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Back-calculated operative sand friction angles from 384 spudcan penetration records in 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. Various approaches are, however, used by practitioners to define the appropriate design friction angle to use as input into the calculations as limited detailed guidance is currently provided in the associated standards.

This study presents the findings from 384 penetration records of spudcans in relatively homogeneous sand soil profiles which have been used to back-calculate the corresponding operative friction angle. The correlation between the operative friction angle and the spudcan diameter, and the sand's relative density inferred from CPT data has also been examined and compared with the results and predictive framework proposed by White et al. (2008).

This work provides an extensive dataset and 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.

Keywords: Foundation; Spudcan; Bearing Capacity; Sand; Friction Angle

1 INTRODUCTION

A critical aspect of a jack-up rig's site-specific assessment is the accurate prediction of the depth into the seabed that its spudcan foundations will penetrate during installation. Where a jack-up is installed at a location with a cohesionless seabed, a range of key parameters will depend upon the spudcans' penetration depth, such as the jack-up unit's foundation capacities and stiffnesses, its available leg length for jacking up to an operational airgap, and the assessed scour risk potential. An accurate assessment of the spudcans' bearing capacity as they penetrate into the seabed is therefore imperative to avoid unnecessary conservatism whilst also ensuring an accurate assessment of any associated foundation risks.

The estimation of the appropriate friction angle, φ', used in the prediction of spudcan penetrations in sand is challenging. The key reasons for this are the difficulty in acquiring undisturbed samples for laboratory testing, the uncertainty in deriving the friction angle from in-situ tests using correlations, and the complexity of defining the appropriate 'operative' friction angle to use in the conventional bearing capacity equations used in standards such as ISO 19905-1 (2023).

1.1 Background

Edwards et al. (2013) and White et al. (2008) have both covered the background to this issue in detail. The former discusses the practical aspects related to jack-ups and approaches being used in industry and used spudcan penetration data from 111 jack-up installations by two jack-ups to evaluate the approach described in the SNAME 5/5A Recommended Practice (2016) and an alternative method proposed by Pucker et al. (2013) that uses the CPT cone resistance profiles directly to predict spudcan bearing capacity. Although the latter provided an improved prediction, both approaches predicted penetrations that were deeper than those observed, especially in looser sands. This is problematic as overpredictions of penetration could result in an underestimation of the scour risk around the spudcans, and overestimate the foundation capacities and stiffnesses.

White et al. (2008) highlighted the three key challenges to accurately predicting the penetration of spudcans in sand:

1. The appropriate bearing capacity factor
2. Foundation 'scale effects'
3. Selection of the operative friction angle

The first of these three has theoretically been addressed by the exact solutions derived by Martin (2004) for flat circular footings for the self-weight and surcharge bearing capacity factors, N_γ and N_q respectively. These factors have been incorporated within ISO 19905-1 (2023) for jack-up site assessments. The standard also includes, as an alternative approach, the lower bound bearing capacity factors derived by Cassidy & Houlsby (2002) for wished-in-place footings with conical bases which, for most typical spudcan geometries, are noted to be approximately 10% higher than the corresponding factors for flat circular footings given by Martin (2004). Whilst the use of the conical bearing capacity factors may give more accurate bearing capacity predictions, the magnitude of improvement would be overshadowed by the larger uncertainties associated with the selection of the operative friction angle.

White et al. (2008) conducted centrifuge model tests of footings with prototype diameters of between 0.6 and 4.8m and noted that the back-calculated bearing capacity factors, N_γ, for the conical-based model footings were *lower* than those obtained for the flat-based model footings, a pattern also observed by other researchers. For dense sand, the factors were half those for flat footings; a smaller difference in bearing capacity factors was observed for medium dense sand. The differences were attributed to the progressive failure of the sand as the conical base of the spudcan penetrates into the sand, shearing an increasingly larger volume of sand. This results in a range of shear strains, and hence friction angles, being mobilised along the failure slip plane, rather than mobilising the peak friction angle simultaneously.

White et al. (2008) also implicitly investigated scale effects by using three different footing diameters (0.6, 2.4 and 4.8m). The back-calculated bearing capacity factors, N_γ, for these conical-based footings were noted to decrease with increasing spudcan diameter, due to the corresponding lower values of mean effective stress along the failure mechanisms, resulting in lower peak friction and dilation angles, and greater variation in the friction angle along the correspondingly longer failure plane. The footing diameters investigated are noted to be significantly smaller than for typical spudcans, which typically range from 6 to 22m.

With respect to the third challenge listed above, ISO 19905-1 lists an extensive range of factors that can affect the sand's operative friction angle which are, in practice, challenging to routinely account for. Consequently, practitioners will often adopt their own approaches to deriving the operative friction angle, such as using empirical correlations to obtain φ' from CPT data and/or the sand's relative density, D_r. Such correlations do not consider the scale effects arising from different spudcans; consequently SNAME (2016) recommended that a 5° reduction in laboratory triaxial friction angle be applied for larger spudcans.

White et al. (2008) back-calculated the operative friction angles of the model conical footings at full embedment using Martin's (2004) solutions for rough, flat, circular footings, obtaining values of between 32 and 33.5°, and between 32.5 and 34.5° in medium dense and dense sand, respectively.

Based on the findings of the model tests, White et al. (2008) proposed a framework to derive the operative friction angle for a range of footing sizes and sand relative densities based on Bolton's (1986) stress-dilatancy relationships with a modified *m*-parameter to capture the influence of the 'stress-level effect' on bearing capacity. The operative friction angles derived were intended to be used in conjunction with Martin's solutions for rough circular footings. The resulting range of operative friction angles was found to lie between the sand's critical state friction angle, 31°, and 34.5° and is plotted in Figure 1 for the range of spudcan diameters typically encountered in practice. As can be seen, higher friction angles are predicted for higher sand relative densities and smaller spudcan diameters. White et al. (2008) suggested that the relatively narrow range of friction angles is due to the effect of progressive failure which reduces the influence of density on friction angle.

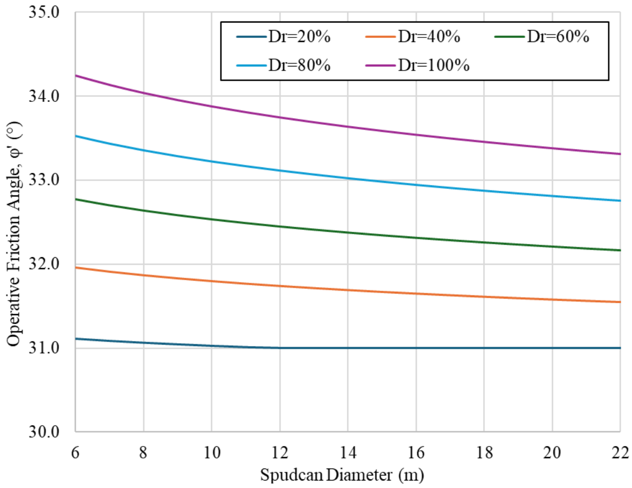

Figure 1. Operative friction angles obtained from the framework proposed by White et al. (2008) for different sand relative densities and footing diameters (for a typical cone angle, β, of 150°).

1.2 Objective of present study

The study by Edwards et al. (2013) suggested further work be undertaken into the prediction of spudcan penetrations in siliceous sands. The objective of this study is a product of this recommendation, with the aim to provide practitioners with a practical approach for predicting the bearing capacity of a conical-based spudcan in sand based on the sand relative density, and to compare White et al.'s (2008) predicted operative friction angles with those back-calculated from actual jack-up installation records.

2 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.

384 individual leg penetration records, from c.160 locations around the world, for spudcan diameters between 6m and 18m and preload bearing pressures at full contact between 372 kPa and 1010 kPa are represented in this study. 231 were from fully penetrated spudcans, and 153 were from partially penetrated spudcans, defined as where the tip penetration into the seabed was 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.

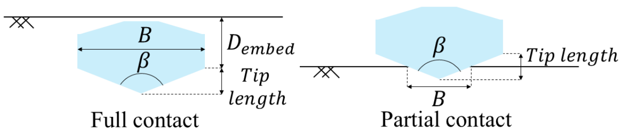

Figure 2. Key dimensions and terminology for fully and partially penetrated spudcans.

Based on our extensive database of spudcans, the records were divided into categories of either "small" or "large" spudcans, where "small" denotes any spudcan with a maximum equivalent diameter less than 10m, and "large" for spudcans with a maximum equivalent diameter greater than 12m. No "intermediate" spudcans with maximum equivalent diameters between 10 and 12m were investigated due to the lack of data. Figure 3 presents the distribution of equivalent spudcan diameters considered within the dataset. A total of 19 unique spudcan designs were represented in this study's dataset.

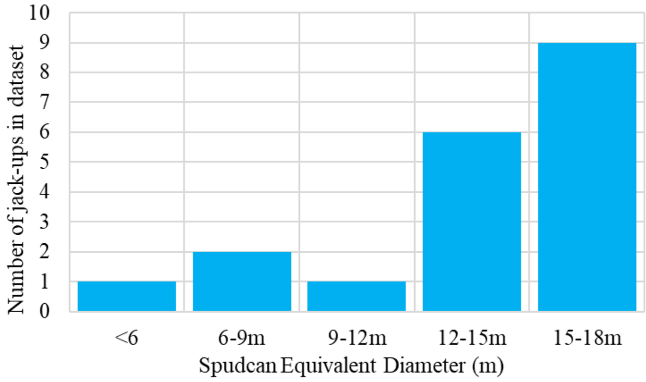

Figure 3. Distribution of equivalent spudcan diameters considered within this study's dataset

3 DATASET ANALYSIS

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

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

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 from results obtained using the software ABC (Martin, 2004) for a flat, rough circular footing; these are the same as those provided in the main informative text in ISO 19905-1, however the software permits derivation of values for a greater range and resolution of friction angle than are provided in ISO 19905-1. The assumption of perfect spudcan roughness is arbitrary, and was made for consistency with White et al. (2008). 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. 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), spudcan penetrations can typically only be estimated to within an accuracy of ±0.3m.

3.1 Sand relative density

The soil profiles' relative densities were derived using the CPT correlation for normally consolidated sands from Baldi et al. (1986). 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.

Where sand layers with varying relative density were encountered, a determination of the dominant sand layer's relative density was made. Any records without CPT data, or where this determination was not obvious or reliably possible, were discarded.

Recorded D_r values have been capped at 100%; any derived relative densities that were 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.

4 RESULTS

The results are presented here in terms of the spudcan diameter (small or large); the number of records for each spudcan size and penetration condition are summarised in Table 1.

Table 1. Distribution of penetration records with spudcan size and penetration condition.

Penetration	**Spudcan size**	
Condition	**Small**	**Large**
Partially Penetrated	22	131
Fully Penetrated	93	138
Total	**115**	**269**

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. Based on the authors' experience, jack-ups with smaller spudcans typically apply higher preload bearing pressures at full contact compared to jack-ups with larger spudcans. Consequently, for a given friction angle jack-ups with smaller spudcans tend to penetrate deeper.

4.1 Back-calculated operative friction angles

Figure 4 presents the normalised, cumulative frequency plot of the back-calculated operative friction angles, φ', for the 384 spudcan penetration records. Whilst the range of operative friction angles derived for both small and large spudcans were broadly similar, it can be seen that the majority of the records lie within a narrower range of between 24 and 35°.

It is noteworthy that approximately 80% of the back-calculated operative friction angles are less than the typical critical state friction angle for sand of 32° (Randolph, et al. 2004).

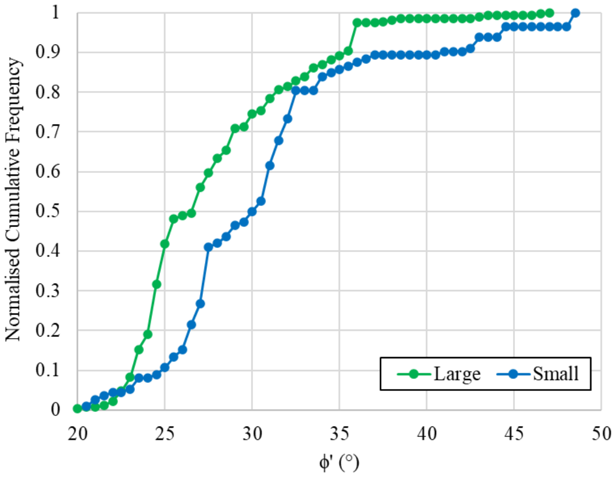

Figure 4. Normalised cumulative frequency curves of the penetration records' back-calculated operative friction angles

4.2 Correlation between operative friction angle and relative density

In order to estimate the appropriate operative friction angle for a location, it is necessary to compare these operative friction angles with the sands' relative density inferred from CPT data.

Relative density data was available for 282 of the 384 penetration records; the sands' relative densities, derived using the normally consolidated CPT correlation from Baldi et al. (1986) assuming $K_o = 1$, ranged from 15% to greater than 100%. Figure 5 presents these records' back-calculated φ' values against the corresponding derived relative density at the jacking location. It can be seen that there is a weak positive correlation between the two parameters.

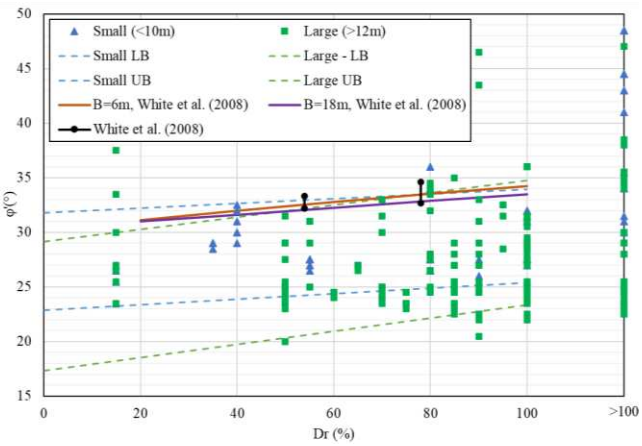

Figure 5. Comparison of linear 80% predictive intervals illustrating the relationship between the back-calculated operative friction angle and the derived sand relative density, experimental model test data in medium dense and dense sands (in black) and predicted values from White et al. (2008).

Linear regression has been used to correlate the friction angle with relative density ($D_r \leq 100\%$) and 80% predictive intervals have been added for each spudcan diameter category to assist the reader in visualising the distribution of D_r, φ' combinations, as numerous combinations had multiple overlapping symbols. The predictive intervals are broadly similar for small and large spudcan diameters, however the larger spudcans mobilise lower friction angles, and show more than twice the sensitivity to the sand relative density ($\delta\varphi' = 5.8°$ between $0<D_r<100\%$) compared to $\delta\varphi' = 2.3°$ between $0<D_r<100\%$ for the small diameter spudcans.

Figure 5 also includes data from White et al.'s (2008) experimental centrifuge model tests in medium dense and dense sands, and the friction angles predicted by that study's proposed framework for spudcan diameters of 6m and 18m, presented in Figure 1, which cover the full range of spudcan diameters in this study. The upper predictive interval for small spudcans passes through the centrifuge model test data and is approximately parallel and coincident with the values suggested by White et al. (2008).

5 DISCUSSION

The weak positive correlation between the relative density of the sand and the back-calculated friction angle shown in Figure 5 is relatively small in relation to the scatter in the data, however accounting for the variation could improve the accuracy of penetration predictions, especially for large diameter spudcans. As noted above, the trend is very similar to that found by White et al. (2008).

The penetration records clearly show that large spudcans generally mobilise a lower operative friction angle than small spudcans for the same relative density. These trends mirror those observed by other researchers, as described in Edwards et al. (2013) and White et al. (2008).

The difference in predictive intervals in Figures 5 for the small and large spudcans, as a result of scale-effects, is larger than implied by White et al.'s (2008) predictive framework, which suggests a difference of less than 1°, but smaller than the recommendation in SNAME (2016) to reduce the design friction angle for large spudcans by 5°. For sands with D_r=0%, the differences between the lower and upper 80% predictive intervals for small and large spudcans are 5.6 and 2.1°, whereas for sands with D_r=100%, the difference is only 2.1 and -0.8°, respectively.

Whilst the range of operative friction angles predicted by White et al. (2008) can represent their small diameter model footing tests, the range of values predicted for the spudcan diameters applicable to the present dataset is narrower and consistently higher than those back-calculated in this study.

The observation that the back-calculated operative friction angle is generally less than the typical critical state friction angle for sand, and hence by definition cannot be predicted by White et al.'s (2008) method, implies that a phenomenon other than pure shear failure, such as compressibility, is contributing to the penetration depths observed in the field. The use of operative friction angles therefore attempts to indirectly account for such effects.

6 IMPLICATIONS FOR SPUDCAN PENETRATION PREDICTIONS

The data presented in Figure 5 indicate the 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 spudcans in sand.

The predictive intervals presented in Figure 5 for each spudcan size could provide a rational, and more realistic, basis for bracketing the range of design friction angles for use in practice.

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 (2004) that are included in the current version of ISO 19905-1 (2023). Furthermore, the relative densities stated herein are calculated using the CPT correlation for normally consolidated sands from Baldi et al. (1986) assuming $K_o = 1$.

7 CONCLUSIONS

384 spudcan penetration records have been analysed and compared to the findings from White et al.'s (2008) centrifuge and theoretical study into the bearing capacity of axi-symmetric footings in sands.

The back-calculations from this study confirm the operative friction angle is weakly related to both the sand relative density and footing diameter.

White et al. (2008) highlighted three key challenges to accurately predicting the penetration of spudcans in sand:

1. The appropriate bearing capacity factor
2. Foundation 'scale effects'
3. Selection of the operative friction angle

The predictive intervals resulting from the present back-analysis provide a solid basis for accounting for the sand relative density and foundation size when selecting the operative friction angle for use in spudcan penetration predictions using exact bearing capacity factors for flat rough circular footings.

The recommendations of this study therefore address the three key challenges above and provide a simple approach for improving the accuracy of spudcan penetration predictions in practice.

7.1 Future work

This assessment will next be supplemented with around one thousand penetration records from offshore windfarm projects to increase the signal-to-noise ratio of the data and attempt to further refine the range and trend of operative friction angles derived in this study with respect to sand relative density.

AUTHOR CONTRIBUTION STATEMENT

S. K. Smith: Data curation, Software, Formal Analysis, Investigation, Visualization, Writing- Original draft. **D. H. Edwards**.: Conceptualization, Methodology, Supervision, Writing- Reviewing and Editing.

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