CPT based design procedure for installation torque prediction for screw piles installed in sand

TA Al-Baghdadi, C Davidson, MJ Brown, JA Knappett and A Brennan
University of Dundee, UK

C Augarde, W Coombs and L Wang
Durham University, UK

D Richards and A Blake
University of Southampton, UK

Abstract
Screw piles (helical piles) have been used widely as foundations for onshore projects due to their ability to provide high compressive and tensile resistance as well as reduced noise/vibration during installation. These types of piles have been proposed as a potential innovative foundation for offshore wind turbines in deeper water. In order to adopt the screw pile technique as an offshore foundation, the geometry of the piles would need to be scaled up so they can provide the high capacities required for this application. Such a change in size and geometry will lead to uncertainties in predicting the required torque for installation in different soil types and stress histories. Without the ability to accurately predict installation torque it is difficult to design screw piles for offshore use or develop appropriate installation plant with the required torque capabilities in different soils. This paper presents centrifuge test results of screw piles and CPT tests undertaken in dense sand. The installation torque (T) has been correlated to the cone resistance q_c to establish a proposed CPT-based design method to predict the required installation torque for modified screw pile geometries.

1. Introduction

Screw piles (helical piles) typically consist of a hollow steel shaft with helical plates (sometimes referred to as flanges) which are installed by applying axial force and torque. This foundation type has been used widely onshore in many different applications (i.e. light poles, transmission towers, excavation bracing, buildings, road-side gantries, etc.) due to the speed and the low noise/vibration generated during installation. Recently, screw piles have been proposed as an alternative foundation for offshore wind turbines on jacket structures in deeper water (in excess of 40m water depth) that are currently founded on traditional monopiles or jackets with conventional driven pile foundations (Byrne & Houlsby, 2015 and Spagnoli & Gavin, 2015). This is partly in response to concerns over the noise and disturbance caused by pile driving operations associated with farm development (i.e. where many individual piles are driven) and their perceived impact on marine mammals (Thomsen et al., 2006).

Screw piles typically used onshore have relatively small shaft (76-325mm) and helix (254-762mm) diameters due to their ability to generate high axial capacity in compression and tension. For use in offshore wind energy structures, with larger overall loads including significant lateral loading, screw pile dimensions will require up-scaling (especially central core diameters to carry lateral loads) and optimisation to provide the required capacity whilst minimising torque installation requirements (Knappett et al., 2014 and Al-Baghdadi et al., 2015). One of the main uncertainties in the design and implementation of up-scaled screw piles is estimation of the installation torque. Currently, the installation torque (T) of onshore screw piles is used in the verification of the final tensile capacity (Q_t) based upon the empirical correlation (K_t) proposed by Hoyt and Clemence (1989) in equation (1):

$$Q_t = K_t T \tag{1}$$

Based upon this empirical relationship, it may be possible to predict the required installation torque from an estimation of the installed screw pile capacity but it is unclear how such an approach captures the subtleties of optimised pile geometry K_c values for screw piles with a single helical plate under compression loading vary typically from 6.5 to $9.6m^{-1}$ with decreasing shaft and helix diameters from D_p = 0.508m and D_h = 1.016m to D_p = 0.324m and D_h = 0.762m, respectively (Sakr, 2010). Often though there may be confidence in predicting vertical compressive capacity Q_c and thus K_c values may also be required which are reported to a lesser extent due to onshore screw piles typically being designed and used for tensile performance. A typical K_c value of 8 for the central core diameter used in this study may be found in Perko (2009) but no regards are made for the number of pile helix plates involved. Analytical techniques proposed by Ghaly and Hanna (1991) and Sakr (2015) to calculate the installation torque of screw-piles in sands show good correlation between measured and predicted torque values for small screw piles (low diameter cores) with low numbers of helices, but have only been validated for limited situations.

As part of on-going research at the University of Dundee into screw pile behaviour, previous studies have included 3D finite element modelling (FEM) of the effects of a near surface helix on lateral capacity (Al-Baghdadi et al., 2015), the effects of combined V-H loading on upscaled screw piles (Al-Baghdadi et al., 2017) and 1g physical modelling/2D FEM investigations into optimal helix spacing (Knappett et al., 2014). This paper describes the initial results of centrifuge pile testing and *in situ* cone penetration tests (CPT) which are used to investigate the suitability of existing torque prediction techniques and potentially develop improved approaches for up-scaled geometry of screw piles based upon insitu testing.

The study reported in this paper forms part of a wider study undertaken by the University of Dundee (UoD), Durham University (DU) and the University of Southampton (UoS) to improve the understanding of upscaled screw piles when used as an alternative foundation system for offshore marine renewable energy systems. In addition to physical modelling, this includes the development of Material Point Modelling approaches to investigate installation effects (DU) (Wang et al., 2017) and field verification of the project findings (UoS).

2. Centrifuge modelling test procedure

2.1 Model pile

Models of straight shafted piles (SSP) and single helix screw piles (SHP) were manufactured from mild steel for this study (Figure 1). Both the SSP and SHP had solid cores of 10mm diameter (D_c) with conical tips (apex angle of 60^{o}), while the SHP included a single helix of 20mm diameter (D_h). Table 1 shows the dimensions of the model piles.

Table 1: Model pile dimensions

Model Pile Geometry	Dimension (mm)
Shaft diameter, D_c	10 (0.5)
Helix diameter, D_h	20 (1)
Helix pitch, p	7.9 (0.395)
Helix thickness, t_h	1.4 (0.07)
Pile embedment length, L	200 (10)
Helix depth below soil surface	187.5 (9.375)

* Prototype shown in parenthesis (m)

Figure 1: Photograph of the model piles

2.2 Container and model soil

The centrifuge tests were carried out on the University of Dundee beam centrifuge. The model piles were installed in flight at an acceleration of 50g in a steel container with internal dimensions of 800mm long, 500mm wide and 580mm deep. A manual sand air-pluviator was used to fill the container up to 450mm depth with dry HST95 silica sand to achieve a relative density (D_r) of 73% to represent dense sand conditions. A summary of the HST95 silica sand properties is shown in Table 2, and more details can be found in Lauder et al. (2013). In order to minimize potential boundary effects, the distance from the pile tip at full installation depth (200mm below the soil surface) to the container bottom was 12.5D_h and the distance from the pile centre to the nearest container side was also 12.5D_h.

Table 2: Sand properties

HST95 silica sand property	Value
Sand unit weight (kN/m^3)	16.75
Minimum dry density (kN/m^3)	14.59
Maximum dry density (kN/m^3)	17.58
Critical state friction angle, ϕ (degrees)	32
Interface friction angle, δ (degrees)	24
D_{30} (mm)	0.12
D_{60} (mm)	0.14

2.3 Pile installation and testing

The centrifuge tests of SSP and SHP were carried out in flight using a servo-controlled actuator developed at the University of Dundee by Al-Baghdadi et al. (2016). The vertical installation speed was related to the rotational speed by the pitch of the screw pile helix so that the screw pile penetrated the soil at a constant rate equal to the helix pitch per one full pile rotation. This screw pile installation procedure has been recommended by others to minimize soil disturbance during installation which may reduce the screw pile capacity (Perko, 2000; Tsuha et al., 2012; and BS 8004, 2015). Following this approach, all piles were installed inflight at a vertical speed of 26.3mm/min with a rotational speed of 3.33rpm. Vertical load during installation and subsequent pile load tests as well as torque were measured using a bespoke combined torque load cell with 20kN axial force capacity and 30Nm torque capacity. A compression test was carried out after the end of the installation at a rate of 1 mm/min. The failure criteria for compression capacity (Q_c) were based on the modified Davisson method (ICC-ES, 2007) that limited to net deflection of 10 percent of the flange diameter ($0.1D_{f\text{-}net}$). The net deflection is the total deflection of the screw pile minus the elastic shortening in the screw pile shaft length due to the applied load (ICC-ES, 2007).

2.4 CPT tests

Centrifuge cone penetration tests (CPTs) were conducted to correlate the cone resistance (q_c) to the installation torque of straight shafted piles and screw piles. A custom CPT probe was fabricated from stainless steel with outer diameter of 14mm and a conical tip with 60^o apex angle. The CPT only measured tip resistance q_c via a 2 kN load cell. Cone shaft resistance was determined from the total cone resistance measured above the penetrating cone arrangement by a 20 kN load cell, with the difference between the tip and total resistance measurements used to determine shaft resistance. The CPTs were carried out in flight under 50g acceleration level in dry dense sand (D_r 73%). The maximum depth reached was 170 mm at which point the tip load cell reached its maximum allowable load; beyond this point, a linear extrapolation was used to determine the q_c at a depth up to 200 mm. The penetration rate was kept constant at 26.3 mm/s. Figure 2 shows the results of a typical centrifuge CPT test. All results from this point on in the paper are referred to in scaled up prototype units to allow comparison with field operations.

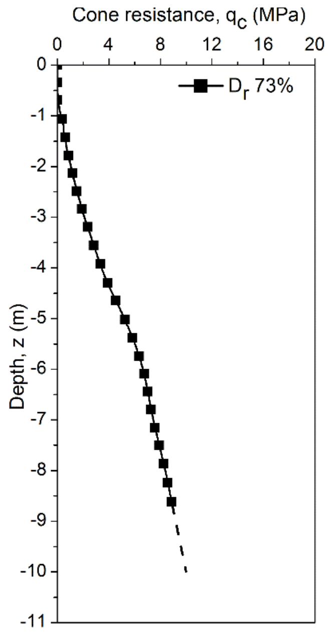

Figure 2: Centrifuge CPT results in dense sand (D_r 73%) at prototype scale.

3. Centrifuge tests results

Installation test results were obtained for two centrifuge tests; the average results of which are shown in Table 3.

Table 3: Centrifuge tests results of SSP and SHP in dry sand at depth 10 m at prototype scale (200 mm at model scale)

Pile	Compressive capacity, Q_c (kN)	Final torque, T (kNm)	K_c (m^{-1})
SSP	1.453 (3632)	4.305x10^{-3} (538)	(6.75)
SHP	2.397 (5992)	8.14x10^{-3} (1018)	(5.9)

* Prototype values shown in parenthesis

4. CPT method to predict the installation torque

The installation torque (T) of the SSP and SHP were correlated to the average cone resistance (q_{ca}) to establish a CPT design method to predict the required installation torque for SSP and SHP installed in dense sand. The average cone resistance (q_{ca}) was computed as the average value over a distance of 1.5 helix diameters above and below the base helix depth (1.5D_f) as suggested by Bustamante and Gianeselli (1982). It was found in these tests that averaging the value of the cone resistance over the 1.5 helix diameters had little effect on the cone resistance magnitude ($q_{ca} \approx q_c$) as the increase in the cone resistance is approximately linear with depth. The CPT correlation method was proposed firstly for straight shafted piles (SSP) and developed later for screw pile with a single helix (SHP).

4.1 Straight shaft pile (SSP)

The torque that develops during installation of a closed-ended straight shafted pile is assumed to be generated due to shaft and base frictional resistances during penetration into the soil. The prediction of the installation torque based on the average cone resistance of CPT centrifuge tests which were carried out in sand was achieved with equations (2) to (4).

$$T = T_s + T_b \qquad (2)$$

$$T_s = aq_{ca} \tan\delta\pi D_c L \frac{D_c}{2} f_1 = aq_{ca} \tan\delta\pi L \frac{D_c^2}{2} f_1 \qquad (3)$$

$$T_b = \int_0^{\frac{D_c}{2}} \left[q_b \tan\delta(2\pi r^2)dr\right] f_2 = \frac{q_b \tan\delta\pi D_c^3}{12} f_2 \qquad (4)$$

Where: T_s: shaft torque resistance; T_b: base torque resistance; a: stress drop index (Lehane et al., 2005) (equal to CPT friction ratio (R_f) divided by tanδ, R_f which was found to be 3 % for the tests here which is in line with a stress drop factor of 0.03 as adopted by Lehane et al., 2005); q_{ca}: average cone resistance; δ: interface friction angle (Table 1); L: pile core length; D_c: pile core diameter; f_1: shaft resistance rotation reduction factor (0.75) (based on the reduction of the pile shaft resistance due to the pile rotation during the installation of staight shafted piles by Deeks & White (2008)); f_2: base resistance rotation reduction factor (0.7) (again from Deeks & White (2008)); q_b: pile end bearing reistance equal to 0.6 q_{cav} for closed-ended pile (Lehane et al., 2005); and r: the radius to the pile centre.

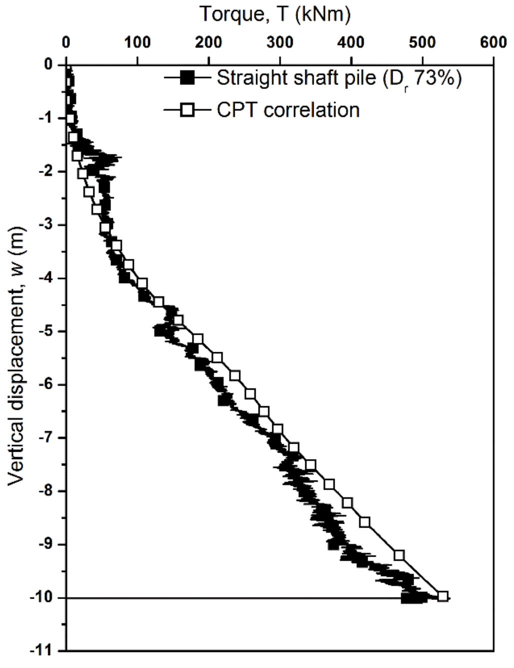

Figure 3: The estimated and measured torque resistance acting on an SSP during installation from centrifuge testing

The results showed a good agreement between the CPT correlation method and the installation force and torque results of the straight shaft pile in sand as shown in Figure 3.

4.1 Screw pile (SHP)

The required torque to install a screw pile with a single helix is the sum of the shaft and base frictional resistance (as per the SSP) in addition to the helix frictional resistance. Therefore, the method proposed in the previous section (Equations 2 to 4) for the straight shaft pile (for estimation of the shaft installation torque and force) was used for torque estimation for the core with a helix contribution added.

The torque exerted during installation of a single helix screw pile was therefore predicted using the following equation:

$$T = T_s + T_b + T_h \qquad (5)$$

The installation torque due to the resistance of the screw pile shaft (T_s) and base (T_b) was estimated using the equations (3) and (4) respectively. The torque exerted due to the helix resistance (T_h) was estimated based on the CPT average cone resistance (q_{ca}) using the following procedure with the individual contributing elements shown in Figure 4:

$$T_h = T_{h_1} + T_{h_2} + T_{h_3} \qquad (6)$$

$$T_{h_1} = \int_{\frac{D_c}{2}}^{\frac{D_h}{2}} \frac{aq_{ca}}{k_o} \tan\delta(2\pi r^2)dr = aq_{ca} \tan\delta \frac{\pi(D_h^3 - D_c^3)}{12k_o} \qquad (7)$$

$$T_{h_2} = aq_{ca} t_h \tan\delta \frac{\pi D_h^2}{2} \qquad (8)$$

$$T_{h_3} = \int_{\frac{D_c}{2}}^{\frac{D_h}{2}} q_{ca} t_h r dr = q_{ca} t_h \frac{D_h^2 - D_c^2}{8} \qquad (9)$$

Where D_h: helix diameter; t_h: helix plate thickness; K_o: is the earth pressure coefficient at rest (K_o = 1-sinϕ` in normally-consolidated soil).

The helix base resistance (T_{h1}) represents the torque applied on the bottom side of the helix during the installation. T_{h1} was calculated by integrating the frictional resistance (aq_{ca}) over the annular helix element area ($2\pi rdr$) multiplied by the distance from the element to the pile centre (r) as shown in Figure

(5). The earth pressure at rest is used to simply vary the radial stress determined from CPT results modified by the stress drop index into a vertical stress on the helix plates during installation.

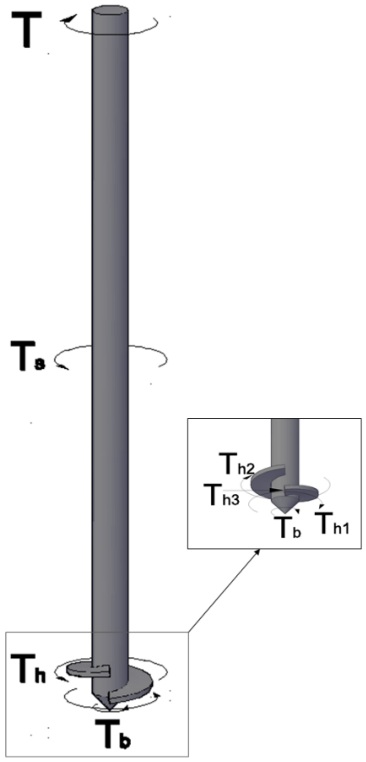

Figure 4: The proposed torque resistances acting on a single helix pile during installation

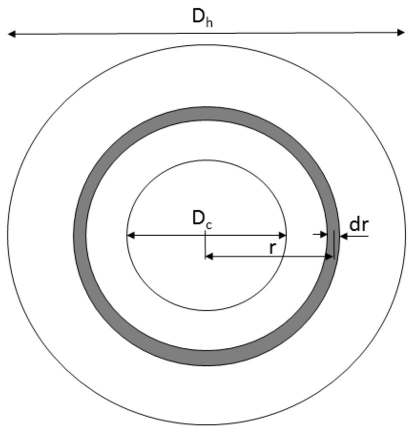

Figure 5: Plan view of the screw pile helix

The helix circumferential resistance (T_{h2}) accounts for the torque applied on the circumference side of the helix during the installation. T_{h2} was calculated by multiplying the frictional resistance (aq_{ca}) by the helix circumference area ($\pi t_h D_h$) times the distance from the helix circumference to the pile centre (D_h).

The helix leading edge resistance (T_{h3}) stands for the torque applied on the leading edge of the helix during the installation. T_{h3} was calculated by integrating the cone resistance (q_{ca}) over the leading edge area ($t_h dr$) multiplied by the distance to the pile centre (r).

This proposed method was used to estimate the installation force and torque of a single helix screw pile and compared with the centrifuge tests results as shown in Figure 6. The results again showed a good agreement between the CPT correlation method and the installation torque results of a single helix screw pile in dense sand. Also, a comparison was made with the installation torque that was obtained based on the K_c value of 8 from Perko (2009). Figure 6 showed that the estimated torque based on the empirical factor K_c under predicts the measured torque. Table 3 suggests that K_c should be closer to 6 and appears to reduce with the inclusion of a helix plate.

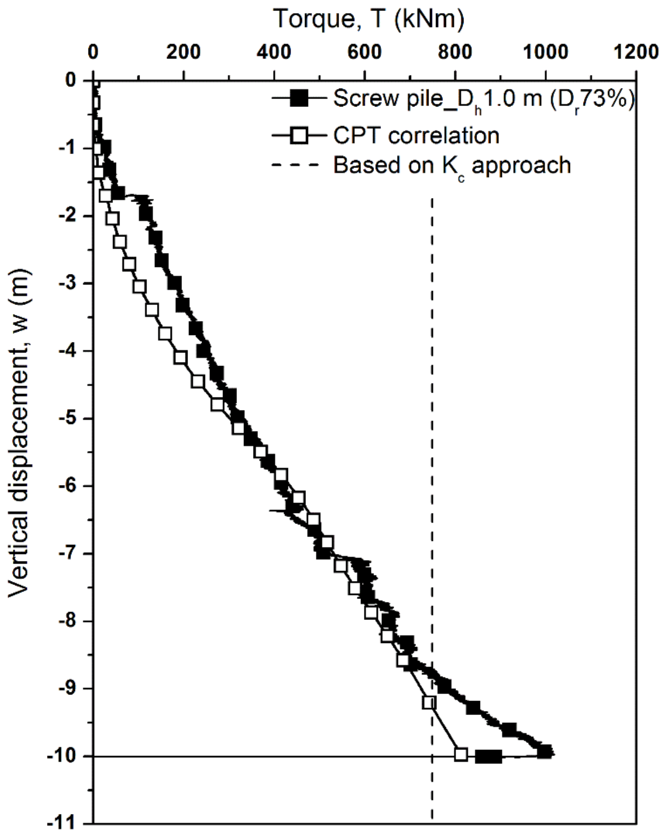

Figure 6: The estimated and measured torque resistance acting on a single helix screw pile during installation

5. Reliability of proposed method for torque estimation

The proposed CPT method was further validated based on the field test results of screw piles in fine sand (D_{50} 0.10-0.15mm) with accompanying CPT data, reported by Gavin et al. (2013). The screw piles had a 0.11m core diameter with a single helix of 0.40m diameter placed 0.13m above the screw pile tip. The data of CPT tests 1 and 9 reported by Gavin et al. (2013) were digitized and used for the proposed CPT method as they provided representative values of the cone end resistance (q_{ca}) and sleeve friction (f_s). The CPT method procedure proposed herein was used to estimate the installation torque based on the average cone resistance and sleeve friction data. The results of the estimated installation torque were compared with field tests of Gavin et al. (2013) as shown in Figure 7 (upper and lower bound screw pile installation torque measures only shown for clarity). The results showed that the proposed CPT method correlates well with the observed installation torque and with that predicted by Gavin et al. (2013).

An existing torque to CPT q_c correlation proposed by Gavin et al. (2013) is also shown in Figure 7 and is based on earlier work by Tsuha and Aoki (2010) on the relationship between uplift capacity and torque correlation factors, adapted to determine uplift capacity from the CPT cone resistance using empirical factors, as shown in equations (10) to (14).

$$T = \frac{Q_s D_c}{2} + \frac{Q_h D_h (\theta + \delta_r)}{2} \tag{10}$$

Where θ and δ_r are the helix angle and interface angles respectively; The helix angle (θ) is given by equation (11)

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

where p is the helix pitch. Q_s and Q_h are the shaft and helix uplift capacities respectively, found using equations (12) and (13).

$$Q_s = q_{cav} \pi D_c L \tag{12}$$

where the average shaft resistance, $q_{cav} = 0.6 f_s$ and

$$Q_h = q_{up} \pi D_h^2 \tag{13}$$

where the helix uplift resistance, $q_{up} = 0.065 q_c$.

Spagnoli (2016) suggested a variation of the approach proposed by Gavin et al. (2013) which replaces the helix diameter (D_h) in equation (10) with the circle diameter corresponding to the helix area, d_c, as shown in equation (14) and (15).

$$T = \frac{Q_c D_c}{2} + \frac{Q_h d_c (\theta + \delta_r)}{2} \tag{14}$$

$$d_c = \frac{2}{3}\left\{\frac{D_h^3 - D_c^3}{D_h^2 - D_c^2}\right\} \tag{15}$$

The shaft capacity (Q_c) in equation (14) is found using equation (12), while the helix capacity is calculated from equations (16) and (17).

$$Q_h = q_{up} \pi A_h \tag{16}$$

$$A_h = \frac{\pi\left(D_h^2 - D_c^2\right)}{4} \tag{17}$$

Spagnoli (2016) uses the same empirical factors proposed by Gavin et al. (2013) to determine the shaft and helix resistances, but suggests that the cone resistance is averaged over a distance of 1.5 helix diameters below the pile tip (i.e. q_{ca} is used instead of q_c).

The proposed method was further verified against another case study following the field work of Mori (2003) on the installation of a "Tsubasa pile". This pile had a core diameter of 0.8m and a wing made of two semi-circular plates, with a diameter of 1.6m, fixed at the pile toe at opposing angles to give a pitch of 1.3m. The pile was installed to a depth of up to 60m in silty fine sand.

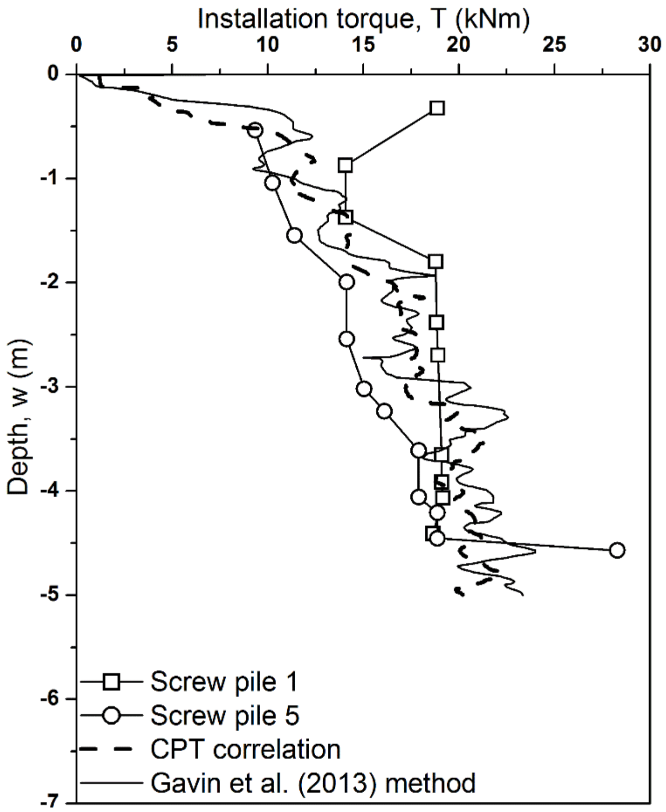

Figure 7: Comparison of field tests results of a single helix screw pile (D_h 0.4 m) of Gavin et al. (2013) with estimated torque proposed CPT method

CPT cone resistance (q_c) was estimated from the interpretation and back calculation of the reported SPT N values using the correlation proposed by Robertson et al. (1986). From the average q_c and overburden stress, the normalised cone resistance was calculated (Lunne, 1997) and from the correlations provided in Lunne (1997), the average friction ratio was assumed to be 1% for the overall silty sand encountered. The proposed CPT method was used to estimate the installation torque and compared with the methods proposed by Gavin et al. (2013) and Spagnoli (2016) in Figure 8.

The results show that the proposed CPT method gave higher predictions compared to the measured installation torque as shown in Figure 8. However, these are much closer than the torque calculated using the equations suggested by both Gavin et al. (2013) and Spagnoli (2016), which both show a significant over prediction of the torque, particularly between 10-15m and 43-53m depth.

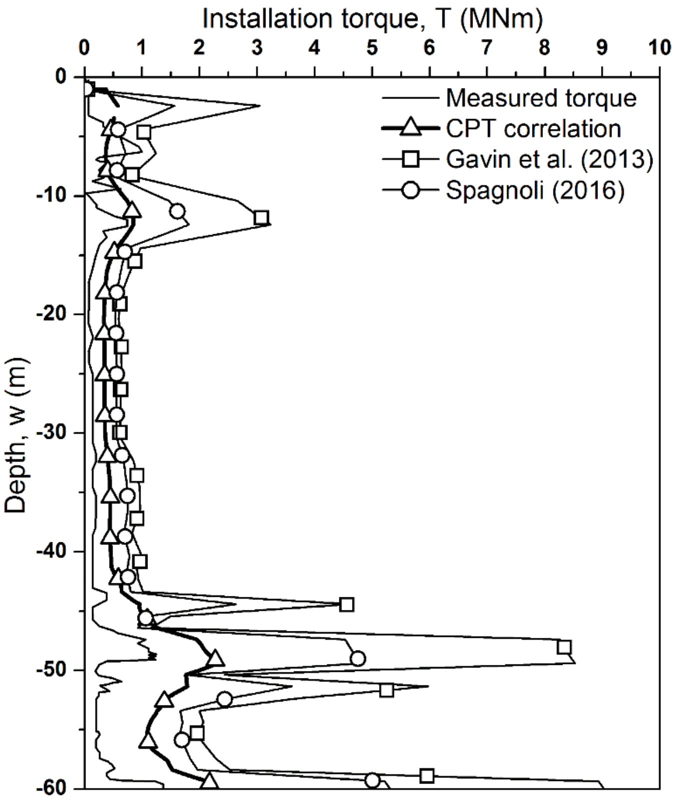

Figure 8: Comparison of field tests results of a helix "Tsubasa pile" (D_c = 0.80m, D_f 1.6m) of Mori (2003) with estimated torque from the proposed CPT method

The difference between the Gavin et al. (2013) and Spagnoli (2016) results highlight the effect of not averaging the cone resistance and of using a simplified approach to the helix area which does not account for the reduction in area caused by the pile core. The general over prediction by all three methods is thought to be in part to the geometry of the pile considered which was not a classic screw pile design but may have resulted in more of a cutting effect during installation, potentially over-cutting the diameter and resulting in the relatively low measured torques seen in Figure 8. It is acknowledged though that it is assumed in the method that the piles wre installed in an appropriate manner without excessive crowding forces or overflighting which have the potential to significantly increase or decrease installation torque requirements respectively. Thus for the proposed methodology to be applicable significant care is needed to maintain proper installation techniques.

6. Conclusions

This paper presented centrifuge test results of a straight shaft pile (SSP), a single helix screw pile (SHP) and CPT test undertaken in dense sand (D_r 73%). The installation torque (T) has been correlated to the cone resistance q_c in order to establish a CPT-based design method to predict the required installation torque for modified screw pile geometries. A CPT cone resistance correlation was proposed to estimate the installation torque of straight shafted piles and single helix screw piles installed in dense sand. The proposed CPT correlation method was validated against field tests results of Gavin et al. (2013) and Mori (2003). The results of both the centrifuge tests and field validations showed that the proposed method can provide good prediction of the installation torque with depth, and potentially improved prediction over the empirical method of Perko (2009) and the CPT based methods of Gavin et al. (2013) and Spagnoli (2016).

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