)^2+\left(\frac{M/D}{m_0V_0}\right)^2-\frac{2eHM/D}{h_0m_0V_0^{\,2}}-\left(\frac{4}{(1+\chi)^2}\right)^2\left(\frac{V}{V_0}+\chi\right)^2\left(1-\frac{V}{V_0}\right)^2=0 \qquad (1)$$

where V_0 is the apex of the surface, which is determined by the pure vertical bearing capacity; h_0 and m_0 determine the yield surface size in the horizontal and moment directions, respectively; e is the eccentricity of the surface in the H:M/D plane and χ is the ratio of the peak vertical tensile capacity to the peak compressive capacity. For the sand-over-clay tests in Hu et al. [6], a value of χ = 0.46 was indicated from the ratio of the peak extraction pressure to the peak compression pressure (though careful consideration must be given to whether this tensile capacity can be related upon in all circumstances). For χ = 0 the expression reverts to the surface spudcans on clay (Martin & Houlsby [3]), yield surface for sand (Gottardi et al. [2]), and is similar to that contained in ISO [1]. The best-fit parameters for the yield surface of the sand-over-clay soil were then obtained using a least squares regression, which agrees reasonably well with the experimental data at the depth of 0.45*D* and 0.70*D*. It also shows that the above framework for single sand and clay soil is also applicable to sand-over-clay soil.

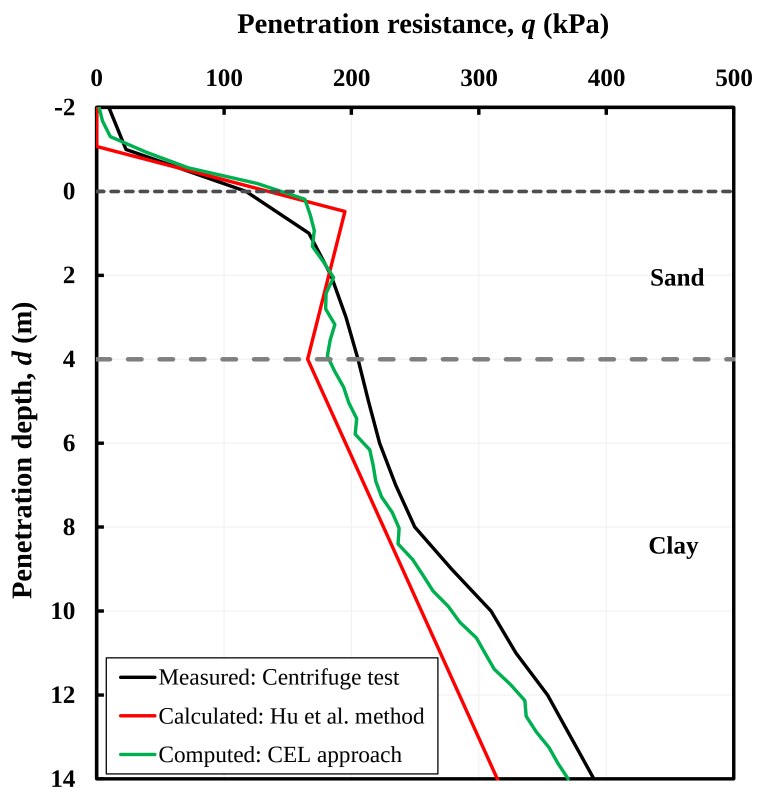
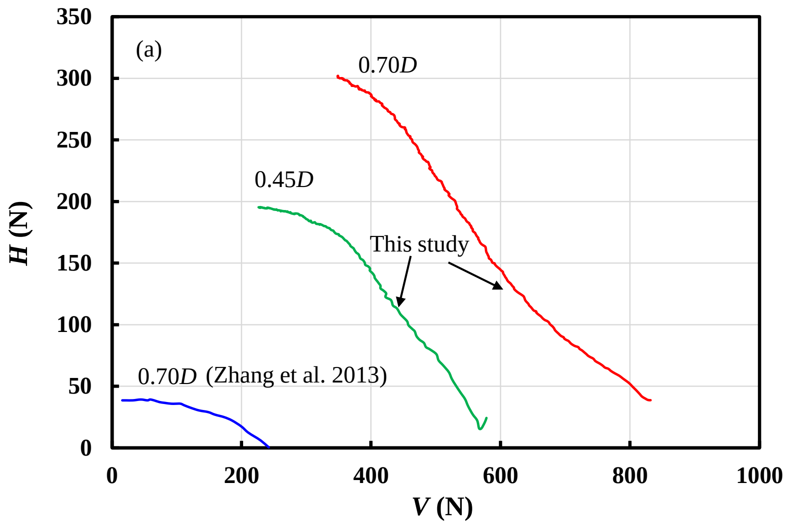


Fig. 2 Spudcan testing load-displacement profile as well as predicted and simulated results

In determining whether a jack-up unit may be safely used at a particular site, two separate analyses of foundation bearing capacity are generally undertaken: prediction of footing penetration during preloading (vertical load only) and assssment of footing stability under designed storm conditions (combined vertical, horizontal and moment load). Fig. 2 shows a typical spudcan load-displacement profile (SP1 in Table 1) in sand-over-clay soil. New analytical methods, such as described in Hu et al. [10-11] can predict the full penetration resistance in sand-over-clay soil reasonably well, as shown for this comparison in Fig. 2. This provides confidence that at least the vertical capacity, which forms the apex of the *VHM* yield surface in the underlying clay layer, can be predicted. Numerous evidence has shown that the use of the ISO [1] methods significantly under-predicts capacity both in the top sand layer and in the underlying clay layer. For the former the reason is that the contribution of the sand is not properly accounted, while for the latter it is because the sand plug trapped below a penetrating spudcan is not considered when calculating the penetration resistance in the underlying clay layer.

Fig. 3 presents the load paths of three similar swipes of $u/D\theta = 0.95$ performed in sand-over-clay soils at 0.45*D* and 0.70*D* and in single clay of Zhang et al. [5] from peak compressive vertical load. For the sand-over-clay case, with increasing embedment depth, the load paths tracked by the swipes obviously enlarged. However, a similar shape is maintained. This illustrates that a simple hardening law can be assumed as the size of the yield surface expands with the increase of current plastic penetration. It is also interesting to note that at 0.7*D* the horizontal load and moment load for sand-over-clay soil are approximately 7.8 and 2.9 times that of the single layer clay. This indicates the effect of sand plug has to be considered when formulating the *VHM* yield surface.



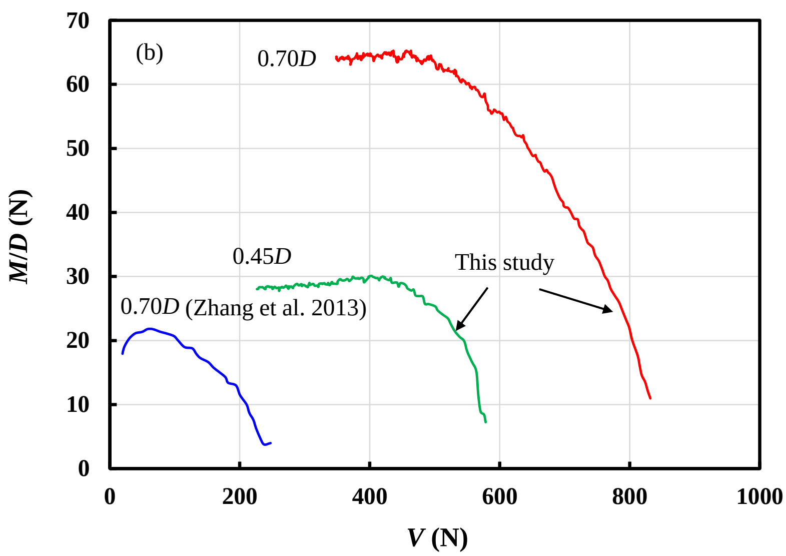


Fig. 3 Comparison of load paths of similar swipe tests

Fig. 4 compares the eccentricity of the *HM* cross-sections of the yield surfaces derived from the 1g experiment of Martin and Houlsby [3], centrifuge tests of Zhang et al. [5], finite element analyses of Zhang et al. [12] in single clay, and the centrifuge tests of Hu et al. [6] in sand-over-clay. The comparison indicates the shape of the yield surface may not remain constant with depth, though nearly constant eccentricity was seen in Martin & Houlsby [3] in single clay test. The reason might be the footing mainly behaved like a surface footing since no obvious backflow was present in the 1g tests. Both the centrifuge tests and numerical analyses reported by Zhang et al. [5, 12] indicate decreasing eccentricity with depth. The eccentricity from sand-over-clay tests contradicts the above findings, as the derived eccentricity of the *HM* cross-section increases with depth. The eccentricity of the yield surface for sand-over-clay might be influenced by the layering effect and it may be a function of the normalised layer thickness. However, due to limited testing data, the trend of eccentricity for further penetration is unknown and additional work is required to clarify this aspect.

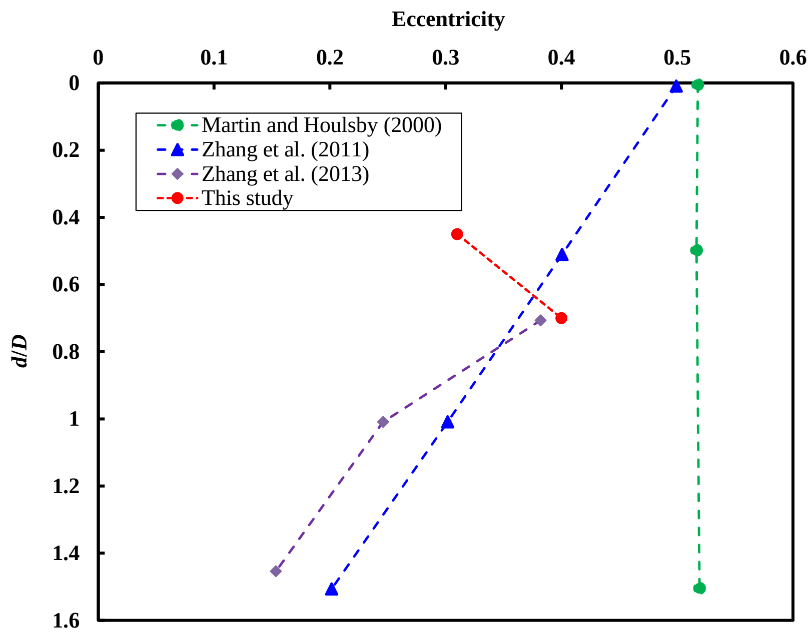


Fig. 4 Variation of eccentricity with normalised penetration depth

While the shape of yield surface is determined by the equation form (e.g. elliptical or parabolic), the size of surface in the normalised load space is determined by the parameters h_0 and m_0. The size and shape of the yield surface of these sand-over-clay centrifuge tests is now compared with the ISO [1] guideline and previous experimental studies on single layer clays.

Fig. 5 shows the trend of normalised peak horizontal capacity h_0 and moment capacity m_0 with normalised penetration depth, d/D. The centrifuge test results in sand-over-clay show that the values of h_0 increase with depth, and the overall trend is similar to the centrifuge test results in single clay (Zhang et al. [5]). The higher h_0 value indicates increased horizontal bearing capacity due to sand backflow and the sand plug. For single clay, softer clay was initially trapped underneath the spudcan and gradually flowed sideways whereas in the layered sand-over-clay the sand has been pushed into the underlying clay by the advancing spudcan. In addition, due to the effect of spudcan spigot, the horizontal capacity is also influenced by a thin zone of material directly beneath the footing. It is further enhanced because of the interaction of the underside of the spudcan and the sand. Although the h_0 values according to ISO are optimistic when compared to the experimental values in clay, they are far less than that from sand-over-clay tests.

A similar comparison of the normalised moment capacity is also illustrated in Fig. 5. Unlike h_0, m_0 is found to be consistent for the whole range of investigated depth at a value of approximately 0.1. The reason might be the increase of moment capacity in absolute terms is in proportion to the increase in vertical capacity. The moment capacity is likely to be enhanced by the sand plug beneath the spudcan, which also has been confirmed to greatly increase the vertical capacity. Therefore, the value of m_0 is not expected to change significantly with layering or strength changes. Zhang et al. [5] provided almost a constant value of 0.09 for m_0 for the range of footing embedment depth investigated (d/D = 0.7 and 1.45). The trend of m_0 in this study is relatively consistent to the above findings, as shown in Fig. 5. The magnitude of m_0 obtained from the sand-over-clay test is found to be lower than those provided in ISO [1], but only marginal difference is observed.

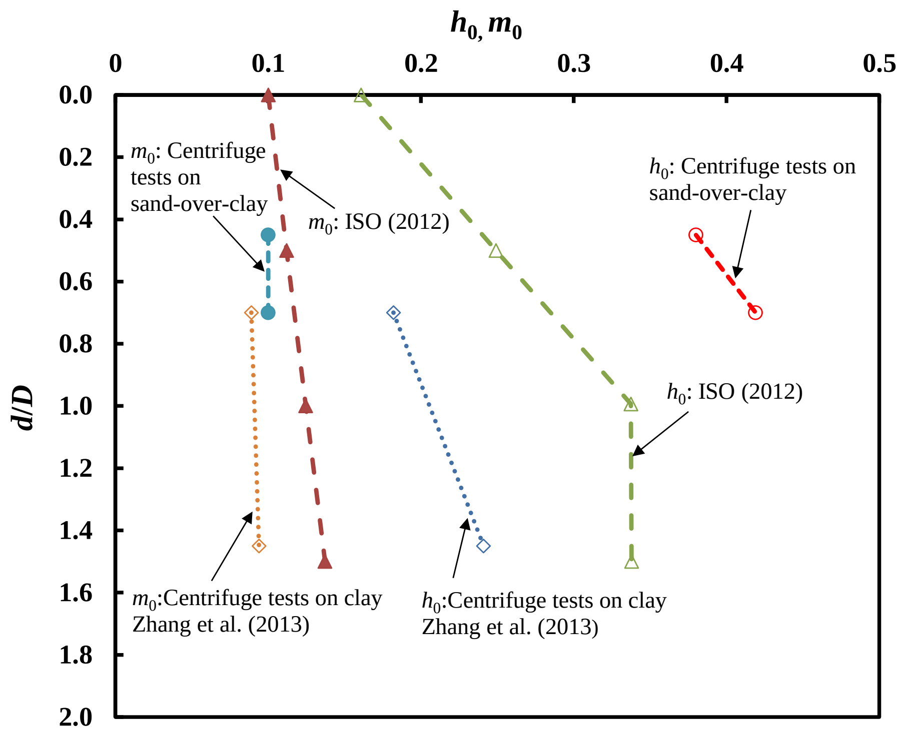


Fig. 5 Variation of h_0 and m_0 with normalised penetration depth

NUMERICAL ANALYSIS

Using finite element analysis to numerically calculate the combined bearing capacity of a spudcan foundation that has penetrated through sand-over-clay is difficult because of the large geometric and material disturbances caused during the installation process. To just "wish-into-place" a spudcan below the sand layer does not suffice because a large plug of sand is trapped below the spudcan and dragged into the clay and the sand above the spudcan is also disturbed. These effect the capacity. Innovatively, recent simulations in spudcans deeply penetrating in clay have used a large deformation finite element (LDFE) approach to simulate the changes that occur in the installation and then meshed these onto a more traditional small strain finite element (SSFE) approach to efficiently calculate the *VHM* capacity at depth (see Zhang et al. [13], Ragni et al. [14]). Only one LDFE simulation is required, whilst accurate *VHM* capacities are simulated using multiple, and computationally efficient, SSFE. A similar approach is taken here, with LDFE simulations used to calculate the load-displacement during the vertical installation and to define the geometry of the sand and clay layers at depth. This geometry is then mapped onto SSFE to calculate combined loading capacities. Though not included here, future work could use this methodology to also account for the changes in material properties due to installation (see Zhang et al. [13], Ragni et al. [14] as examples).

LDFE using the CEL approach

In order to investigate the shape of the back-fill soil and sand plug and the disturbance of the material after spudcan penetration, the Coupled Eulerian-Lagrangian (CEL) approach in the commercial package Abaqus/Explicit was adopted to simulate the overall spudcan installation process. Currently only three-dimensional elements are available in CEL analyses. Some examples of employing the CEL approach with a hypoplastic constitutive model to simulate spudcan installation in sand-over-clay can be found in Qiu and Henke [15], Qiu and Grabe [16] and Bienen et al. [17]. Hu et al. [11] also used CEL but adopted a modified Mohr-Coulomb model to reduce the computational time, updating the friction angle and dilation angle to consider the softening effect. This modified Mohr-Coulomb model was used in the simulation of this paper. The underlying clay was modelled as a linear elastic-perfectly plastic material obeying a Tresca yield criterion, taking the effect of progressive softening into account. More details of the models are provided in Hu et al. [11]. The CEL analysis was performed to simulate spudcan vertical penetration centrifuge test SP1 (see Table 1) and the numerical penetration resistance profile is shown in Fig. 2. The difference between the profiles from centrifuge test and CEL analysis is mostly less than 10% for the overall penetration depth.

The soil profile after the spudcan has penetrated to 0.45*D* is shown in Fig. 6. The partial back-flow of sand above the spudcan can be seen clearly. The most accurate modelling will be to assume the shape of sand, as presented in Figure 6, but for interest simulations of a full backflow and regular sand plug are also conducted.

The shape of soil deformation from this CEL analysis is consistent with visualisation experiments of half-spudcans penetrating against a perspex window, conducted in geotechnical centrifuges. Hu et al. [8] reported 11 spudcan and flat footing centrifuge model tests in sand-over-clay soils investigating the effect of footing shape on the penetration resistance. Experimental evidence has confirmed that a trapped sand plug with width equivalent to the spudcan diameter and height of $0.9H_s$ was pushed into the underlying clay layer. The height of the plug in the CEL was 3.52 m ($0.88H_s$). For the back-fill sand on top of the spudcan, the average experimental measurement of the inclination angle of the slope to the horizon at depth of 0.45*D* and 0.70*D* are 37.1° and 37.0°, respectively, with small standard deviation of 1.95 and 2.05. This is consistent with the CEL which has an angle of ~37.4°. For simplicity, the inclination angle of 37.0° is used in the SSFE simulation.

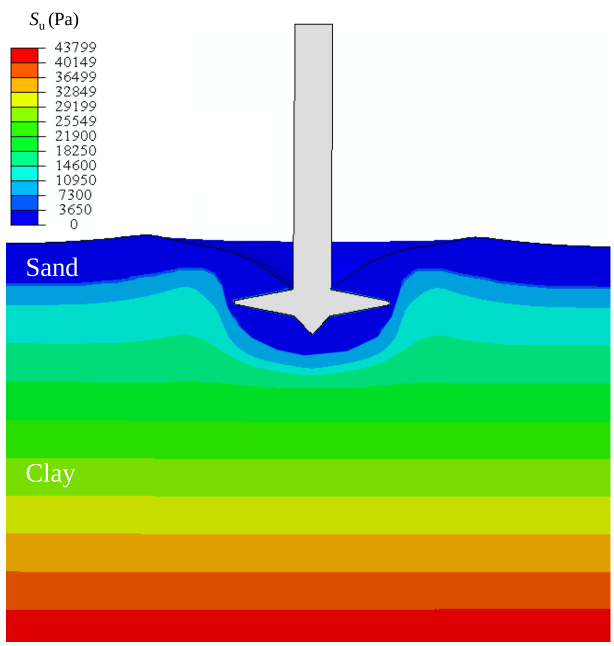


Fig. 6 Soil profile at 0.45*D* depth in the CEL analysis

SSFE analyses using deformed geometry

A wished-in-place spudcan with partial back-fill sand and sand plug underneath is modelled, with the dimensions as calculated in the CEL and as described above. A comparison is also made with the sand plug but with complete back flow of sand above the spudcan. Fig. 7 shows both models for the spudcan embedded in 0.45*D* below the soil surface. The finite element analyses were carried out using the commercial finite element software Abaqus 6.14. The spudcan was modelled as a rigid body with frictional contact with the soil. The leg of the spudcan is also included in the analysis to simulate the testing conditions. A semi-cylindrical finite element mesh of 8*D* in diameter and 8*D* in depth was adopted to minimise boundary effects. Finer mesh was used in a semi-cylindrical zone close to the spudcan, for which the mesh was convergent as results were found not to change with further mesh refinement. The critical state friction angle of the sand used in the centrifuge test is 31° (see White et al. [18] and Lee et al. [19]), which was adopted in the numerical simulation as it is argued that the sand will reach critical state after experiencing large strains during large deformation vertical penetration. The shear strength of clay was expressed as s_u = 9.26 + 1.04d kPa, as interpreted from T-bar penetrometer tests.

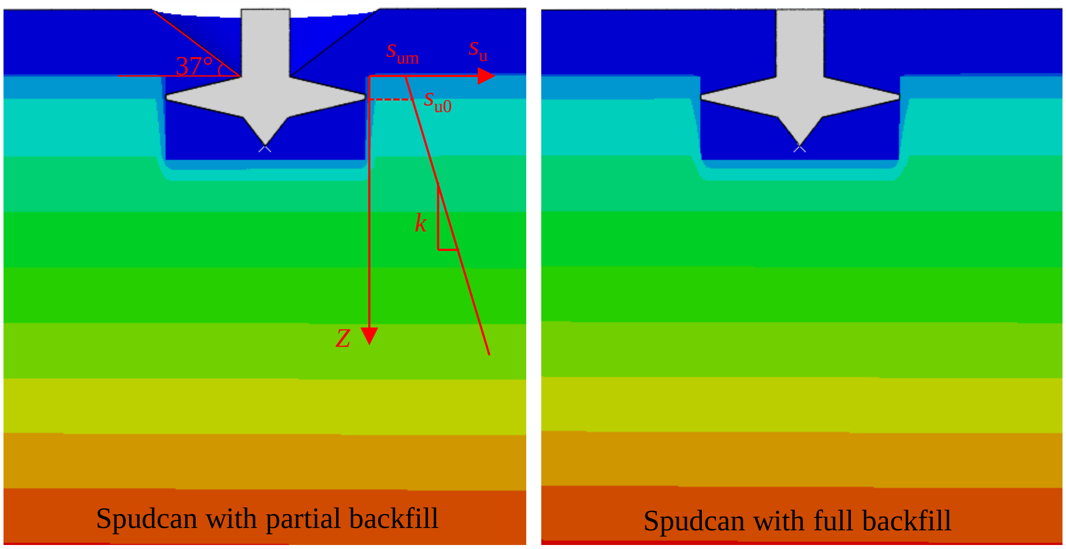


Fig. 7 Model settings in SSFE analysis

Analysis of the SSFE simulations

Only preliminary vertical and horizontal SSFE simulations have been conducted to date, with more planned in the future. Centrifuge tests PS1 and PS6 in Table 1 have been simulated. Results, such as the vertical and horizontal bearing capacity factors at penetration of 0.45*D* and 0.70*D*, are listed in Table 2. For the horizontal movement, the rotation in plane was not constrained, allowing the moment to be maintained at zero and obtaining the normalised peak horizontal capacity h_0. The following sections provide detailed discussions on these bearing capacity factors.

Vertical bearing capacity

The current ISO guideline only accounts for the contribution of the soil capacity from the underside of the spudcan. This is a reasonable and conservative assumption in stiff clay as the cavity is likely to remain open. However, in sand-over-clay soils, the sand has been shown to flow back over the spudcan immediately after embedment. Fig. 8 compares the vertical mechanisms for spudcan with partial and full back-fill. For the model with partial back-fill, the top soil shows a tendency of backflow to seal the spudcan. For the model with complete back-fill, the shear plane above the spudcan appears to be more vertical, though a rigid block in both cases was seen moving with the penetrating spudcan. The vertical bearing capacity factor, N_{cv} (=V_{ult}/As_{u0}), was inferred to be 19.11 from the centrifuge test and 19.05 from the CEL. The N_{cv} calculated from the SSFE analysis with partial back-fill was 17.49, corresponding to 7.85% difference with the testing value. On the other hand, the N_{cv} derived from the full back-fill model was 16.90, which corresponds to 11.6% lower than the testing value. For the full back-fill case, the soil on top of the spudcan cancels out the surcharge in the surroundings. Therefore, less force is needed to mobilise the soil to failure, which is reflected as a smaller N_{cv} value. The comparison also confirms the current settings for inclination angle and sand plug height is appropriate to investigate the failure envelope for spudcan combined loading in sand-over-clay soils.

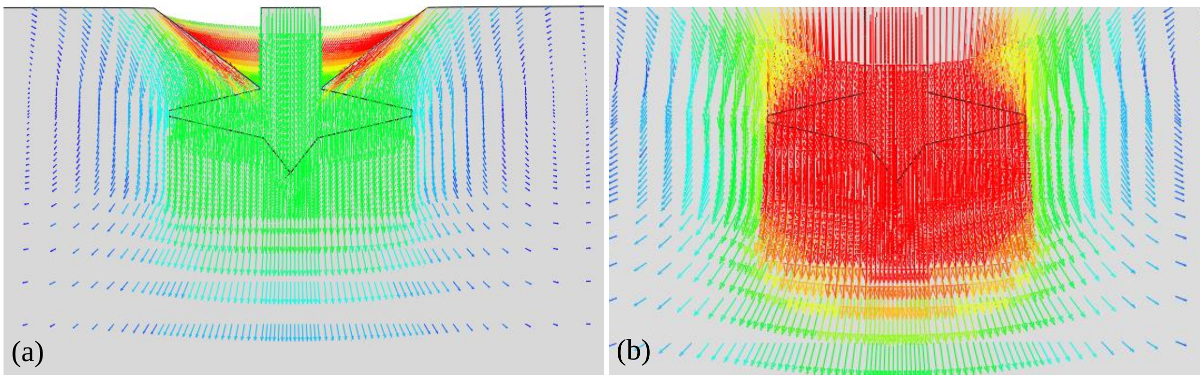


Fig. 8 Comparison of the vertical mechanism for spudcan penetration of 0.45*D*: (a) partial back-fill; (b) full back-fill

For sand-over-clay soil, the vertical bearing capacity factor for the underlying clay is not explicitly recommended in the ISO [1] guideline. Alternatively, the classical method of Skempton [20] that is based on the solution for a surface strip footing, and modified with shape and embedment factors is widely used in the jack-up industry. Accordingly, the vertical bearing capacity factor N_{cv} increases from 6 at the surface to 9 at depth of 2.5*D* or greater. The N_{cv} from Zhang et al. [5] in both centrifuge test and LDFE simulation in clay is approximately 10. The result of this study is significantly higher than the above values and the main reason lies in the sand plug underneath the spudcan. The sand plug increases the friction force along the vertical footing-soil interface. Besides that, the sidewall also deters the clay from flowing around from below the spudcan through the footing edge to the top; therefore, the clay soil is forced to take a longer route to flow around. This mobilises more soil with higher shear strength surrounding the spudcan and sand plug in the mechanism. Thus, higher vertical bearing capacity factor is derived for sand-over-clay case. The vertical bearing capacity factor when the spudcan penetrates through the top sand into the underlying clay layer could be calculated using the expression given in Hu et al. [11], which was derived on the basis of 51 centrifuge tests and 60 numerical analyses cases for vertical penetration of a spudcan into sand-over-clay.

Horizontal bearing capacity

The horizontal bearing capacity factors (N_{ch} = H_{ult}/As_{u0}) from centrifuge test at penetration depth of 0.45*D* and 0.70*D* are 6.03 and 6.37. If, as a basic assumption, the spudcan and sand plug were considered to be just one composite footing, the ratio of height to diameter T/D = 0.3. The N_{ch} for such a composite footing in just single clay, according to Zhang et al. [21], is 6.56, which is comparable to the centrifuge testing result.

The results from the numerical analyses in this study indicate N_{ch} of 5.58 and 5.51 for both depths, and the trend of an increase in capacity factor with depth is also observed. The SSFE analyses for a spudcan embedded in single clay (no sand plug below) and assumed complete back-flow were also conducted in Zhang et al. [12]. The derived N_{ch} for penetration depth at 0.7*D* is 3.19, which is almost half the magnitue from the sand-over-clay tests. This comparison also shows the contribution of the sand plug underneath the spudcan to the horizontal bearing capacity is significant and it should not be neglected.

Table 2 also shows the experimental and numerical normalised peak horizontal capacity h_0, which determines the size of the yield envelope in the horizontal direction. The h_0 increases with depth over the range of embedment considered. A trend of an increase in h_0 is also found from the numerical analyses, though the numerical results suggest smaller surface sizes than that from the experiment.

Table 2 Comparison of the experimental and numerical bearing capacity factors and normalised peak capacity

Depth		0.45*D*			0.70*D*		
Displacement	Capacity factor/Normalised peak capacity	Experimental	Numerical	Difference (%)	Experimental	Numerical	Difference (%)
Pure vertical	$N_{cV} = V_{ult}/As_{u0}$	19.11	17.61	-7.85	17.3	15.95	-7.80
Pure horizontal	$N_{ch} = H_{ult}/As_{u0}$	6.03	5.58	-7.46	6.37	5.51	-13.50
	h_0	0.38	0.32	-15.79	0.42	0.35	-16.67

The above analyses illustrate the current settings in SSFE analyses are feasible to comprehensively investigate the *VHM* failure envelope when spudcan penetrates to the underlying clay layer in sand-over-clay soils. Additional numerical simulations to fully define the *VHM* are in progress.

CONCLUSIONS

This paper presents the post-analyses of both the centrifuge experimental data of a spudcan model subjected to combined loading in clay after penetrating through a sand layer and under stress levels relevant to field conditions and the accompanied numerical simulations. The key observations of this study are:

- The *VHM* yield surface for a spudcan rests on the underlying clay layer after it penetrated through the top sand of the sand-over-clay soil is substantially larger than that in single layer clay.
- A SSFE model with appropriate geometirc input of the inclination angle of sand above the spudcan and the sand plug height below the spudcan is feasible to investigate the combined *VHM* yield surface in sand-over-clay soils.
- The sand plug was found to influence the vertical, horizonal and moment capacity to a great extent, a factor that needs to be accounted when formulating the *VHM* bearing capacity formulations. Neglecting it by considering the capacity from just a clay layer is shown to be conservative.

The combined experimental and numerical results database will form the basis to develop an analytical expression for the yield interaction, accounting for spudcan penetration depth, soil stratigraphy and characteristics. Numerical analyses are required to provide evidence at more embedment depths and soil conditions.

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