SPUDCAN PENETRATION ANALYSES FOR THREE CASE HISTORIES IN SAND OVERLYING CLAY

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ABSTRACT

The presence of problematic seabed profiles presents challenges for the stability of jackup rigs during spudcan installation. An example is a soil profile that consists of a relatively thin layer of sand, which temporarily supports the spudcan, underlain by a weak clay layer. Such soil stratigraphy is one of the main causes of spudcan punch-through, which in turn may lead to substantial damage to the leg structures. The International Standards Organisation (ISO) recommends to use either a load spread method or the punching shear method to calculate the peak resistance for a spudcan on sand overlying clay, for which the failure mechanisms were based on small scale experiments. The formation and subsequent progression of the sand plug trapped below a penetrating spudcan is not considered when calculating the penetration resistance in the underlying clay layer. Therefore, the accuracy of the prediction is limited not only by the reliability of the interpreted soil strength parameters, but also by the applicability of the design method currently in use. In this paper, comparisons between the methods recommended in the ISO industry guideline and a recently published method of the full load-displacement profile (called the Hu et al. method here) were made. By back-analysing three field cases, the Hu et al. method shows a significant improvement in predicting the spudcan bearing capacity-depth profile, which could not be achieved by existing methods based on a wished-in-place shallow foundation assuming a single failure mechanism applied repeatedly at different penetration depths. The Hu et al. method captures the essential characteristics of spudcan penetration behavior in sand overlying clay, which in turn enables the potential punch-through failure and the corresponding punch-through distance to be better assessed.

KEY WORDS: Punch-through, spudcan, bearing capacity, offshore engineering, foundations

INTRODUCTION

In offshore oil and gas fields, drilling in water depths up to 120 m are performed from self-elevating mobile jack-up rigs due to their flexibility and cost-effectiveness (Dean [1]). Most of these jack-up rigs are supported by three independently jacked legs with individual footings with conical undersides, commonly called spudcans. When the jack-up rig arrives at a new location, the platform legs are jacked down to the seafloor. Penetration of a jack-up spudcan into the seafloor occurs as the applied bearing pressure exceeds the bearing capacity of the soil at that level of penetration. For single-clay, single-sand and closely stratified profiles consisting of weak soils interbedded with stronger soils, the penetration normally occurs without incident and it can generally be predicted. However, installation of spudcans in sand overlying clay can be accompanied with potential punch-through problems which can subsequently often involve serious structural damage of the jack-up rig (Osborne and Paisley [2]). During punch-through failure, the load-penetration profile comprises of a peak followed by either a reduction in bearing resistance, or a constant bearing resistance with depth. For such profiles settlement of the jackup legs of several metres can occur very rapidly.

Before a jack-up is installed at any site, the spudcan penetration resistance profile must be predicted to identify potential punch-through hazards. While a conservative calculation of bearing capacity is suitable for many geotechnical situations, the full penetration profile of the spudcan needs to be calculated accurately to assess the potential for and severity of a punch-through failure. The construction of a simplified method for design requires interpretation on two stages: (i) the peak resistance in the sand layer, q_{peak}, and (ii) the penetration resistance when the spudcan reaches the depth of the original sand-clay interface and beyond. The bearing capacity for jack-up rig footings on sand overlying clay is usually calculated using the load spread method and punching shear method in the industry guidelines (SNAME [3], ISO [4]). Recently, a new method that accounts for the stress level, dilatant response of sand and the sand plug effect was proposed in Hu et al. [5]. Detailed discussion of the above methods can be found in the next section.

Although a number of small-scale model tests on layered soils involving strong soils overlying weak soils have been performed to validate the above methods (Teh et al. [6],[7]; Lee et al. [8]; Hu et al. [9],[10]), relatively few comparisons have been made with actual full-scale field data. This paper presents three case histories of actual punch-through failure (or prone to failure) that have occurred in three active offshore drilling regions. Observed bearing capacity and penetration are compared with that calculated by the ISO methods and Hu et al. method.

Overview of the prediction methods

Methods in the guidelines

In the SNAME and ISO guidelines, the load spread method and the punching shear method are the two recommended methods to predict the bearing capacity of jack-up foundation in a layered soil system.

The fundamental assumption of the load spread method is that the foundation load is spread through the sand layer and merely supported by the underlying clay as seen in Figure 1(a), described by Equation 1:

$$q_{peak} = \left(1 + 2\frac{H_s}{D}\tan\alpha\right)^2 \left(s_u N_c s_c d_c + q_0\right) \tag{1}$$

where H_s is sand thickness; D is the diameter of the spudcan; α is the projection angle; s_u is the undrained shear strength of clay; N_c is the bearing capacity factor of clay; s_c is the shape factor and d_c is the depth factor; and q_0 is the effective overburden pressure. As the projection angle governs the extent of load spread at the sand-clay interface, it greatly affects the accuracy of the bearing capacity evaluation. In view of the reported wide variation of the projection angle, SNAME and ISO recommended a range of spread from 1:3 to 1:5 (horizontal:vertical) for offshore spudcan foundation design consideration. A load spread ratio of 3 was used in the following comparison as it has been verified for centrifuge experiments in Lee et al. [11] and Hu et al. [9] that a ratio of 3 performs better than a ratio of 5 in predicting q_{peak}.

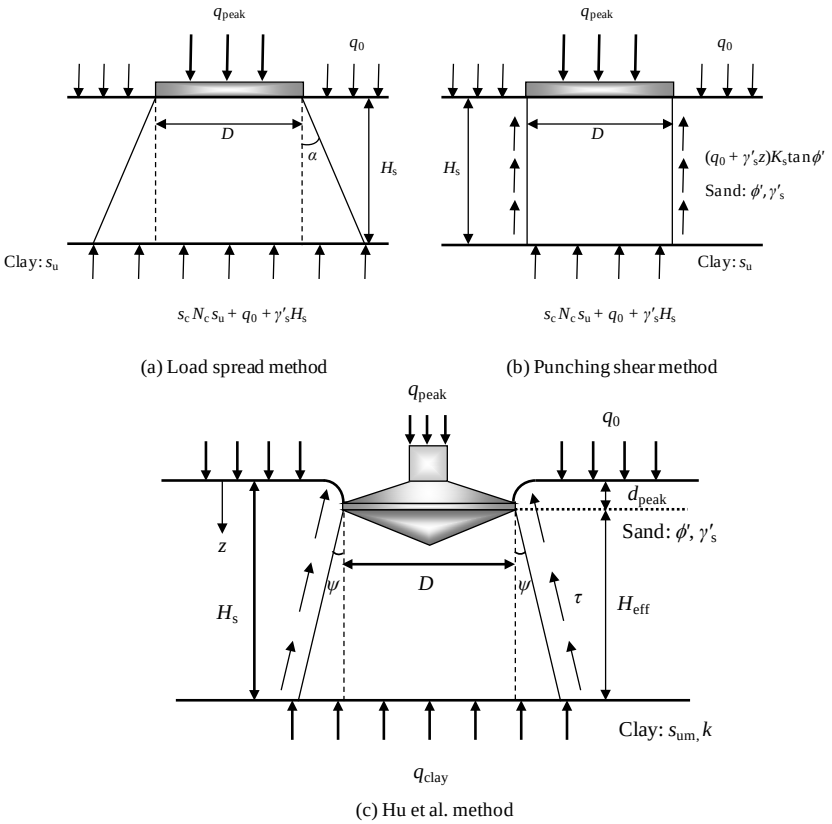


Figure 1 Conceptual model for peak resistance from the ISO load spread method, punching shear method and Hu et al. method

Alternatively, the bearing capacity may be calculated following Hanna and Meyerhof's [13] simplified failure mechanism as shown in Figure 1(b). The foundation bearing capacity on sand overlying clay is comprised of clay bearing capacity and the frictional resistance of the vertical slip surface and it is expressed as:

$$q_{peak} = s_u N_c s_c d_c + \frac{2H_s}{D}\left(\gamma'_s H_s + 2q_0\right) K_s \tan\phi' + q_0 \tag{2}$$

where γ'_s is the effective unit weight of the sand; K_s is the coefficient of punching shear and ϕ' is the sand friction angle. K_s depends on the strength of both the sand and clay layer, and it is obtained from the chart presented by Meyerhof and Hanna [14].

The penetration resistance in the underlying clay, q_{clay}, is expressed below:

$$q_{clay} = s_u N_c s_c d_c + q_0 \tag{3}$$

As recommended in ISO, the expression of N_c from Houlsby and Martin [15] was used in Equation 3. It has been reported in Teh et al. [6], Lee et al. [8] and Hu et al. [10] that a sand plug was trapped underneath the spudcan when it penetrates through the sand layer into the underlying clay layer. However, such sand plug effect is ignored in the current design method.

ISO and SNAME provide Equations 1 and 2 for estimating q_{peak} only. In reality, the spudcan is a rigid body moving downward during the installation rather than at a fixed elevation as in onshore foundation cases. As a standard practice in the industry, the penetration resistance should be calculated all the way through the sand

layer into the clay layer. In practical applications the full profile is obtained through the following procedure: The penetration resistance is initially calculated assuming the spudcan bearing area is at the top of the sand layer. Then, the penetration resistance is calculated assuming the spudcan is at a level (e.g. 1 m) deeper than the sand surface. Calculating all the way down to the bottom of the sand layer and then into the clay layer provides a full load-penetration profile. For the load spread method, the enlarged area projected on the surface of the underlying clay reduces as the spudcan penetrates deeper. For the punching shear method, where the underlying clay bearing capacity remains constant, the shear resistance mobilised along the failure plane in the upper sand layer reduces with penetration of the spudcan. Both phenomena lead to a lower bearing capacity as the spudcan is displaced into deeper soil and the bearing capacity-depth profiles will eventually converge to a minimum value as the spudcan reaches the sand-clay interface.

Hu et al. method

Following the framework proposed in Teh [16] and Lee [17] and based on a series of centrifuge tests and accompanying large deformation finite element analyses, Hu et al. [5] proposed a new method to predict the full profile when spudcan penetrates sand overlying clay. At stage (i), the peak resistance is predicted using a modified failure stress dependent model:

$$q_{\text{peak}} = \left(N_{\text{c0}} s_{\text{um}} + q_0 + 0.12\gamma'_{\text{s}} H_{\text{s}}\right)\left(1+\frac{1.76H_{\text{s}}}{D}\tan\psi\right)^{E^*} + \frac{\gamma'_{\text{s}} D}{2\tan\psi(E^*+1)}\left[1-\left(1-\frac{1.76H_{\text{s}}}{D}E^*\tan\psi\right)\left(1+\frac{1.76H_{\text{s}}}{D}\tan\psi\right)^{E^*}\right] \tag{4}$$

where N_{c0} is the bearing capacity factor for clay at the base of a circular foundation, which is obtained using the relationship proposed by Houlsby and Martin [15] for circular foundation with shear strength increasing linearly with depth:

$$N_{\text{c0}} = 6.34 + 0.56\frac{k\left(D+1.76H_{\text{s}}\tan\psi\right)}{s_{\text{um}}} \tag{5}$$

where s_{um} is the undrained shear strength of clay at the sand-clay interface; ψ is the dilation angle of sand; and E^* is a parameter to simplify the algebra:

$$E^* = 2\left[1+D_{\text{F}}\left(\frac{\tan\phi^*}{\tan\psi}-1\right)\right] \tag{6}$$

where D_{F} is a distribution factor that relates the local stress along the failure surface to the average vertical stress, or the ratio of the normal effective stress at the slip surface to the mean vertical effective stress. For spudcans with conical base greater than 7°, use

$$D_{\text{F}} = 0.642\left(\frac{H_{\text{s}}}{D}\right)^{-0.576} \quad as \quad 0.16 \le \frac{H_{\text{s}}}{D} \le 1.0 \tag{7}$$

whereas for flat footings, use

$$D_{\text{F}} = 0.623\left(\frac{H_{\text{s}}}{D}\right)^{-0.174} \quad as \quad 0.21 \le \frac{H_{\text{s}}}{D} \le 1.12 \tag{8}$$

ϕ^* is a reduced friction angle caused by non-associated flow that can be expressed (after Drescher and Detournay [18]) as:

$$\tan\phi^* = \frac{\sin\phi'\cos\psi}{1-\sin\phi'\sin\psi} \tag{9}$$

One advantage of the model is that it relates the friction angle and dialtion angle of sand to q_{peak} using a modified form of Bolton's [19] equations, i.e.,

$$I_R = I_D\left(Q - \ln(q_{peak})\right) - 1 \qquad 0 < I_R < 4 \tag{10}$$

$$\phi' - \phi_{cv} = 2.65 I_R \tag{11}$$

$$0.8\psi = \phi' - \phi_{cv} \tag{12}$$

where I_R is a dilatancy indicator in degree, I_D is the relative density of sand, Q is the natural logarithm of the grain crushing strength expressed in kPa and ϕ_{cv} is the critical state friction angle.

q_{peak} is obtained through an iteration procedure using Equations (4)-(12) in a spreadsheet analysis. Thus, q_{peak} is a function of the bearing capacity of the underlying clay, the frictional resistance in the sand and the weight of the sand frustrum. The depth of the peak penetration resistance, d_{peak}, is $0.12H_s$, as suggested by Teh et al. [7] and verified through dense and medium dense sand overlying clay centrifuge tests in Hu et al. [9].

For stage (ii), the penetration resistance in the underlying clay is calculated using Equation 13, for which the N_c was summarised based on a comprehensive set of numerical and testing data and it was expressed in Equation 14 (Hu et al. [5]).

$$q_{clay} = N_c s_{u0} + H_{plug}\gamma'_c = N_c s_{u0} + 0.9 H_s \gamma'_c \qquad \left(0.16 \le \frac{H_s}{D} \le 1.00\right) \tag{13}$$

$$N_c = 11\frac{H_s}{D} + 10.5 \qquad \left(0.16 \le \frac{H_s}{D} \le 1.12\right) \tag{14}$$

where s_{u0} is the soil strength at the lowest elevation of the spudcan widest cross-sectional area, H_{plug} is the sand plug height and γ'_c is the submerged unit weight of clay. The above N_c expression accounts for the sand plug effect in mobilising higher clay strength underneath the bottom of the plug.

Verification and Discussion

The Hu et al. method has been verified against 71 sets of centrifuge data from Teh et al. [7], Lee et al. [8] and Hu et al. [9],[10]) and was reported in Hu et al. [12]. The performance of the above methods will be examined through back-analyses of three sets of field data which have typical sand overlying clay soil profiles.

Case history 1

The first case is a punch-through failure that occurred in the South China Sea. This case involved a three-legged jack-up mobile drill rig with footing configuration and dimensions shown in Figure 2(a). Initial leg penetrations

ranged from 3.5 to 5.1 m, measured from seafloor to the tip of the spudcan. Punch-through of the starboard leg occurred during the third round preloading and an additional penetration from 4.7 m to 13.5 m occurred rapidly.

Prior to preloading, the soil investigation was performed by drilling a soil boring to a depth of 40 m. The results of this field investigation are shown in the boring log in Table 1. CPT data in Figure 3(a) showed the first 1.3 m of material was extremely weak, therefore, the equivalent sand thickness was deemed as 4 m, as from 1.3 m to 5.3 m the sand was much stronger. Thus the normalised sand thickness H_s/D was taken as 0.22. Stratum 3 and 4 were composed of clay with slightly different properties, so they were combined as one layer in the current analysis. The shear strength of clay was thus estimated as $s_u = 30 + 1(d - H_s)$, where d is the spudcan penetration depth relative to the lowest level of the spudcan widest cross-sectional area (see Figure 2b).

The load spread method, punching shear method and the Hu et al. method were used to determine the resistance profile, with the design parameters shown in Table 1. The I_D was estimated to be between 35% and 65% for medium sand while ϕ_{cv} was assumed as 31°. Both peak penetration resistance and the punch-through distance were used to evaluate the potential and severity of punch-through failure. The punch-through distance was defined as the distance from the depth of q_{peak} to the depth where $q_{clay} = q_{peak}$.

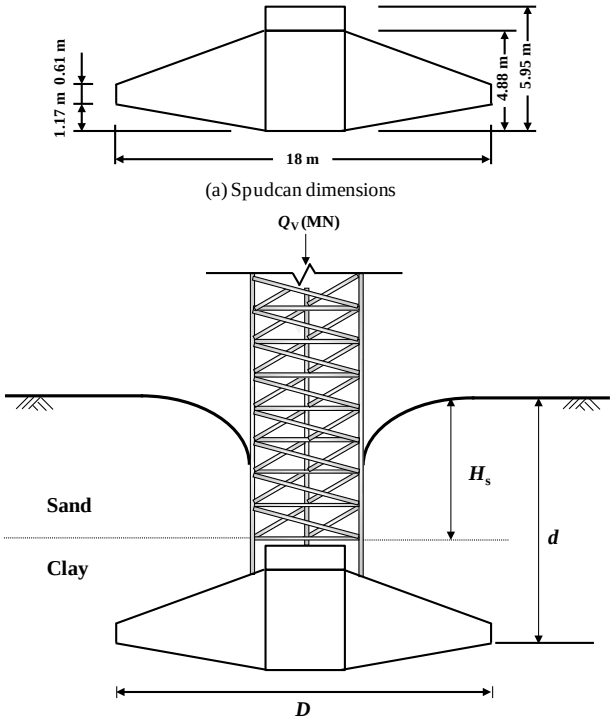
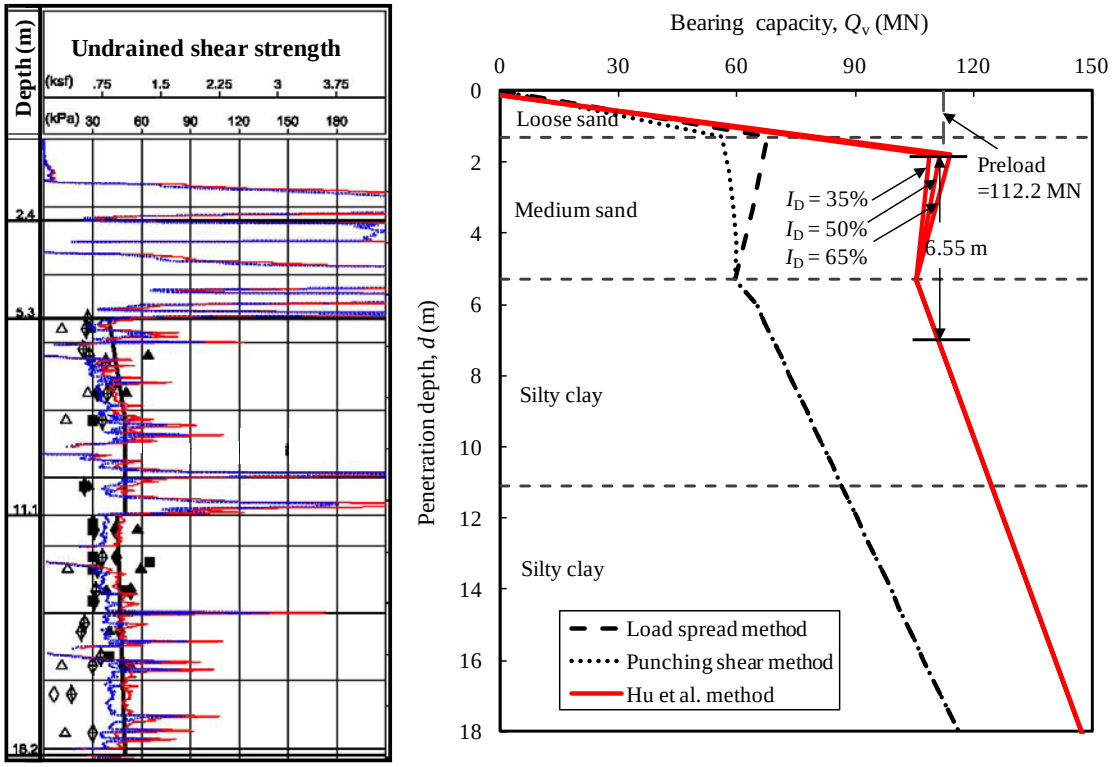


Figure 2 Spudcan dimensions and notations of spudcan penetration in sand overlying clay

As shown in Figure 3(b), both the load spread and punching shear method underpredict the full profile considerably, while the Hu et al. method produces good prediction compared with field measurement. Although punch-through potential was predicted from the load spread method recommended in the ISO guideline, actually it was based on coincidence as both the peak bearing capacity and the bearing capacity in the underlying clay layer were under-predicted significantly. The q_{peak} was underestimted by ~ 40%, while the under-prediction in the clay layer is attributed to the soil plug effect being ignored in the calculation of the bearing capacity in the clay layer. In contrast, the calculated peak bearing capacity from Hu et al. method ranged between 108.9 MPa and 113.9 MPa when H_{plug} was taken as 4 m, which bracket the preload of 112.2 MN recorded in the field. As

punch-through severity is conventionally demonstrated by the 'additional penetration' before the peak resistance is re-established, the punch-through distance was estimated as 6.55 m (based on I_D = 50%) and it is also comparable to the field record of 8.8 m. Both the comparison of peak bearing capacity and punch-through distance validate the effectiveness of the Hu et al. method.



(a) Undrained shear strength test results

(b) Comparison of various prediction method

Figure 3 Undrained shear strength test results and comparison of various prediction method for case history 1

Table 1 Log of boring in South China Sea

Stratum	Soil profile	Soil description	Depth (m)		Submerged unit weight (kN/m^3)	Shear strength of clay (kPa)	
			From	To		From	To
1		loose fine sand	0	1.3	8.7	—	
2		medium silty fine sand	1.3	5.3	8.5	—	
3		silty clay to sandy silt	5.3	11.1	7.1	30	35.8
4		silty clay to sandy silt	11.1	18.2	7.7	35.8	52.9

Case history 2

The performance of the above methods are further validated by back-analysing an in-field event (Case 3) reported by Baglioni et al. [20]. A three-legged jack-up mobile drill rig was installed in the North Sea. The spudcan footing had a diameter, *D*, of 10.67 m and a conical point extending approximately 6.10 m beneath the

lowest elevation of the widest cross-sectional area of the spudcan. The boring log is shown in Figure 4a. This log shows that a fine to silty fine sand layer above a clay deposit. The punch-through distance was not reported.

Based on the spudcan dimensions and measurements given in Figure 4a, the I_D was estimated to be between 35% and 85%, covering the range from loose to dense sand while ϕ_{cv} was assumed as 31°, which is typical of siliceous sands. These values provide bounds for the calcualtion of the peak resistance, which was preferred to inferring the relative density from CPT-based correlation methods. The clay shear strength was taken to increase linearly with $s_u = 24.3 + 2.5(d - H_s)$ kPa. This represents a lower bound on the clay strength, which in turn leads to the lowest bearing capacity in the clay layer and thus the largest punch-through distance. One profile was constructed (based on I_D = 85%) for load spread and punching shear method in the guideline, which represents the most severe scenario for the predictions. Figure 4b presents the penetration force profiles calculated using the Hu et al. method with the upper and lower bounds on the sand relative density. In addition the full profiles predicted by the load spread and punching shear methd are also shown for comparison.

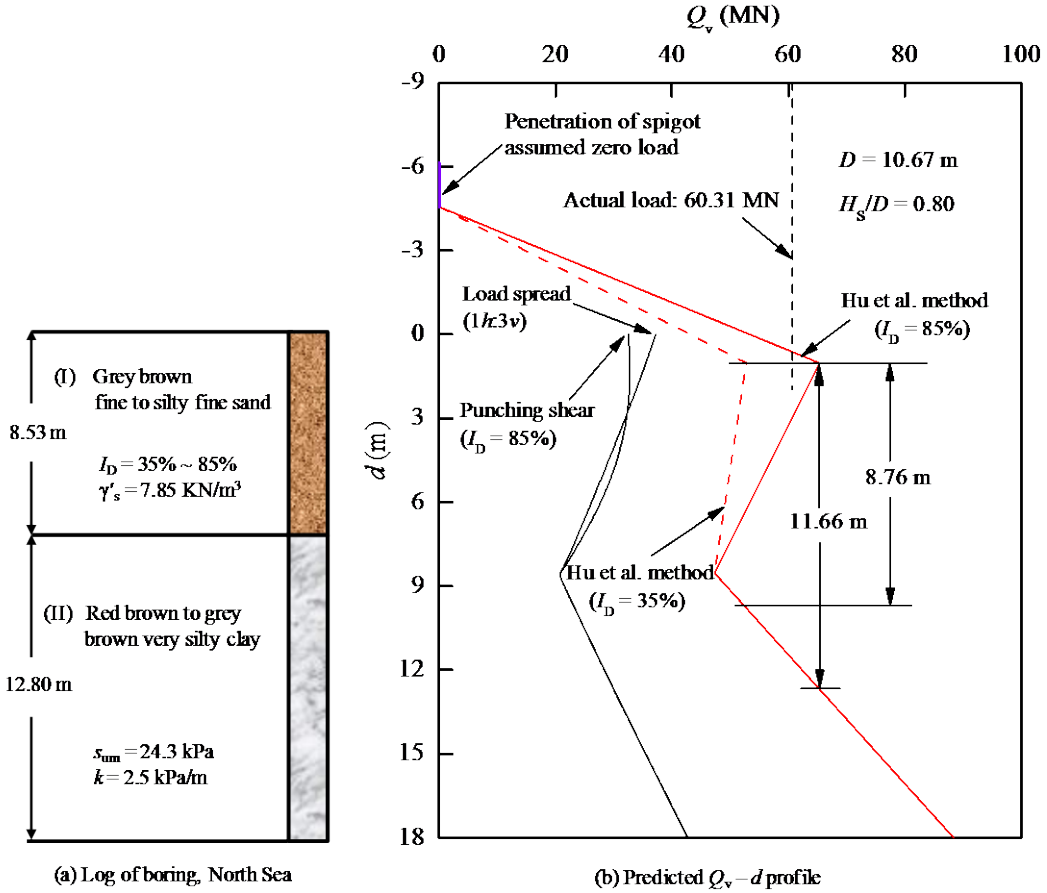


Figure 4. Prediction of full penetration resistance profile based on the parameters from field (*h* = horizontal; *v* = vertical)

When originally installed, the spudcan was preloaded to a maximum of 60.31 MN without experiencing punch-through (thus a punch-through distance was not reported). The Hu et al. method predicts values that bound this preload level of 65.32 MN (I_D = 85%) and 52.75 MN (I_D = 35%) with corresponding punch-through distances of 11.66 m and 8.76 m. These predictions indicate that a severe punch-through failure was a hazard and could have

occurred if the peak resistance had been exceeded. The fact that the spudcan did not experience punch-through indicates that the soil was likely toward the denser bound (I_D = 85%) and thus very close to failure. None of the other methods generate predictions that are close to the applied preload. Though based on the most severe scenario, the peak resistances produced by the load spread and punching shear methods deviated from the preload significantly and they are found to be extremely conservative. About two years after the rig was originally placed on location, a review of the rig stability was necessary to that it could be used as a permanent satellite production facility. Using the original soil investigation information, Baglioni et al. [20] perfomed a revised analysis and indicated that the rig would punch-through if leg loads approached the maximum preload condition. The above predictions are consistent with this findings.

Case history 3

Van Dijk and Yetginer [21] reported a case concerns a Marathon LeTourneau Design, Class 116-C jack-up rig, installed in the Gulf of Mexico. The spudcans were preloaded to 53.4 MN. The spudcan had a dimater of 14 m, effective area of 144 m^2 and a volume of 383 m^3. The soil conditions consisted of a 7 m thick medium dense to dense fine sand layer overlying soft to stiff clay. Figure 5 presents measured s_u, as well as the design lines (best estimate and lower bound estimate) used in this comparison. The sand was treated as medium dense sand with an I_D of 65%, considering the limited soil parameters made available.

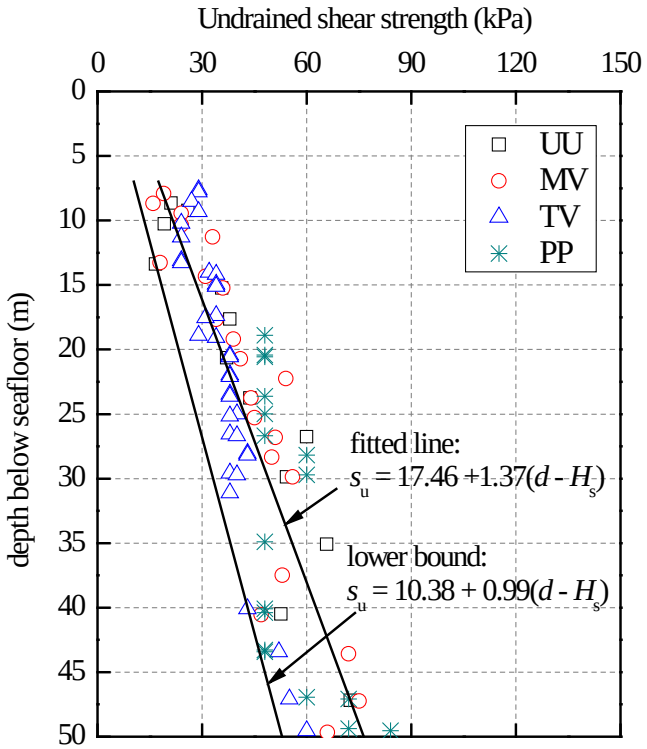


Figure 5. Interpreted undrained shear strength data

Predictions and measured spudcan penetrations are presented in Figure 6. It is noted that, between 0.7 m and final penetration depth, the measured vertical bearing capacity has been estimated in Van Dijk and Yetginer[21] considering percentages of applied load and hull buoyancy. Measured spudcan penetrations show punch-through at approximately 0.7 m (4 m measured from the tip of the spudcan) near the preload. This is similar to the prediction of Hu et al. method, which predicted the maximum preload at the depth of 0.84 m. However, the load spread method can only predict the maximum preload at the soil surface.

The load spread method anticipated punch-through for a spudcan load between 20 MN and 34 MN, i.e., much less than the reported leg load between 53 MN and 56 MN at which punch-through occurred. Using similar soil strength parameters, the re-evaluation was carried out using Hu et al. method. Based on the fitted s_u line, the Hu et al. method assessed a punch through load of 60.9 MN, close to the measured preload, though the punch-through distance was underestimated. Although the preload was underpredicted by 20% based on the lower bound analysis, the spudcan penetration would terminate at ~ 15.7 m at the preload of 53 MN, which is comparable to the field measurements between 15.2 and 17.7 m. Compared with the load spread method, the Hu et al. method has better prediction on the preload and the full profiles are bounded by the best and lower bound estimates.

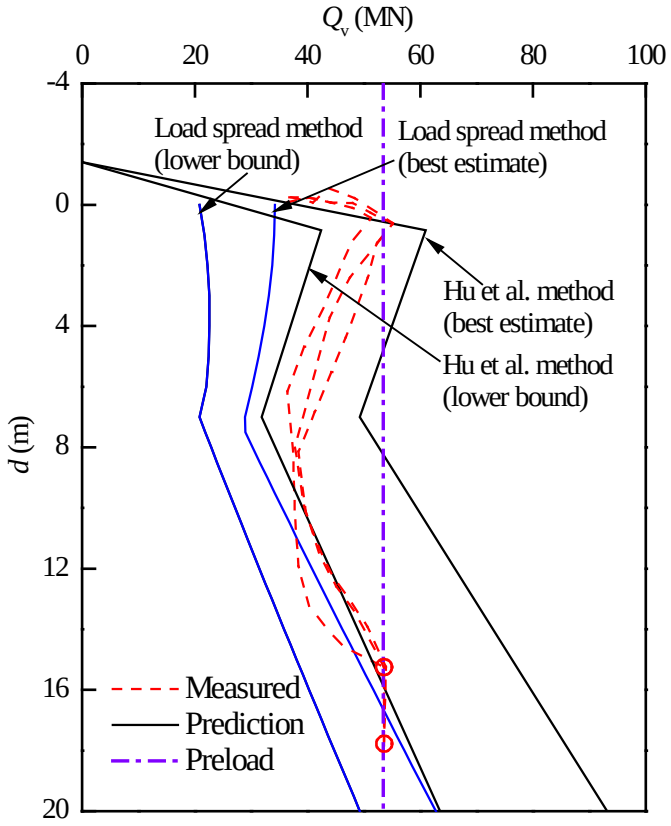


Figure 6. Measured penetration and predictions for case history 3

Conclusions

Theoretical bearing capacities of the jack-up spudcan bearing in sand over clay were computed using the methods recommended in SNAME [3] and ISO [4] and the Hu et al. method for three case histories. Comparisons on the measured and predicted peak bearing capacity and punch-through distance were made where possible and the following conclusions were obtained:

1. The existing methods in the guidelines are based on a wished-in-place shallow foundaiton assuming a single failure mechniasm applied repeatedly at different penetration depths. A limitation with the guideline methods is the general lack of consideration of the plug of soil trapped beneath the spudcan during penetration in the underlying clay layer. During a punch-through failure, the plug base, where end bearing resistance is mobilised, is located in the underlying clay and moves down with the advancing spudcan. The frictional resistance around the periphery of the accumulating soil plug augments the penetration resistance, an asepct that should be

considered in the methods recommended in offshore industry guidelines. Ignoring this aspect can lead to significant underestimation of the bearing capacity in the underlying clay.

2. Both the load spread method and punching shear method are observed to under-predict the bearing capacity of the soil when a spudcan penetrates sand overlying clay. In general, the Hu et al. method shows an improvement in predicting the spudcan bearing capacity-depth profile, which is illustrated by the comparison with field data.

3. Apart from the spudcan full penetration-resistance profile, comprehensive soil data was also not available for all the cases investigated here. This possibly causes differences between predictions and measurements. The observed discrepancy in the predictions is mostly due to variances in data interpretation and selection of parameters. This paper illustrates that the accuracy of any prediction depends not only on the quality of the data and parameter selection, but also on the sophistication of the prediction method.

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