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A modified CPT based installation torque prediction for large screw piles in sand

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ABSTRACT: Screw piles have been suggested as an alternative foundation solution to straight-shafted piles for jacket supported offshore wind turbines in deep water. The significant environmental loads in the marine environment will require substantially larger screw piles than those currently employed in onshore applications. This raises questions over the suitability of current design methods for capacity and installation torque. This paper aims to address this issue by presenting a screw pile installation torque prediction method based on cone resistance values from Cone Penetration Test (CPT) data. The proposed method, developed using centrifuge modelling techniques in dry sand, provides accurate predictions of installation torque for both centrifuge and field scale screw piles. Furthermore, unlike existing CPT-torque correlations, the proposed method is shown to be applicable to multi-helix screw piles.

1 INTRODUCTION

Although originally developed for the marine environment (Jacob, 1953, Lutenegger, 2017), screw piles have been widely adopted in numerous onshore applications such as, for guyed towers, light poles and underpinning of existing foundations. The helical plate(s), mounted on the central core of a screw pile allow for their installation by application of continuous axial and rotational forces. This installation method is significantly quieter than the pile driving methods employed in conventional straight-shafted pile installation. The effects on marine life from such noise is of growing concern and has led to strict regulations and the use of expensive mitigation techniques thus making screw piles ideal for this type of application.

The helical plates of a screw pile also generate substantial axial capacity during compression and tensile loading conditions. Furthermore, when the helices of a multi-helix screw pile are spaced apart at less than 2.5 helix diameters (Knappett et al., 2014), enhanced levels of shaft-friction are mobilized from the soil-soil shear which develops over the inter-helix interval, in comparison to the soil-steel interface associated with shaft friction along straight-shafted piles.

It is these benefits, offered by screw piles, which have led some authors (Byrne and Houlsby, 2015, Spagnoli and Gavin, 2015) to suggest their use in the offshore environment, as foundations for deep water offshore wind energy projects.

The expansion of offshore wind energy into deeper water may require alternative foundations and support structures, as concern has been raised over increasing the size of the most commonly used solution of monopile structures (Golightly, 2014). As alternative to monopiles, steel jackets founded on piles can be used. This solution is already in use in the Beatrice Offshore Wind Farm, in the Moray Firth, UK, which is sited in the deepest water to date for an offshore wind farm in the UK.

Replacing the straight-shafted piles typically used as the foundations for the jackets, with screw piles can eliminate any concerns over installation noise and potentially lead to a reduction in the amount of steel required for the foundations due to the improved efficiency of the load carrying mechanism.

To attain the in-service capacities required to sustain the forces created by the combined self-weight and environmental loads, the geometry of current screw pile designs will need to be significantly varied and upscaled. Rotating screw piles into the soil requires significant amounts of torque from the frictional resistance of the soil-steel interface. Thus, increasing the surface area of the screw pile will lead to greater installation torque requirements.

Estimating the installation torque of a screw pile is a critical factor in the development of larger pile geometries for offshore wind applications and is an active area of research (Schiavon et al., 2016, Spagnoli, 2016, Tsuha, 2016). The magnitude of the installation torque (T) of onshore piles is typically used in the verification of the axial tensile capacity (Q_t) through the empirical factor, K_t, developed by Hoyt and Clemence (1989), given in equation 1. Byrne and Houlsby (2015) have developed this further with the use of a dimensionless torque factor. However, BS 8004:2015 (British Standards Institution, 2015) states that screw piles should not be designed solely using empirical methods. Thus, predicting the torque from the axial capacity is not recommended. This would seem appropriate as Al-Baghdadi (2018) showed that the pile's core was the greatest contributor to required torque where Q_t is dictated by the helix plate diameter rather than the core diameter.

$$Q_t = K_t \mathrm{T} \quad (1)$$

Alternatively, analytical techniques developed by Ghaly and Hanna (1991) and Sakr (2015) decompose the torque into the various contributing components from the helices and core. Ghaly and Hanna (1991) had limited field verification of their method which was developed from 1g model scale tests in dry sand. However, the Sakr (2015) approach has been validated against field data for screw piles with core and helix diameters up to 0.508 and 1.016m respectively and installation depths up to 12.8m. Although, such geometries are likely to be inadequate for the loads anticipated in the deep water offshore wind sector.

Correlations between the cone resistance from Cone Penetration Test (CPT) data and the axial capacity of straight-shafted piles have been demonstrated to be potentially more reliable and accurate compared to other analytical and empirical methods. Consequently, several authors have suggested correlations which relate CPT data to the installation torque of screw piles (Gavin et al., 2013, Spagnoli, 2016, Al-Baghdadi et al., 2017).

This paper aims to provide an improvement on the method proposed by Al-Baghdadi et al. (2017), based on further centrifuge modelling of screw piles in dense sand. The method is also validated against multi-helix screw piles to address the lack of available CPT-torque prediction methods for such piles.

This work was undertaken as part of a wider project investigating the development of screw piles for offshore wind energy foundations. In addition to the physical modelling, partly discussed herein, Durham University are developing Material Point Method techniques (Wang et al., 2017) to model screw pile installation effects, while the University of Southampton will conduct field scale tests for verification of the model-scale and numerical investigations.

2 CENTRIFUGE MODELLING

All tests were conducted on the Actidyn beam centrifuge at the University of Dundee at 50g acceleration.

2.1 *Model piles*

Two 1/50 th scale model screw piles (Figure 1) consisting of single and multi-helix designs, both

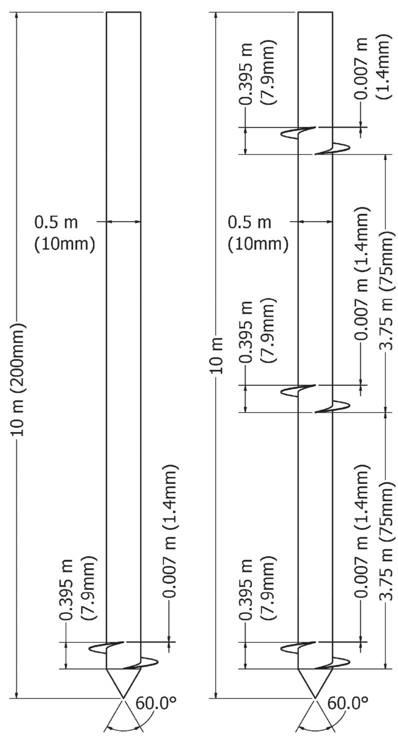

Figure 1. Model screw piles used in centrifuge tests at prototype scale (model dimensions in brackets).

Table 1. HST95 sand material properties (Al-Defae et al., 2013, Lauder et al., 2013).

Property	Value
Grading description	Fine
Effective particle size, D_{10} (mm)	0.09
Average particle size, D_{50} (mm)	0.14
Critical state friction angle, ϕ'_{crit} (°)	32
Soil-steel interface friction angle, δ_{crit} (°)	27
Angle of dilation*, ψ (°)	14
Maximum dry density, ρ_{max} (kN/m^3)	17.58
Minimum dry density, ρ_{min} (kN/m^3)	14.59

*As measured at 73% relative density (Al-Defae et al., 2013).

with 10 mm and 20 mm core and helix diameters respectively, were manufactured from mild steel. Pile shafts were closed-ended with a 60° conical tip.

2.2 *Soil properties*

All centrifuge tests were conducted using HST95 sand. The behavior and properties of this fine grained quarzitic sand are well characterised, having been used in numerous previous studies at the University of Dundee (Jeffrey et al., 2016, Al-Baghdadi, 2018). A minimum ratio of the average (d_{50}) particle size to shaft diameter of 71 satisfied the recommendations made by Garnier et al. (2007) with respect to particle size-pile diameter scaling.

2.3 *Model container and soil preparation*

A steel container with internal dimensions of 500 × 800 × 550 mm, used in all tests, allowed for two tests to be completed in one container by moving the installation/testing rig between centrifuge flights. The minimum spacing between the screw pile and container walls was greater than 10 times the largest helix diameter to ensure no boundary effects were present (Phillips and Valsangkar, 1987, Bolton et al., 1999).

The sand bed was prepared to a depth of 450 mm and a relative density of 73% using an air-pluviation method detailed in Jeffrey et al. (2016).

2.4 *Pile installation*

A custom dual-axis actuator, developed at the University of Dundee by Al-Baghdadi et al. (2016) provided the necessary rotational and vertical forces to install the screw piles. The vertical speed and revolutions per minute are linked by the pitch of the screw pile. Installation of a screw pile must occur such that the screw pile penetrates the soil by an amount equal to the helix pitch for each complete revolution to minimize soil disturbance (Perko, 2009, British Standards Institution, 2015). Thus, a displacement controlled installation, at a penetration speed of 26.3 mm/min and rotation speed of 3.33 rpm, was used for all tests.

The vertical and rotational installation forces were measured with a bespoke F310-Z combined axial loadcell and torque transducer supplied by Novatech Measurements Ltd.

2.5 *Cone penetration tests*

To acquire data to validate the CPT-torque correlation method for screw piles, CPT were conducted in-flight to measure the cone resistance (q_c) of the sand. A custom CPT probe was manufactured for this purpose from stainless steel, with a 14 mm diameter, 440 mm long shaft and a 60° conical tip mounted to a 2 kN loadcell from Novatech Measurements Ltd. The CPT probe was not designed to measure separate skin friction, with average skin friction measurements (not used in this paper) deduced from the total resistance measured at the top of the CPT shaft (via the F310-Z loadcell) minus the CPT tip loadcell readings.

At a penetration depth of 140 mm, the CPT reached the maximum permissible load of the loadcell and the test was stopped. Thus, rather than extrapolating data, the installation torque of the piles are only considered up to this depth. The cone resistance data are presented in Section 4 in the context of verification of the proposed method with field data.

3 CPT-TORQUE CORRELATION METHOD

Screw pile installation torque has been correlated to CPT cone resistance to provide a method to predict the installation torque of both single and multiple helix screw piles in dense sand. In-line with the suggestion of Bustamante and Gianeselli (1982) for pile capacity determination, the cone resistance data was averaged over a distance of 1.5 helix diameters above and below the depth of interest in the calculations.

The torque which develops from the installation of a screw pile into sand is assumed to be created by the frictional resistance between the soil and the entire surface area of the pile. In terms of the proposed CPT-torque correlation method, the torque contribution from the upper surface of the helical plates(s) to the total torque is negligible and can be ignored.

The torque required to install a screw pile with *n* number of helices can therefore be predicted using

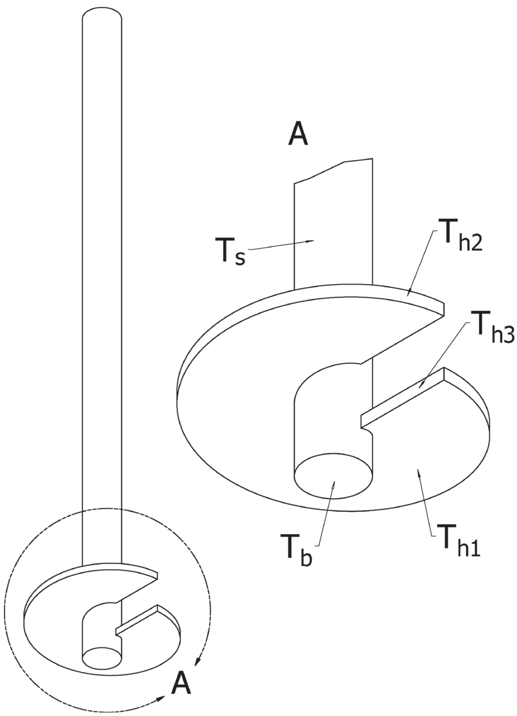

Figure 2. Installation torque resistances acting on a screw pile.

equations 2 to 11, with the components shown visually in Figure 2. In each of equations 4 to 8, the torque is calculated by integrating the relevant frictional resistance multiplied by the appropriate lever arm.

$$T = T_s + T_b + \sum_{1}^{n} T_{h(n)} \tag{2}$$

$$T_h = T_{h1} + T_{h2} + T_{h3} \tag{3}$$

$$T_s = \sum_{\Delta x=1}^{\Delta xi=L} a\bar{q}_c \tan\delta_{crit} \pi \Delta x \frac{d_c^{\,2}}{2} \tag{4}$$

$$T_b = \bar{q}_c \tan\delta_{crit} \pi \frac{d_c^{\,3}}{12} \tag{5}$$

$$T_{h1} = a\bar{q}_c \tan\delta_{crit} \pi \frac{D_h^{\,3} - d_c^{\,3}}{12k_0} \tag{6}$$

$$T_{h2} = a\bar{q}_c \tan(\delta_{crit} + \theta) \pi t \frac{d_c^{\,2}}{2} \tag{7}$$

$$T_{h3} = a\bar{q}_c t \frac{D_h^{\,2} - d_c^{\,2}}{4} \tag{8}$$

$$a = \frac{F_r}{\tan\delta_{crit}} \tag{9}$$

$$k_0 = 1 - \sin\phi \tag{10}$$

$$\theta = \tan^{-1}\left(\frac{p}{\pi}\frac{D_h - d_c}{2}\right) \tag{11}$$

where: T is the total torque resulting during installation; T_s is the torque associated with the shaft area of the central core of the pile with diameter d_c; T_b is the torque from the base of the central core; T_h is the torque resulting from the helix (with diameter of D_h, pitch of p and thickness of t), which is made up of three components - T_{h1} the friction on the underside of a helix during penetration, T_{h2} torque associated with the thin outer peripheral edge of the helix and T_{h3} from the leading edge of the helix cutting into the soil.

The torque from the shaft area of the core is calculated from the sum of intervals of length Δx over the total length of the screw pile core, L. A stress drop index (a) equal to the CPT friction ratio (F_r) divided by $\tan(\delta_{crit})$ (Lehane et al., 2005) is used to compute the radial stress acting on the screw pile. Although the Lehane et al. (2005) method is associated with driven piles, the stress drop index used was derived from CPT data and does not apply to any particular pile installation technique. To account for the inclination of the screw pile helix, the pitch angle (θ) is added to the interface friction angle (δ_{crit}). The earth pressure at rest (k_0) provides a mechanism to convert the radial stress (aq_c) into a vertical stress acting on the underside of the helices during installation. As in other torque prediction methods, any influence from temperature change during installation were disregarded.

The proposed equations differ to those suggested by Al-Baghdadi et al. (2017) in several ways. Firstly, the rotation force reduction factors required for the shaft and base components (f_1 = 0.75 and f_2 = 0.7, respectively) for force prediction during rotary installation, after Deeks and White (2008), have been omitted from equations 4 and 5. These factors were somewhat greater than those found by Deeks (2008) for installation force reduction and is it not clear why they are required for torque prediction.

Secondly, in equation 5, q_b equal to $0.6q_c$ was used. This is often adopted for pile capacity prediction where this may be below ultimate resistance or at 0.1 pile diameters. Therefore, during full flow installation, it would be more appropriate for q_b to equal q_c (Randolph and Gourvenec, 2011). Thirdly, an erroneously absent $\tan(\delta_{crit})$ term in Al-Baghdadi et al. (2017) has been correctly added to equation 5. Fourthly, equation 8 addresses an integration error and uses the radial stress instead of the full cone resistance value. Finally, the stress drop index is no longer universally assumed to equal 0.03 and is instead calculated by equation 9, using the CPT friction ratio and interface friction angle of the screw pile.

4 CPT-TORQUE PREDICTIONS

The proposed method was used to predict the installation torque for both model screw piles from centrifuge tests and field-scale data from Gavin et al. (2013) and Spagnoli (2016). CPT cone resistance data from the centrifuge tests and field data are presented in Figure 3. The q_c values for the CPT testing in the centrifuge test were verified against the prepared relative density (checked by density pot measurements) and gave good correlations to the conventional CPT correlations for relative density by Jamiolkowski et al. (2001) at mid-height of the centrifuge container. Low values of q_c near the surface are associated with the transition to a full-flow mechanism which is not seen in the field data due to the high density or over consolidated near surface soils.

4.1 *Model-scale screw pile torque predictions*

The prediction of installation torque of the single and multi-helix screw piles in the centrifuge tests are shown in Figure 4. The predictions show a good level of correlation with the measured values from the centrifuge tests. Additionally, a prediction based on the method in Spagnoli (2016) is also shown in Figure 4a for the single helix screw pile, where an 80% over-prediction of the torque is evident at 5.5 m.

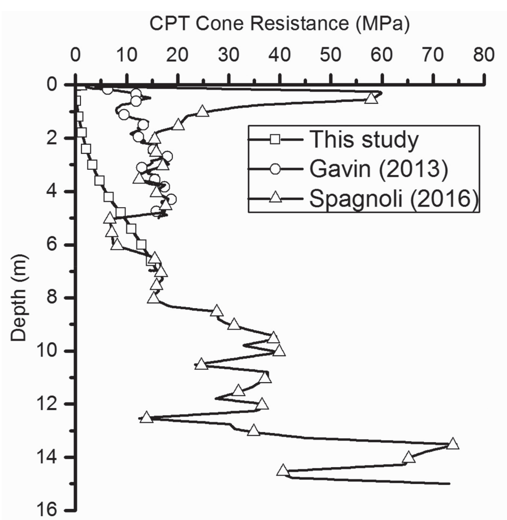

Figure 3. CPT cone resistance from: this study, Gavin et al. (2013) and Spagnoli (2016).

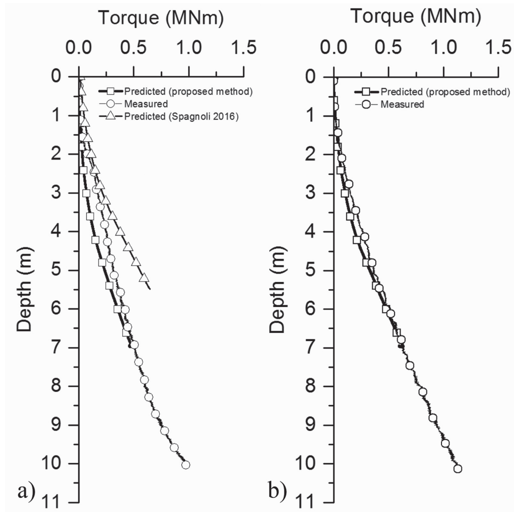

Figure 4. Predicted and measured prototype installation torque from centrifuge tests: a) single helix; b) multi-helix screw pile.

Averaging the CPT cone resistance over a distance of $\pm 1.5D_h$ requires that the CPT extends beyond the screw pile installation depth by $1.5D_h$. In all data in this study, this requirement was not met and thus, the torque predictions only extend to at a depth of $1.5D_h$ above the deepest q_c data point instead of to the full penetration depth of the screw pile.

The proposed method performs well in both cases and it is suggested that the method is applicable for multi-helix screw piles. Previous publications (Gavin et al., 2013; Spagnoli, 2016; Al-Baghdadi et al., 2017) regarding CPT-torque correlations have restricted their predictions to single helix piles only.

4.2 *Field-scale screw pile torque predictions*

Al-Baghdadi et al. (2017) presented a torque prediction based on field data for a single helix screw pile with 100 and 400 mm core and helix diameters respectively, installed to 4.5 m (Gavin et al., 2013). The process is repeated here with the proposed method.

The results (Figure 5a) show close correlations between the predicted and observed installation torque, particularly from a depth of 0.8 to 2.1 m. From 2.1 m to 4.5 m, there is an approximately 15% overprediction of the torque. This is obviously more satisfactory for design than an underprediction. Figure 6b shows a comparison to field testing from Spagnoli (2016) for 16 m long, large diameter single helix screw piles with 368 mm

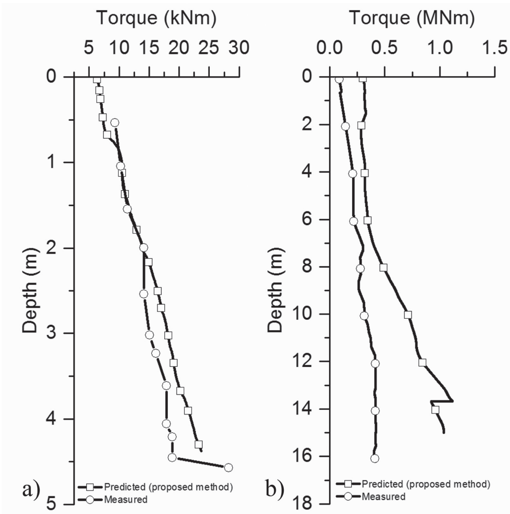

Figure 5. Predicted and measured installation torque from field scale screw piles in: a) Gavin et al. (2013); b) Spagnoli (2016).

diameter cores at a test site in Germany, where the only method available to install the screw pile with the 1500 mm helix diameter (due to torque limitations) was to "surge" the pile up and down, inevitably resulting in unwanted changes to in-situ soil conditions. This may explain the overprediction using the proposed method for the screw pile reported in Spagnoli (2016), with a 750 mm helix diameter, and highlights the need for controlled installation.

5 CONCLUSIONS

This paper presents modifications to the CPT-torque prediction method for screw pile installation proposed by Al-Baghdadi et al. (2017) based on centrifuge tests of single and multi-helix screw piles in dense, dry sand. The changes include: removal of the force rotation reduction factors, which are not deemed appropriate for torque calculations; for the base of the core, a missing $\tan(\delta_{crit})$ term is added and the full q_c value is used to reflect the full flow conditions during installation; the stress drop index used to modify the cone resistance to a radial stress is related to the interface friction angle and CPT friction ratio as well as being incorporated into the helix leading edge calculation. The updated method gives good prediction of the measured centrifuge test data and was further validated by field data from Gavin et al. (2013) and Spagnoli (2016). The modified method also provides further capability in the ability to predict installation torque of multi-helix screw piles.

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