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An experimental study on the effects of bearing pressure on the friction angle for spudcan penetration analysis

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ABSTRACT: Prediction of the penetration of spudcans into sand involves using bearing capacity calculations, which are dependent on the chosen friction angle. This has led to discussions on which value of the friction angle should be used for spudcan penetration analysis. The mobilised friction angle during spudcan penetration is influenced by the relative density of the soil and the size of the spudcan, and, consequently, the stress level in the failing soil. In fact, the bearing pressure under spudcans can be very high, causing a decrease in the peak friction angle, due to lower dilation caused by high confining stresses. Therefore, as stated by ISO 19905-1 (2023), using the peak friction angle directly for design may not be appropriate, as it may lead to an overestimation of soil resistance. The main goal of this study was to demonstrate the widely reported effects of high confining stresses on the peak friction angle, by conducting a series of drained triaxial tests on sand at different relative densities with increasing values of mean effective stress. The values of the friction angle derived from laboratory testing were then compared with values estimated using a strength-dilatancy relationship. Finally, the results obtained from the laboratory were used to assess the differences between existing guidelines for spudcan penetration analysis, taking into account the typical bearing pressure values encountered in the field.

Keywords: Friction angle; spudcan penetration analysis; bearing pressure; drained triaxial tests; dilation

1 INTRODUCTION

Jack-up platforms are widely employed in the offshore oil and gas industries and are increasingly being used in the implementation of offshore wind farms. The accident exposure associated with these structures is significantly high; therefore, estimating the performance of the foundations during installation, particularly leg penetration, is critical for the design of jack-up rigs. The available guidelines for the design of these structures mainly focus on the stability and structural integrity of the jack-up and on methods for predicting spudcan penetration during installation. However, there is not yet an established agreement on methods for selecting appropriate friction angles or a method to account for the scale effects that lead to discrepancies in behaviour between small-scale tests and those observed in the field (White *et al.*, 2008).

Spudcan penetration analysis in sand is based on traditional ultimate bearing capacity calculations, which depend largely on the chosen friction angle. According to ISO 19905-1 (2023), the friction angle mobilised during spudcan penetration in sand is influenced by the relative density of the soil, the spudcan geometry, and as a result, by the stress level underneath the spudcan. The bearing pressure under spudcans can be quite high, which leads to a decrease in the peak friction angle due to reduced dilatancy caused by high confining stresses. This may result in significant errors in estimating the resistance of the soil, and consequently, it may not be advisable to use the peak friction angle for design purposes (ISO 19905-1, 2023).

The goal of this experimental study was firstly to illustrate the well-documented effects of stress level and relative density on the friction angle. This was achieved by performing a series of drained triaxial tests on sand at different relative densities with increasing values of mean effective stress. Secondly, to confront the values of the friction angles obtained in the laboratory with values estimated using the strength-dilatancy correlations proposed by Bolton (1986); and thirdly, to evaluate the results against existing guidelines and assess the implications of relative density, stress level and dilatancy on the selection of appropriate values of the friction angle for spudcan penetration analysis.

2 SPUDCAN PENETRATION ANALYSIS

Predicting spudcan penetration involves the use of ultimate bearing capacity calculations at various spudcan tip penetrations. The spudcan is typically modelled as a flat, circular, shallow foundation (SNAME, 2008), or a circular foundation in plan, with conical undersides (InSafeJIP, 2011). Each plan section is converted to a circle with an equivalent diameter taken as the area of the actual spudcan cross-section in contact with the seabed, or as the largest cross-sectional area in plan if the spudcan is fully embedded. The bearing capacity calculations are then performed at the greatest embedment depth of the maximum cross-sectional area in contact with the soil.

2.1 Bearing capacity factors

The methodologies currently available for predicting spudcan penetration account for the specific conditions encountered offshore, by modifying the general bearing capacity equation. SNAME (2008) assumes a flat, circular spudcan, and recommends using the bearing capacity factors proposed by Vesic (1975), along with depth and shape factors. It should be noted that this methodology does not take into account the roughness or the conical shape of the spudcan. InSafeJIP (2011) suggests applying the values of N_γ provided by Cassidy and Houlsby (2002) for conical-shaped footings. These values depend on the spudcan roughness and cone apex angle. Since no values of N_q have been calculated specifically for conical spudcans, those described by Vesic (1975) should be used, along with the incorporation of shape and depth factors (InSafeJIP, 2011). Alternatively, the values of N_γ and N_q for soil friction angles ranging from 20° to 40°, as given in Martin (2003) for a flat, rough, circular footing, can also be used for conical spudcans, since the error involved is relatively small when compared with the uncertainties in selecting the soil friction angle (ISO 19905-1, 2023). Regardless of the methodology used to derive N_γ and N_q, these factors are highly sensitive to the selected soil friction angle.

2.2 Friction angle: effects of relative density and stress level

According to ISO 19905-1 (2023), the apparent friction angle mobilised during spudcan penetration is primarily controlled by the relative density, with denser samples exhibiting higher strength. However, for a given relative density, the angle of friction reduces as the stress level increases (Houlsby, 1991). As widely reported by several authors, the peak friction angle decreases due to lower dilation caused by high confining stresses (Bolton, 1986; De Beer, 1965; Lade and Bopp, 2005). This reduction of the peak friction angle is crucial for spudcan penetration analysis, as it results in a design friction angle that is much lower than expected, leading to an overestimation of soil resistance. In foundation design, the accuracy of bearing capacity calculations is not usually critical since large safety factors are commonly employed; however, it is of the utmost importance for the prediction of spudcan penetration (InSafeJIP, 2011). As mentioned in ABS (2018), using a conservative estimate for the friction angle, common in other bearing capacity assessments, may not be appropriate for jack-up installation calculations since an accurate estimate of actual penetration is required. Therefore, to account for the aforementioned effects, it is essential to assess the friction angle by conducting laboratory tests (e.g., triaxial compression tests) performed at the appropriate relative density and stress level (InSafeJIP, 2011). Typical values of bearing pressure reported under spudcans for standard jack-up units are close to 600 kPa (Osborne *et al.*, 2009; Edwards *et al.*, 2013). However, current testing practices often involve conducting triaxial tests at low confining stresses, which may not accurately reflect actual *in situ* conditions during spudcan preloading.

Alternatively, the design value of the friction angle, ϕ'_d (°), can be estimated from the relative density, I_D, and the critical state friction angle, ϕ'_{cv} (°), using the strength-dilatancy framework established by Bolton (1986), which takes into consideration the effect of the mean effective stress, p'(kPa), during bearing failure:

$$\phi'_d = \phi'_{cv} + mI_{RD} \quad (1)$$

$$I_{RD} = I_D[Q - ln\, p'] - 1 \quad (2)$$

where m is a constant equal to 3 for triaxial strain, I_{RD} is the relative dilatancy ($0 \leq I_{RD} \leq 4$), and Q, the particle crushing strength on a natural logarithmic scale. Reported values of Q and ϕ'_{cv} derived from triaxial compression tests for silica sands show minor variations: $Q = 10 \pm 1$ and $\phi'_{cv} = 32° \pm 1°$ (InSafeJIP, 2011; Randolph *et al.*, 2004).

2.3 Scale effects

Although the methodology described above accounts for the effects of relative density and stress level on the friction angle, careful consideration should also be given when selecting the design value of the friction angle for spudcan penetration analysis, if there is a possibility of progressive failure (White *et al.*, 2008). Since significant displacements are necessary to mobilise the available theoretical bearing capacity in sands, the soil resistance will be significantly overestimated for a penetration process such as that of an approximately conical spudcan, as during penetration, the deformations in the soil will be insufficient to have mobilised the full strength of the sand (InSafeJIP, 2011). As a result, the apparent friction angle mobilised during spudcan penetration will be lower than the peak value obtained in the laboratory due to mechanisms of progressive failure (ISO 19905-1, 2023). Various authors have conducted centrifuge tests that indicate there is a scale effect in extrapolating from small-scale tests to the geometries associated with spudcans in the field (Craig and Chua, 1990; White *et al*., 2008). Based on these observations, SNAME (2008) proposes that the friction angle derived from laboratory triaxial tests should be lowered by 5° for the prediction of large-diameter footing penetrations in silica sands. According to InSafeJIP (2011), this process involves the use of unrealistically low friction angles. An alternative approach is suggested in which the soil resistance is calculated using a realistic value of the friction angle, followed by the application of a mobilisation factor to the calculated resistance (recommended values for the reduction factor, F_{mob}, range from 0.25 to 0.5, based on back analysis of case records).

Although several methods have been proposed in the current literature for jack-up assessments, spudcan penetration will ultimately be dependent on the adopted friction angle and on the methodology used, as each method will lead to different results. Therefore, clearer guidelines for selecting engineering design parameters for spudcan penetration analysis are essential to ensure consistency and accuracy in predictions (Osborne *et al*., 2009; Edwards *et al*., 2013).

3 LABORATORY TESTING

The main goal of this experimental study was to demonstrate the well-documented effects of relative density and high confining stresses on the peak friction angle by conducting drained triaxial tests compacted to different target dry densities. All laboratory tests were carried out at Fugro's Advanced Geotechnical Laboratory in the company's UK headquarters in Wallingford, Oxfordshire.

3.1 Properties of sand

The laboratory tests were carried out using a silica sand (99.8% content of SiO_2), closely graded, washed, and dried, from the Lower Greensand formation in Bedfordshire, UK. The particles are subangular to rounded, with over 99% passing through the 0.6 mm sieve and less than 1% passing the 0.063 mm sieve. The particle density is 2.65 g/cm^3.

3.2 Specimen preparation

To achieve the desired dry density, specimens with 70 mm diameter and 140 mm height were prepared in 9 layers at an initial water content of 10% using the moist tamping method, following Ladd's under-compaction procedure. The saturation process involved flushing the specimens with carbon dioxide and de-aired water – carbon dioxide is more soluble in water than nitrogen (air), which facilitates saturation. To ensure all voids were filled with water, the cell pressure and back pressure were increased while maintaining an effective stress of 10 kPa, allowing more water to flow into the specimens. A B value greater than 0.95 was achieved for all tests. Next, the specimens were isotropically consolidated to a specific mean effective stress and then sheared in compression under drained conditions at a strain rate of 1.3%/h.

3.3 Testing programme

Five sets of drained triaxial compression tests were performed at target dry densities of 1.30, 1.50, 1.56, 1.62, and 1.68 Mg/m^3. The tests carried out at a dry density of 1.30 Mg/m^3 correspond to an extremely loose specimen. The tests conducted at a dry density of 1.68 Mg/m^3 relate to a specimen compacted to the maximum dry density achievable by Ladd's under-compaction procedure. For each dry density, a series of tests was conducted at increasing values of mean effective stresses, p', of 100, 250, 400, 600, 1300, 2000, and 3000 kPa. A high pressure triaxial cell (maximum confining pressure of 4000 kPa) was used for the tests performed at an effective stress of 2000 and 3000 kPa. Table 1 summarises the testing programme used in this experimental study.

Table 1. Testing Programme

Target Dry Density (Mg/m^3)	**Relative Density** (%)	**Mean Effective Stress** (kPa)
1.30	0	100 | 250 | 400 | 600 1300 | 2000 | 3000
1.50	60	
1.56	80	
1.62	90	
1.68	100	

3.4 Properties of sand

Figure 1 illustrates the variation of the peak friction angle, ϕ', with the mean effective stress, p', for all dry densities tested. The graph shows that for any given value of mean effective stress, the peak friction angle is higher for sands tested at higher dry densities, as would be expected. For instance, under a mean effective stress of 100 kPa, the peak friction angle differs by approximately 9° between the highest and lowest dry density tested.

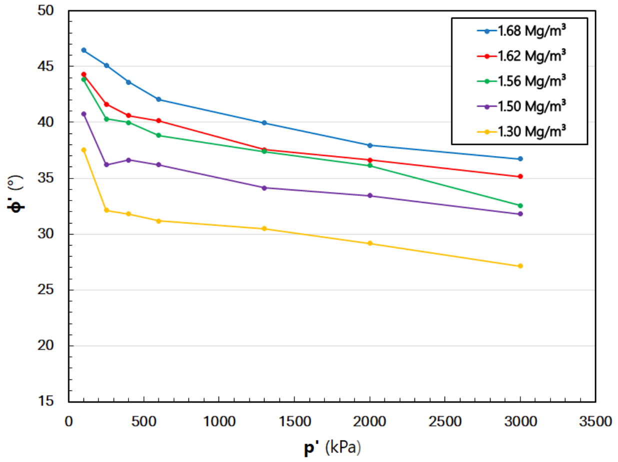

Figure 1. Variation of peak friction angle (ϕ') with mean effective stress (p') for all dry densities tested.

As reported by several authors, the peak friction angle decreases significantly as the mean effective stress increases for all dry densities. In fact, a variation in p' from 100 to 3000 kPa can lead to a reduction of the corresponding peak friction angle of up to 11° for the sand tested at a target dry density of 1.56 Mg/m^3 as shown in Figure 1. This decrease in the peak friction angle is caused by a significant reduction in the dilation rate at high stress levels (Bolton, 1986; De Beer, 1965; Lade and Bopp, 2005). This is well demonstrated in Figure 2, which shows the evolution of volumetric strain during shear, ε_v (%), with axial strain, ε_a (%), for the sands tested at the minimum and maximum achievable dry density for mean effective stress values of 600 and 3000 kPa.

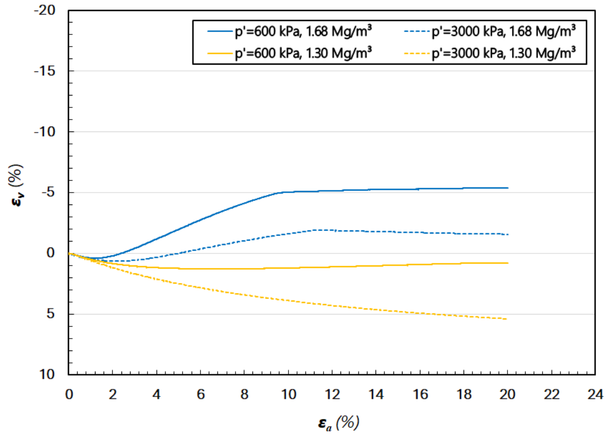

Figure 2. Axial strain versus volumetric strain.

A decrease in volume (contraction) was observed for the sand compacted to the lowest achievable dry density for both stress levels. This volume reduction is even more pronounced as the confining stress increases, indicating that high pressures significantly suppress the sand's tendency to dilate. On the contrary, the sand compacted to the maximum achievable dry density experienced a volume increase (dilation) after an initial reduction in volume for both stress levels applied. In a dense sand, the particles are more closely packed and have limited space to move. As stress is applied during shear, the particles tend to move upward and sideways, leading to an increase in volume. At higher stress levels, the results showed that the rate of dilation of the dense sand decreased significantly, resulting in a lower value of the friction angle.

These conclusions are essential for understanding how the relative density of the soil and confining pressure influence the friction angle, which is crucial for spudcan penetration analysis. Current practice involves scheduling low values of mean effective stress for triaxial testing, which may not accurately represent the conditions in the field. Given that typical bearing pressure values reported under spudcans are close to 600 kPa, it is interesting to highlight that as p' increases from 100 to 600 kPa, the friction angle decreases by approximately 5° for all tested dry densities. This decrease aligns with the guidelines proposed by SNAME (2008), which recommend reducing the peak friction angle obtained from triaxial tests by 5° to account for scale effects associated with large-diameter footings as well as other effects.

4 EVALUATION OF RESULTS IN LIGHT OF CURRENT PRACTICE

To better understand the effects of relative density and stress level on the friction angles obtained from the laboratory tests, the results were contrasted against the values derived using Bolton’s strength-dilatancy framework. Subsequently, the bearing capacities and leg penetrations estimated following the available guidelines outlined by SNAME (2008), InSafeJIP (2011) and ISO 19905-1 (2023) were compared. Friction angles obtained from the laboratory tests conducted at a low confining stress of 100 kPa were used, as it is common procedure when scheduling pressures for triaxial testing. These results were then compared with those obtained from the tests performed at a higher stress level of 600 kPa, to attempt to replicate the bearing pressures typically encountered in the field.

4.1 Bolton's strength-dilatancy framework

A comparison of the peak friction angles obtained in the laboratory with those derived from Bolton's equations was conducted by plotting the differences in results, Δ (°), as illustrated in Figure 3 (values of Q=10 and ϕ'_{cv}=32° were used). The provided difference represents the peak friction angles from the laboratory tests subtracted by the peak friction angles calculated using Bolton's framework. Bolton's expressions are only valid for a relative dilatancy index greater than zero; hence, they may not be applicable to low relative density sands. Consequently, the friction angles for the sand tested at the minimum achievable dry density (1.30 Mg/m^3) were excluded from this comparison.

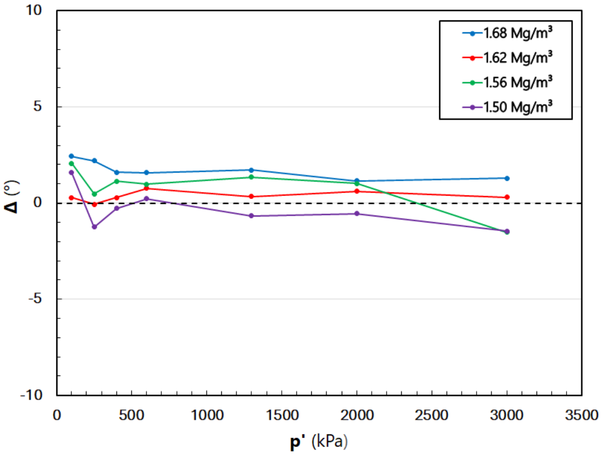

Figure 3. Difference between laboratory results and Bolton's strength-dilatancy framework.

Figure 3 indicates that the laboratory tests generally yield higher peak friction angles. Overall, the peak friction angles derived using Bolton's framework were very similar to the laboratory values across the range of dry densities and confining stresses tested, with a maximum discrepancy of only 2.4°. For p' values lower than 400 kPa, the difference between results for all dry densities appears to fluctuate slightly.

Therefore, it may be preferred to perform the tests at a representative stress level to avoid the slightly higher variability in the peak friction angle measured at lower stresses. The close alignment between the data indicates that Bolton's framework is a reliable method for predicting friction angles across a wide range of dry densities and confining stresses, as observed by several authors. Moreover, the strong correlation between Bolton's framework and the laboratory results suggests that the need for extensive laboratory testing may be reduced, saving time and resources in geotechnical investigations.

4.2 Bearing capacity calculations

Bearing capacity calculations were performed for a conical spudcan with a diameter of 20 m, assuming an effective unit weight of 10 kN/m^3 for the sand. The friction angles used in the calculations were taken from the tests performed at mean effective stresses of 100 and 600 kPa. In accordance with SNAME (2008), the friction angles obtained from the triaxial tests were reduced by 5° and the bearing capacity factors proposed by Vesic (1975) were employed. Predictions following InSafeJIP (2011) were carried out using the peak friction angles and a mobilisation factor of 0.5 to account for partial mobilisation of shear strength. The bearing capacity calculations based on the recommendations set by ISO 19905-1 (2023) were also conducted using the peak friction angles achieved in the laboratory tests. The bearing capacity factors, N_γ, for the calculations following InSafeJIP (2011) and ISO 19905-1 (2023) were interpolated from the values provided in Cassidy and Houlsby (2002), assuming a roughness factor of 0.5 and a cone angle of 150°. The values of N_q proposed by Vesic (1975) were used along with shape and depth factors. All the parameters used in the calculations are shown in Table 2.

Table 2. Parameters used in the calculations

Parameters	**SNAME (2008)**		**InSafeJIP (2011)**		**ISO 19905-1 (2023)**	
	p'=100 kPa	p'=600 kPa	p'=100 kPa	p'=600 kPa	p'=100 kPa	p'=600 kPa
$\boldsymbol{\phi'}$	41.4°	37.1°	46.4°	42.1°	46.4°	42.1°
$\boldsymbol{N_\gamma}$	102.9	47.9	724.0	209.7	724.0	209.7
$\boldsymbol{d_\gamma}^*$	1.0	1.0	1.0	1.0	1.0	1.0
$\boldsymbol{s_\gamma}$	0.6	0.6	1.0	1.0	1.0	1.0
$\boldsymbol{N_q}$	78.7	43.3	170.4	86.1	170.4	86.1
$\boldsymbol{d_q}^*$	1.0 – 1.1	1.0 – 1.1	1.0 – 1.1	1.0 – 1.1	1.0 – 1.1	1.0 – 1.1
$\boldsymbol{s_q}^*$	1.7	1.6	2.1	1.9	1.0	1.0

*InSafeJIP (2011) uses different notations for these parameters. The depth factors d_γ and d_q are designated as $\xi_{h\gamma}$ and ξ_{hq}, respectively. The shape factor s_q is denoted as ξ_{sq}

Two scenarios were examined: one with the spudcan fully embedded resting at the surface of the seabed, and another with an embedment depth of 10 m. Figure 4 shows the differences between the available guidelines. To facilitate the comparison of results, only the values corresponding to the sand compacted to the maximum achievable dry density (1.68 Mg/m³) were presented, as the trends were consistent across all dry densities tested. No backflow was considered.

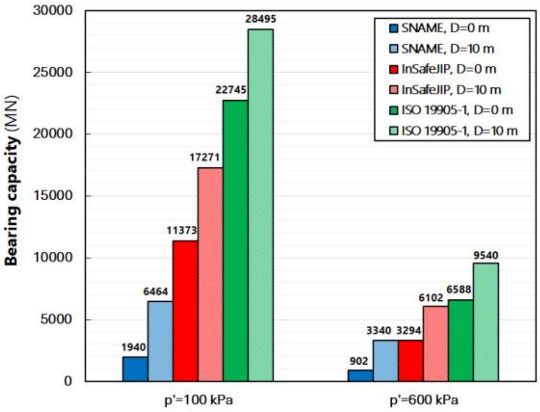

Figure 4. Comparison of available guidelines for spudcan penetration analysis (bearing capacity).

The results show that InSafeJIP (2011) and ISO 19905-1 (2023) predict significantly higher bearing capacity values compared to SNAME (2008). As expected, the bearing capacity increases considerably with embedment depth for both stress levels and methodologies. As the stress level increases, the discrepancy between methods decreases for both scenarios. The graph also highlights the potential for inaccuracies in bearing capacity predictions that can arise from using friction angles from tests conducted at low confining stresses. This is evident from the differences in the estimated bearing capacities at both stress levels. For instance, when the spudcan rests at the seabed surface, the calculations using ISO 19905-1 (2023) show a decrease in bearing capacity from 22745 MN (p'=100 kPa) to 6588 MN (p'=600 kPa), indicating a significant reduction with increased stress. Using the friction angle correspondent to tests performed at low mean effective stresses, as is the standard practice when scheduling triaxial tests, leads to unrealistic estimations of bearing capacity, which may not accurately reflect the actual conditions in the field.

4.3 Leg penetration

The predicted penetrations for each methodology were also compared, as illustrated in Figure 5. It should be noted that the penetration depth (m) refers specifically to the tip of the spudcan. The results indicate that SNAME (2008) underestimates the bearing capacity compared to the other guidelines, resulting in higher values of predicted penetration. Figure 5 also shows that ISO 19905-1 (2023) significantly overestimates the bearing capacity, leading to lower values of predicted penetration.

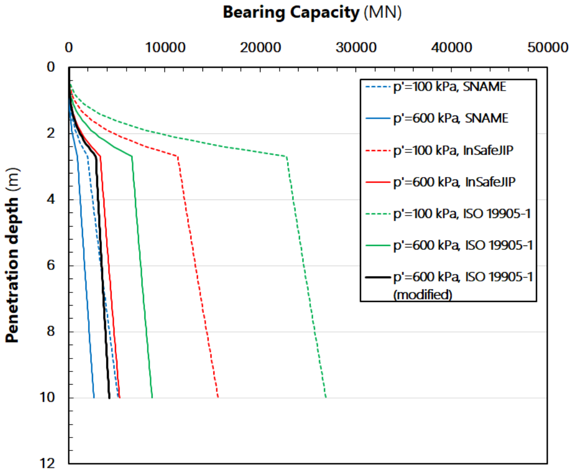

Figure 5. Comparison of available guidelines for spudcan penetration analysis (leg penetration).

Although the results highlight the differences in leg penetration estimated using the various methods, in the present case of a single-layered dense soil, the spudcan would not be expected to fully penetrate the soil (partial penetration). Consequently, leg penetration would not be a major concern in this case. However, the implications of selecting the appropriate friction angle for each methodology are more significant in layered soils, where there is a potential for punch-through. It is interesting to note that the leg penetration estimated using InSafeJIP (2011) at a representative stress level (p'=600 kPa), shows close alignment with the penetration calculated using SNAME (2008) at a low confining stress (p'=100 kPa). This underscores the need of reducing the peak friction angle by 5° when conducting triaxial tests at low confining pressures, as recommended by SNAME (2008). The considerable differences in leg penetration between InSafeJIP (2011) and ISO 19905-1 (2023) should also be emphasized, with the latter predicting significantly lower penetrations. This discrepancy arises from the reduction factor used in the application of InSafeJIP (2011) to the calculated resistance. This also highlights the importance of accounting for scale effects, such as progressive failure, in spudcan penetration analysis. An additional calculation was conducted using ISO 19905-1 (2023). The friction angle corresponding to a stress level of 600 kPa, reduced by 3° (ϕ'=39.1°), was used in the calculations (N_γ and N_q values of 90.0 and 56.4 were applied). The predicted penetrations using this methodology yield more consistent results, aligning closely with other established guidelines, as demonstrated in Figure 5. Adopting the friction angle obtained from triaxial tests performed at a representative stress level and reducing it by 3° appears to be a more appropriate approach, leading to more accurate predictions for spudcan penetration analysis.

5 CONCLUSIONS

This experimental study illustrated the well-known effects of relative density and confining stress on the friction angle. As the pressure increased, the friction angle significantly decreased due to a reduction of the rate of dilation at high stress levels. The laboratory results were closely aligned with Bolton's framework, hinting at a potentially reduced need for extensive laboratory testing programmes. Comparisons with published guidelines showed significant discrepancies in bearing capacity calculations when using friction angles from triaxial tests conducted at low confining stresses, highlighting the importance of considering actual *in-situ* conditions for accurate bearing capacity calculations. Finally, an adjustment to ISO 19905-1 (2023) was proposed, whereby the friction angle derived from tests performed at a representative stress level is reduced by 3° to achieve more accurate predictions for spudcan penetration analysis.

AUTHOR CONTRIBUTION STATEMENT

N. C. Santos: Investigation, Data curation, Writing – Original Draft. **T. Carrington**: Conceptualization, Validation, Writing – review & editing. **R. Newby**: Resources, Supervision. **E. Cole**: Investigation. **M. Francis**: Validation, Writing – review & editing.

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