BACK-CALCULATED FRICTION ANGLES FROM 716 SPUDCAN PENETRATION RECORDS IN UNIFORM AND LAYERED SANDY SEABEDS

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ABSTRACT

The accurate prediction of spudcan penetrations into sand has many consequences to the assessed operability of a jack-up at a given location. Existing standardised approaches for predicting penetrations, such as those provided in ISO 19905-1 (2023), are typically based on general bearing capacity equations using sand friction angles inferred from CPT or laboratory data acquired at the planned installation location.

This study presents the findings from an extensive dataset of penetration records of spudcans in sandy soil profiles which have been used to back-calculate the corresponding operative friction angle. Building on previous work, records from offshore wind farm locations and layered sand profiles have been considered from which the correlation between the operative friction angle and the spudcan diameter and the sand's relative density inferred from CPT data has been examined.

This work provides predictive intervals that bound the appropriate friction angle values to be used in conjunction with the classical bearing capacity formulae and associated factors provided in ISO 19905-1 (2023) that should allow for more reliable assessments of both jack-up foundation capacities and stiffnesses, and the potential for seabed risks.

KEY WORDS: Foundation; Spudcan; Bearing Capacity, Sand; Friction Angle

INTRODUCTION

A critical aspect of a jack-up unit's site-specific assessment is the accurate prediction of the depth into the seabed that its spudcan foundations will penetrate during installation. For locations with a cohesionless seabed, key parameters such as the jack-up unit's foundation capacities and stiffnesses, available leg length and scour risk rely on the accurate prediction of its spudcans' penetration depths.

The selection and estimation of the appropriate friction angle, φ', to use in spudcan penetration predictions poses challenges – mainly due to the difficulty in acquiring undisturbed samples for testing, the inherent uncertainty from the use of correlations, and the complexity in defining the appropriate "operative" friction angle to use in conventional bearing capacity equations used in standards such as ISO 19905-1 (2023) [1].

White et al. [2] highlighted the three key challenges faced in accurately predicting the penetrations of spudcans in sand: selection of the appropriate bearing capacity factors, scale effects arising from spudcan geometry, and the selection of the operative friction angle.

Martin [3] addresses the first of these challenges with theoretical solutions using flat, rough, circular footings that have since been incorporated into the ISO 19905-1 standard. Additional factors are also provided in ISO 19905-1 from Cassidy and Houlsby [4] from wished-in-place conical footings.

White et al. [2] studied the second challenge using centrifuge tests with various spudcan diameters, and found larger spudcan diameters mobilise lower peak friction angles and less dilation due to the lower mean effective stresses occurring along the failure mechanisms and greater variation in friction angle mobilised along their longer

failure planes. It is noted that the SNAME [5] Guideline recommends applying a friction angle reduction of 5° to larger spudcans to account for 'scale effects'.

The third challenge in selecting an operative friction angle proves to be more complex, with practitioners often using different correlations to derive an appropriate operative friction angle, sometimes using correlations with the sand's relative density.

Penetration response in homogeneous sand profiles

Smith & Edwards [6] back-analysed 384 spudcan penetration records from a range of spudcans and locations with relatively homogeneous sandy seabeds to explore the relationship between the sand's relative density, inferred using the CPT-based correlation proposed by Baldi et al. (1986) [7], and the operative friction angle and to compare with the findings of White et al. [2].

Smith & Edwards [6] observed the back-calculated operative friction angle of the sand to have a weak, positive correlation with the relative density and a weak negative correlation with the spudcan diameter, as shown in Figure 1. It can also be seen that the range of friction angles proposed in White et al.'s framework [2] followed a broadly similar trend with relative density to the back-calculated friction angles, but the variation with spudcan diameter was too small to adequately represent the observed penetration records, lying at the high end of the back-calculated friction angles. Smith & Edwards [6] did note a similar trend to White et al. [2] and Edwards et al. [8] whereby larger spudcans were observed to mobilise a lower operative friction angle than smaller spudcans, for a given relative density.

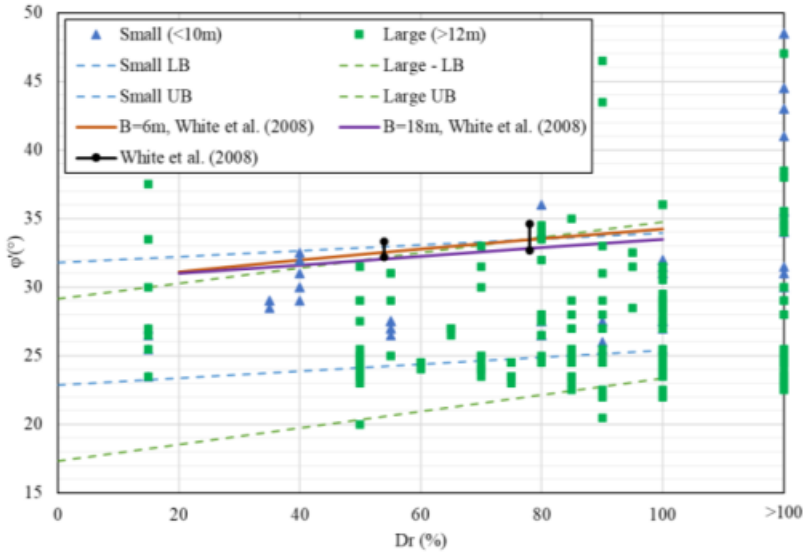

Figure 1 Comparison of linear 80% predictive intervals illustrating the relationship between the back-calculated operative friction angle and the derived sand relative density, experimental model test data in medium dense and dense sands (in black) and predicted values from White et al. [2], from Smith & Edwards [6].

Penetration response in looser-over-denser sand profiles

Jack-up units are frequently installed into seabeds comprising layered sand deposits in areas such as the North Sea, the Gulf of Thailand, the South China Sea, the Arabian Gulf and offshore India [9]; the existence of such layering further complicates the selection of appropriate operative friction angles when predicting spudcan penetrations.

Kim et al. [10] reviewed past studies into the effect of layered sand deposits on the ultimate bearing capacity of a spudcan, or other shallow footing. They also used 3D large displacement finite element analyses (3D LDFE) to

perform a parametric study using differing thicknesses of top sand layers of differing relative densities for both denser-over-looser, and looser-over-denser sand profiles, and also considered the effect of spudcan size on the penetration response. The study found that for a spudcan penetrating into looser-over-denser deposits, the looser, top layer has minimal effect on the ultimate penetration resistance which is, instead, governed by the underlying denser layer. For the most extreme case they investigated, the analysis using a sand with a very loose 15% relative density of 5m thickness over a very dense layer with 100% relative density showed only the initial penetration response was influenced by the looser sand's properties. As the spudcan penetrated toward the denser layer of sand, the observed penetration resistance merges with the response of that of a spudcan penetrating into a uniform very dense sand.

OBJECTIVE

Building on the work in Smith & Edwards [6], this study examines further the effect of relative density and spudcan size on the back-calculated operative friction angle in sandy seabed profiles through the addition of further offshore wind farm penetration records. Additional case histories for soil profiles comprises looser sand layers overlying denser sand layers have also been analysed to explore the effect of the looser sand layer upon the penetration response into a sandy seabed with the aim to verify, or otherwise, the conclusion of Kim et al [10] that the looser shallow sand has an insignificant effect upon the penetration resistance.

DATASET SELECTION

Data for this study was drawn from DNV's extensive database of spudcan penetration records from both oil and gas drilling rigs and offshore wind turbine installation vessels. The jacking records were screened to only include locations with predominantly sandy seabeds for this study. Any sites with carbonate sands, calcarenite or cemented soils, or where clay layers would have influenced the penetration responses, were excluded.

716 individual leg penetration records, for spudcan diameters between 6m and 18m and preload bearing pressures between 370 kPa and 1250 kPa are represented in this study. The records include both fully and partially penetrated spudcan records. Partial penetration is defined here as a spudcan tip penetration into the seabed that is less than the height difference between the spudcan's tip and its lowest elevation of maximum bearing area, (referred to here as the '*tip length*'), as illustrated in Figure 2.

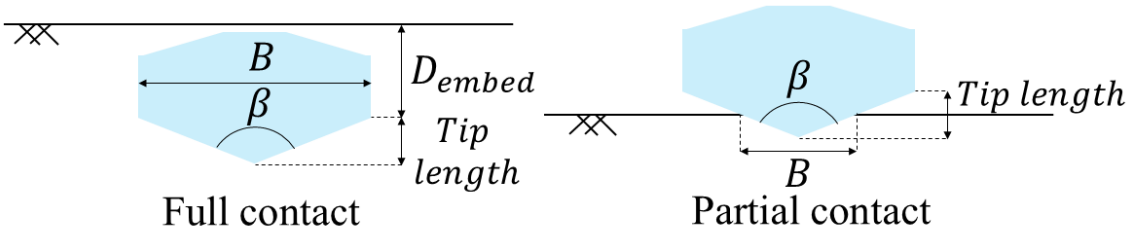

Figure 2 Key dimensions and terminology for fully and partially penetrated spudcans

Based on our extensive database of spudcans, the records were divided into categories of "small", "intermediate" or "large" spudcans, where "small" denotes any spudcan with an equivalent diameter less than 10m, "intermediate" denotes spudcans with an equivalent diameter between 10 and 12m, and "large" for spudcans with an equivalent diameter greater than 12m.
Smith & Edwards [6] used category definitions based on the **maximum** equivalent spudcan diameter. To better explore how the definition of spudcan size may affect the operative friction angle in records with partially penetrated spudcans, these size categories have been refined in the present study, to consider the spudcan-soil **contact** diameter corresponding to each penetration record, not the spudcan's maximum spudcan diameter.

Figure 3 presents the distribution of the equivalent spudcan diameters considered within the dataset. A total of 24 jack-up units were represented in this study's dataset.

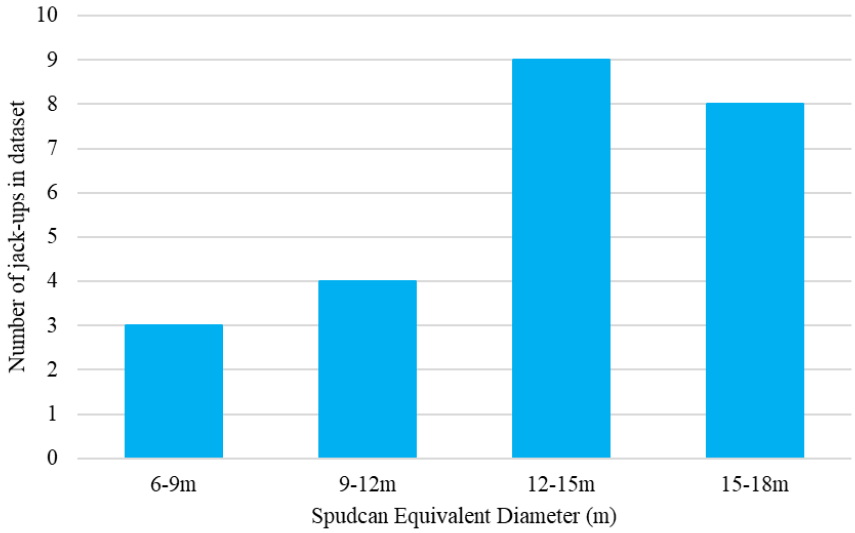

Figure 3 Distribution of equivalent spudcan diameters considered within this study's dataset

DATASET ANALYSIS

Back-calculations of the operative friction angle φ' were conducted iteratively using the bearing capacity equation given in ISO 19905-1 :

$$V = \frac{\pi\gamma' B^2}{8}(2d_q N_q D_{embed} + B d_\gamma N_\gamma) \qquad (1)$$

where V (kN) is the gross vertical bearing capacity, assumed to be equal to the applied preload at the spudcan, γ' (kN/m^3) is the submerged soil unit weight, B (m) is the spudcan diameter in contact with the soil, and D_{embed} (m) is the penetration depth of the lowest elevation of the spudcan's maximum bearing area. N_q and N_γ are the bearing capacity factors for surcharge and self-weight terms for circular footings in the general bearing capacity equation and d_q and d_γ are the associated depth factors (noting that d_γ = 1).

Values for the N_q and N_γ factors were derived using the software ABC [3] for a flat, rough circular footing; these are the same as those provided in the main informative text in ISO 19905-1 [1], however the software permits the calculation of bearing capacity factor values for a greater range and resolution of friction angles than those provided in ISO 19905-1. The assumption of perfect spudcan roughness is arbitrary, and was made for consistency with White et al. [2]. As the precise roughness of a spudcan is unknown, some kind of arbitrary roughness assumption is required. For practical application it is the combination of operative friction angle and corresponding bearing capacity factors that is required to predict bearing capacity. For example, if smooth bearing capacity factors had been used, higher operative friction angles would have been obtained in this study, but they would likely result in the same predictive accuracy.

All γ' values were set to typical values of 9.5 kN/m^3 for sand for this study's back-analysis. It is noted that the bearing capacity is relatively weakly dependent upon γ' compared to the operative friction angle.

The partially penetrated records used a similar approach, accounting for the precise spudcan-seabed contact diameter based on the detailed geometry of each spudcan.

It is noted that small inaccuracies in the reported penetrations can have a significant influence upon the back-calculated value of N_γ and hence operative friction angle. As noted in Edwards et al. (2013) [8], spudcan penetrations can typically only be estimated to within an accuracy of ±0.3m (1ft) which can result in a relatively large scatter in the back-calculated friction angles, especially for partially penetrated spudcans.

Sand relative density

The soil profiles' relative densities were derived using the CPT-based correlation for normally consolidated sands from Baldi et al. [7]. Whilst other correlations could have been used, the purpose here is to assess whether there is a trend between the sand's relative density and the back-calculated operative friction angle; it is not expected that alternative correlations would significantly alter this study's findings.

Any records without CPT data, or where this determination was not obvious or reliably possible, were discarded for this exercise.

Derived D_r values have been capped at 100%; any values greater than 100% were ascribed an indicative D_r value of >100% for presentation purposes, as it is likely that those sands were overconsolidated. Those penetration records were excluded from the statistical correlation between friction angle and relative density presented later in this paper.

For the looser-over-denser sand penetration records, two values for relative density were derived – one for the looser, top layer, and the other for the denser, bottom layer. The top layers' densities were noted to be between very loose to medium dense sand whilst the bottom layers were described as either dense, dense to very dense, or very dense sand.

RESULTS

The results are presented here in terms of the spudcan-soil contact diameter (small, intermediate or large); the number of records for each spudcan size and soil condition are summarised in Table 1. Many of the records from the dataset used by Smith & Edwards [6] that were categorised as large in that study have, in this study, been reallocated to the small or intermediate categories based on the spudcan-soil contact diameter definition.

Table 1. Distribution of penetration records with spudcan size and soil profile.

	Spudcan size		
Soil Profile	**Small**	**Intermediate**	**Large**
Looser-over-denser	102	63	4
Uniform	253	39	255
Total	**355**	**102**	**259**

A large proportion of the smaller spudcans achieved full contact into the seabed, whereas the larger spudcans only achieved full contact into the seabed in around half of the cases.

Back-calculated operative friction angles in looser-over-denser sand profiles

Figures 4 and 5 plot the back-calculated operative friction angles from the penetration records for the looser-over-denser soil profiles against the derived relative density inferred for the top and bottom layers, respectively.

For both the top and bottom layers, no strong correlation is observed between the back-calculated operative friction angle and the layer's derived relative density for all spudcan size categories. Intuitively, one would expect a positive correlation between the soil's relative density and back-calculated friction angle, however only the records within the Small spudcan-soil contact diameter category suggested such a correlation with the top layer's relative density and only the Intermediate spudcan-soil contact diameter category suggested a positive correlation with the lower sand layer's relative density. The latter would seem unusual compared to the other spudcan sizes, so is likely a result of a limited number of data points.

It is notable, however, that when compared to the data presented later in this paper in Figure 7, the back-calculated friction angles for each spudcan size are within the range expected for denser sands, not looser sands, implying that the upper layer does not influence the penetration response of the spudcans. This observation agrees with the conclusions made by Kim et al. [10] who concluded that spudcan penetration response in looser over denser sands was dominated by the denser, lower layer.

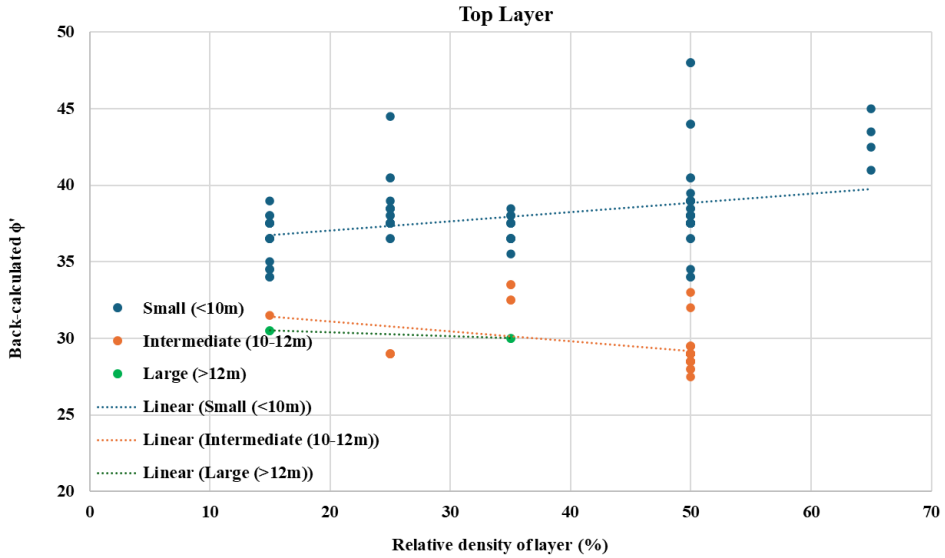

Figure 4 Back-calculated friction angle against derived relative density of the top, looser sand layer

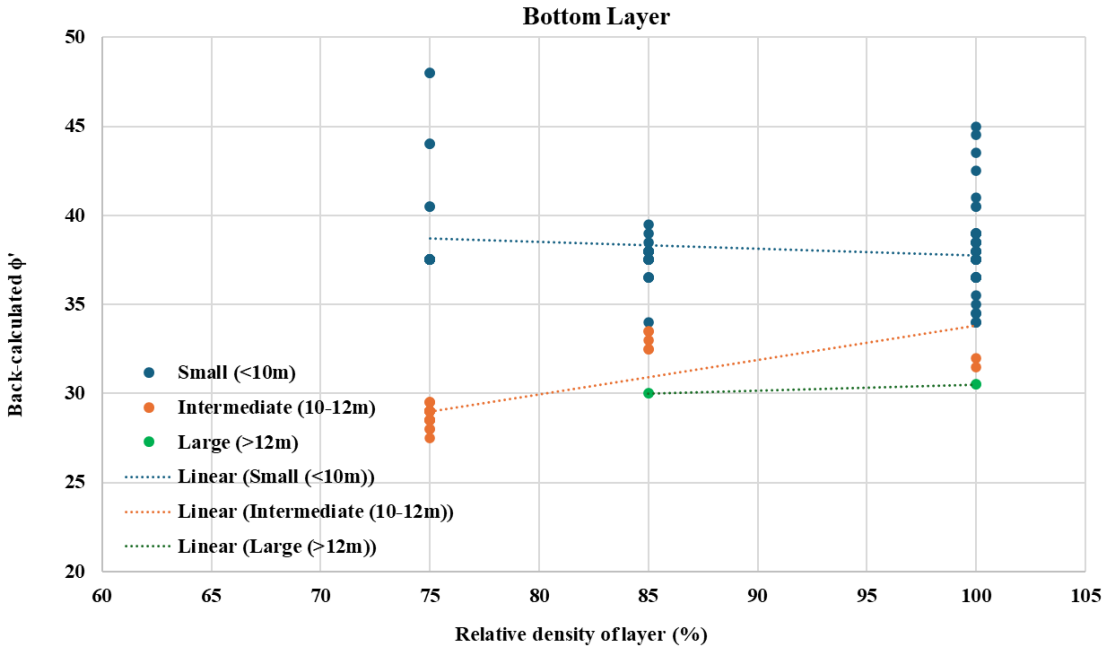

Figure 5 Back-calculated friction angle against derived relative density of the bottom, denser sand layer

Back-calculated operative friction angles

Figure 6 presents the normalised, cumulative frequency plot of the back-calculated operative friction angles, φ', for the 716 spudcan penetration records collated. The range of back-calculated operative friction angles for the Small spudcan-soil contact diameter category is noted to be larger than for the Intermediate and Large diameter spudcan categories.

It is noted that approximately 80% of the back-calculated operative friction angles in the intermediate category and almost all of the large category records are less than or equal to the typical critical state friction angle for sand of 32° (Randolph, et al. [11]). The small category results showed only around 35% of records with an operative

friction angle less than or equal to the typical critical state friction angle value of 32°. This may be due to the assumption of perfectly rough spudcan-sand contact, which results in lower operative friction angles than if a less rough contact assumption had been made.

A general trend can be seen in Figure 6 whereby larger spudcans typically mobilise a lower operative friction angle compared to their smaller counterparts, however more detailed conclusions cannot be drawn without considering the corresponding sand relatively density for each case to ensure penetration records for similar soil properties are compared.

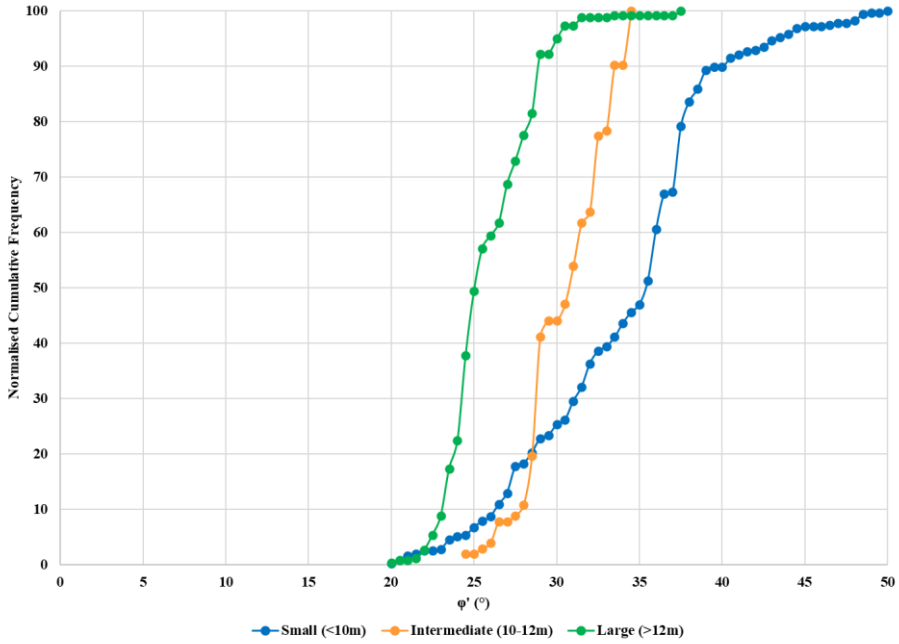

Figure 6 Normalised cumulative frequency curves of the penetration records' back-calculated operative friction angles

Correlation between operative friction angle and relative density

Figure 7 plots the back-calculated operative friction angles against the inferred sand relative density for the three spudcan size categories and the associated 90% confidence intervals using linear regression. The aim of the confidence intervals is to both provide a visual representation of the data distribution that accounts for overlapping data points with the same D_r, φ' combination (which cannot be visualised in the plot), and to bound the range of values practitioners may use in practice in their assessments. The looser-over-denser penetration records included have used the relative density corresponding to the bottom denser sand layer, given the earlier findings that the penetration response appears to be governed by the bottom sand layer.

A very weak positive correlation can be seen in the confidence interval lines between the back-calculated operative friction angle and relative density for large spudcans (over 12m in effective diameter) – $\delta\varphi' = 0.6°$ between $0 < D_r < 100\%$. A stronger positive correlation is observed for penetration records with effective diameters less than 12m ($\delta\varphi' = 11.8°$ between $0 < D_r < 100\%$ for the small category, and $\delta\varphi' = 9.7°$ between $0 < D_r < 100\%$ for the intermediate category). It is also noted that the confidence interval lines for the small and intermediate categories have similar gradients and the lower bound intervals both start at around $\varphi' = 20°$ for $D_r = 0\%$.

Whilst the small and intermediate categories both show a positive correlation between relative density and back-calculated operative friction angle, the range between upper and lower confidence intervals is over double in the small category than those in the intermediate. The larger scatter in data seen in the small category may be attributed

to the fact that the definition of the category covers all effective diameters between 0 and 10m, whereas the intermediate category only covers effective diameters between 10 and 12m.

The confidence intervals for the large spudcans are lower than those of the small and intermediate spudcans. This observation is consistent with the conclusion of White et al. [2] that a larger spudcan will mobilise a lower friction angle due to its lower mean effective stresses along its failure planes. The Small category's confidence intervals reach the highest friction angle values; which may be attributed to the large bearing pressures on the areas of the spudcan in contact with the seabed and smaller failure mechanisms which White et al. [2] suggested are more likely to simultaneously mobilise the peak friction angle.

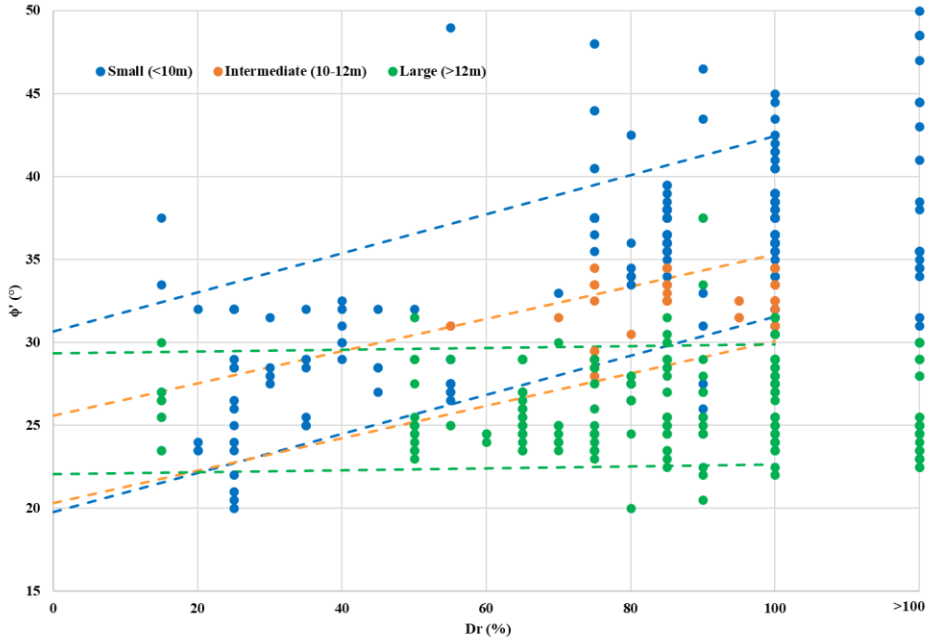

Figure 7 Back-calculated friction angle vs. relative density with confidence intervals for each spudcan size category

IMPLICATIONS FOR SPUDCAN PENETRATION PREDICTIONS

The data presented in Figure 7 indicate that operative friction angles are significantly less sensitive to the sand relative density than is typically assumed by practitioners when deriving appropriate design friction angles for penetration predictions of large spudcans in sand. However, a positive correlation can be seen in the small and intermediate size categories, suggesting that relative density does play a role in the operative friction angle mobilised by such spudcans.

The predictive intervals presented in Figure 7 for each spudcan size could provide a rational, and more realistic, basis for bracketing the range of design friction angles for use in practice. In particular, a lower bound operative friction angle of 22° would seem to provide a sensible lower limit to the range of friction angles for most situations and spudcan sizes.

Small diameter spudcans, or spudcans that are predicted to achieve spudcan-soil contact diameters less than 12m, will mobilise higher operative friction angles that will depend upon the sand's relative density.
If the spudcan is predicted to achieve a spudcan-soil contact diameter that is greater than 12m, the operative friction angle mobilised will reduce to a value between 22° and 30°.

Such a situation implies that a multi-step, or iterative, process may be needed in order to incorporate such variations with contact diameter into a spudcan penetration predictions; this would be more likely to be required for spudcans

with larger maximum diameters. The spudcan penetration analysis could first be calculated using friction angle ranges corresponding to the sand relative density for a small spudcan diameter (<10m); if any spudcan is predicted in this initial step to achieve a spudcan-soil contact diameter that is greater than 10m, then the calculation should be repeated using the appropriate range based on either the intermediate or large category, and so on.

In order to avoid step changes in the operative friction angle ranges used, the ranges should ideally be based on a continuous expression related to the spudcan-soil contact diameter, however due to time constraints it has not yet been possible to develop this further refinement.

CONCLUSIONS

716 spudcan penetration records have been assembled, categorised and analysed in order to investigate the effect of a number of variables upon the operative friction angle for use in spudcan penetration predictions using the exact bearing capacity factors included within ISO 19905-1 [1]. The key findings from this study are:

- It is important to account for the spudcan-soil contact diameter corresponding to the reported spudcan penetration depth when analysing and categorising spudcan penetration records.
- By incorporating the spudcan-soil contact diameter, a more rigorous analysis of spudcan penetration records has been achieved compared to that reported in Smith & Edwards [6].
- The range of back-calculated operative friction angles increases with reducing spudcan-seabed contact diameter.
- The results show that smaller spudcan-soil contact diameters mobilise higher operative friction angles, likely due to the higher mean effective stresses within the soil at failure.
- Situations that result in smaller spudcan-soil contact diameters would be expected to have higher bearing pressures and hence soil compressibility may also play more of a part compared to lower bearing pressure scenarios. Greater compression of sand would be expected to occur for looser sands, which may explain why the observed sensitivity of the mobilised operative friction angle to the sand relative density reduces with increasing spudcan-soil contact diameter, becoming almost zero for spudcan-soil contact diameters > 12m.
- Spudcans that are predicted to achieve spudcan-soil contact diameters > 12m are observed to mobilise an operative friction angle of between 22 and 30 degrees that is not influenced by the sand's relative density.
- Spudcan penetration records in looser-over-denser sand soil profiles resulted in back-calculated operative friction angles that closely resembled those of the lower denser sand. Consequently, it is concluded that the presence of a thin loose sand layer overlying denser sand layers can effectively be ignored without significant error in spudcan penetration analyses, endorsing the findings of Kim et al. [10].
- To account for these findings, the selection of the operative friction angle will need to include consideration of the predicted spudcan-soil contact diameter and multiple steps may be required to determine the appropriate final operative friction angle for the spudcan penetration prediction.

The authors hope to further analyse the current dataset to further develop a comprehensive framework for predicting spudcan penetrations in sand that can also account for factors such as the preload bearing pressure and that can provide a continuous relationship between the operative friction angle and spudcan-soil contact diameter.

LIMITATIONS

It is emphasised that the results and recommendations stated here are for friction angles to be used with the rough bearing capacity factors for flat footings derived by Martin [3] that are included in the current version of ISO 19905-1 [1]. Furthermore, the relative densities stated herein are calculated using the CPT-based relative density correlation for normally consolidated sands developed by Baldi et al. [7].

REFERENCES

[1] ISO 19905-1:2023(E) Oil and gas industries including lower carbon energy – Site-specific assessment of mobile offshore units – Part 1: Jack-ups: elevated at a site.

[2] White DJ, Teh KL, Leung CF & Chow YK. A comparison of the bearing capacity of flat and conical foundations on sand. Géotechnique:2008 58(10), p. 781-792.

[3] Martin CM. User Guide for ABC - Analysis of Bearing Capacity. Department of Engineering Science, University of Oxford, United Kingdom, 2004.

[4] Cassidy MJ & Houlsby GT. Vertical bearing capacity factors for conical footings on sand. Géotechnique:2002 52(9), p. 687-692.

[5] The Society of Naval Architects and Marine Engineers. Guidance for Site Specific Assessment of Mobile Jack-Up Units, Technical and Research Bulletin 5-5A Rev. 3 including Corrigenda. USA, 2016.

[6] Smith SK & Edwards, DH. Back-calculated operative sand friction angles from 384 spudcan penetration records in sandy seabeds. In: Proceedings of 5th International Symposium on Frontiers in Offshore Geotechnics, Nantes, 2025, p. 2560-2565.

[7] Baldi G, Bellotti R, Ghionna V, Jamiolkowski M & Pasqualini E. Interpretation of CPTs and CPTUs. 2nd Part: Drained Penetration. In: Proceedings of 4th International Geotechnical Seminar, Singapore, 1987, p. 143-156.

[8] Edwards D, Bienen B, Pucker T & Henke S. Evaluation of the performance of a CPT-based correlation to predict spudcan penetrations using field data. In: Proceedings of the 14th International Conference: The Jack-Up Platform – Design, Construction & Operation, London, 2013.

[9] InSafeJIP, Improved Guidelines for the Prediction of Geotechnical Performance of Spudcan Foundations During Installation and Removal of Jack-up Units, 2011.

[10] Kim YH, Hossain MS, Edwards D & Wong PC. Penetration response of spudcans in layered sands. Applied Ocean Research 82:2019, p. 236-244.

[11] Randolph MF, Jamiolkowski MB & Zdravkovic L. Load carrying capacity of foundations. In: Proceeding of the Skempton Memorial Conference, London, p. 207-240.