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Field investigation to evaluate the uplift capacity and installation performance of screw piles in sand

Enquête sur le terrain pour évaluer la capacité de soulèvement et les performances d'installation des pieux vissés dans le sable

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ABSTRACT: This paper presents results from an ongoing investigation examining the installation requirements (thrust and torque) for screw piles in sand as well as the static uplift capacity of these piles. The tests described in this paper here were conducted on field-scale piles in medium dense aeolian siliceous sand at the University of Western Australia's Shenton Park Field Station. The thrust and torque were measured during installation to investigate the interaction between thrust, torque, and the advancement ratio of the pile. Static tension tests were undertaken to examine the relationship between the uplift capacity and installation torque and to assess the suitability of existing prediction methods. The test results and observations contribute to the assessment of the practical applicability of screw pile technology at the scale required for offshore wind applications, where limitations on the available installation thrust and torque exist. exist.

RÉSUMÉ : Cet article présente les résultats d'une étude en cours sur les exigences d'installation de pieux vissés dans des matériaux sableux, ainsi que leur résistance au tension chargement statique vertical. Les expériences décrites dans cet article ont été réalisées sur des pieux à grande échelle dans un sable éolien siliceux de densité moyenne, à la Shenton Park Field Station de l'Université d'Australie-Occidentale. La force de poussée verticale et le couple ont été mesurés au cours de l'installation dans le but d'évaluer l'interaction entre la force de poussée, le couple et l'avancement du pieu. Des essais de chargement statique tension vertical ont été réalisés pour analyser le lien entre capacité et couple d'installation et pour évaluer l'adéquation des méthodes de prédiction existantes. Les observations et les résultats des essais contribuent à démontrer le potentiel d'utilisation de pieux vissés à une échelle requise pour une déploiement dans le domaine de l'éolien offshore, pour lequel il existe des limites quant aux capacités d'installation disponibles (force de poussée verticale et couple).

KEYWORDS: screw piles, torque, CPT, sand, offshore.

1 INTRODUCTION

The use of screw piles as deep foundations has increased tremendously in recent years largely because of their good performance in both axial compression and tension in a variety of different ground conditions. The installation of these piles is carried out by applying torque and thrust to the upper end of the shaft that typically comprises of one or two helices with a helix to shaft (or core) diameter ratio (D_h/d_s) varying from1.5 to 8 (Perko 2009). The relatively high capacities of screw piles coupled with a rapid, quiet and low-vibration installation procedure contribute to the growing popularity of this pile type (Sakr 2009).

Screw piles are being considered as an alternative to driven monopiles to support offshore wind turbines (Davidson et al. 2018, Richards et al. 2019, Sharif et al. 2020 among others) and and have already been successfully used in marine environments (Spagnoli et al. 2020). However, their geometries will require substantial enhancements to meet the large loads applied in the offshore environment and concerns have been raised over these enhancements and the need to accommodate the large installation loads and torque into new equipment.

Tsuha and Aoki (2010) and Spagnoli et al. (2020) contest that the torsional resistance measured during installation is related directly to the the uplift capacity of screw piles. The torsional resistance is also needed to determine structural strength requirements for the shaft and helix (Spagnoli and Gavin 2015).

The prediction of the installation torque in typical onshore piles is often based on one of three methods (Davidson et al. 2020), namely (i) correlation of field measured torque with anticipated or measured pile capacity (Hoyt and Clemence, 1989; Perko, 2009); (ii) modification of empirical pile capacity design methods (Ghaly and Hanna 1991; Tsuha and Aoki, 2010; Sakr, 2015) and (iv) direct correlation with the cone penetration test (CPT) end resistance (Gavin et al. 2013; Spagnoli et al. 2016; Al-Baghdadi et al. 2017; Davidson et al. 2018a).

The assessment of a reliable method relating uplift capacity and installation torque is clearly of significant importance to the estimation of both the installation requirements and pile capacities for larger offshore screw piles. Several studies involving installation torque and axial capacity of small-scale screw piles such as Malik and Kuwano (2020), Nagai et al. (2018), Davidson (2018, 2020) have been published in recent years. However, results from field-scale screw piles are still limited in the literature. This paper extends the database of good quality field trials on a number of screw pile geometries in sand and used these results to evaluate existing predictive approaches for uplift capacity as well as shedding light on the influence of the geometry on uplift capacity.

2 METHODOLOGY

2.1 *Test Site*

The site of the screw pile tests is located in Perth, Western Australia and it has been widely investigated using a range of in-situ and laboratory tests (e.g., Lehane et al. 2004; Schneider et al. 2008) as well as being used for a number of field experiments (Schneider 2007; Xu 2007, Anusic et al. 2019, Bittar et al. 2020). The stratigraphy at the site comprises a 5 to 7 m thick deposit of medium dense aeolian siliceous sand overlying weakly cemented Tamala limestone. Cone penetration tests (CPT) were conducted in the test area and the results are summarized in Fig. 1.

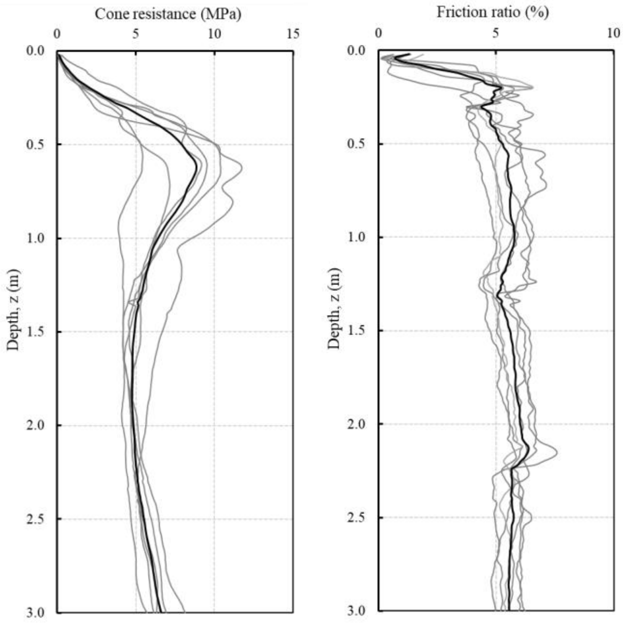
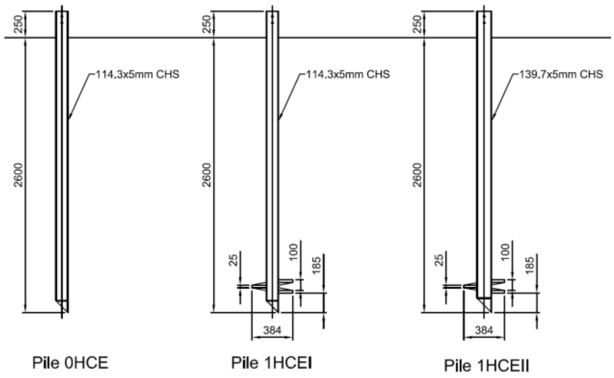


Figure 1. Cone resistance (q_c) and Friction ratio (Fr) measured at Shenton Park field test. Bold lines represent average values.

2.2 *Pile details*

The field test program involved four screw piles and one straight pile with no helix. Pile geometries are detailed in Fig. 2. The pitch (p) and helix diameter (D_h) of all screw piles tested were 100 mm and 384 mm respectively. Two different shaft diameters (d_s) of 114 mm and 140 mm were fabricated for this investigation. Double helix piles were fabricated such that the spacing ratio (S/D_h) equaled 2; this ratio was selected based on the recommendations of Alwalan et al. (2021) to ensure separate failure mechanisms occur at the helices. Closed and ended bases on the shafts were also examined.



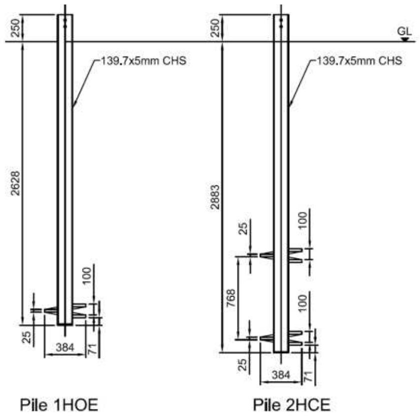


Figure 2. Test pile geometries (measurements in mm)

2.3 *Installation and Testing*

The piles were installed using a torque head supported by a 10 tonne excavator machine. All the piles, including the pile with no helix, were installed to depths (H) of between 2.6 and 2.8 m, giving a H/D_h ratio of 7 for the single helix piles that promoted a deep failure condition (Das 1990). Installation was controlled to achieve minimum possible thrust (which would be difficult to provide for offshore installations) and 5 revolutions per minute (rpm). A plug length ratio (PLR) of 0.78 was determined from plug measurements taken after installation.

Torque (T), thrust (V) and angular rotation (θ) were measured during pile installation using a ProDig® Intelli-Tork® C441-S400 wireless monitoring system load cell. Data were sampled, recorded and transmitted in real time via an on-board 2.4 GHz wireless transmitter to the Intelli-Tork® App operating on an Android smartphone.

All the static load tests were conducted no more than one week after the pile installation. The axial load was applied using an electric pump connected to a hydraulic jack. The load was measured at the pile head and recorded by a digital load cell and verified by a pressure gauge connected to the calibrated hydraulic jack. The pile head displacements were measured using two linear variable differential transformers (LVDTs) mounted on an independent reference frame. The load was applied in 4 increments of approximately 20 kN and then reduced to 10 kN increments as failure was approached. Each increment was maintained until creep became negligible.

3 RESULTS

3.1 *Installation Measurements*

Fig. 3 illustrates the torque (T) measured during installation of each of the pile geometries shown in Fig. 2. For the pile with no helix and a closed end (0HCE), very low torque was measured up to 0.5 m penetration depth. This increased to T=2.3 kNm over the next 0.4 m and remained relatively constant at this value until the pile reached its target depth of 2.6m. A similar trend was observed for all the screw piles with a single helix i.e. low T up to 0.5m, a rapid increase in T over the next 0.5m followed by a relatively mild rate of increase in T to the final penetration depth. The T profile for double helix pile is comparable although the rate of increase of T with depth is larger. In general, it is observed that when enlarging d_s or adding one more helix increases the torque, but also increases the rate of torque gain with depth.

A comparison of the T values for the piles with $d_s = 114$ mm indicates that a single (368 mm diameter) helix contributes about 60% to the total maximum installation torque (see 1HCEI). Fig. 3 also shows that an increase in d_s from 114 mm to 140 mm with the consequent reduction of the net helix diameter (D_h-d_s) led to almost doubling of the T value at the end of installation, which is a surprising result. The addition of one helix to the 140 mm shaft screw pile increased the maximum torque at the end of installation by 4 kNm, which is comparable to the difference in torque between the 114 mm pile shafts with and without a helix.

Torque measurements for piles 1HCEII (d_s = 140 mm, closed ended) and 1HOE (d_s = 140 mm, open ended) are virtually identical indicating that the end condition (open or ended) does not affect the installation torque (at least for the studied shaft diameters).

The thrust forces applied to the screw piles during installation are plotted on Figure 4. This force was kept to a minimum (as stated previously) but needed to be as high as 18 kN to allow insertion of the pile with no helix. For the screw piles, in general, no thrust was required after an initial penetration of about 0.5m below which depth the rotating helix essentially pulled the piles into the ground. The additional thrust applied to Pile 1HCEI is related to poor installation control (as it was the first screw pile installed).

Advancement ratios (or pitch) of the installed piles were calculated from rotational and vertical pile penetration records. Fig. 5 shows advancement ratios (AR) of all the piles installed and the 'perfect pitch' line (AR = 24.1), also referred to as 'pitch matched' or 'perfect' installation which is defined as the ratio of the circumference of the outer edge of the helix to the helix pitch (Lutenegger, 2019). For example, at perfect installation, the screw pile with a geometrical pitch of 100 mm should penetrate the soil at a vertical movement rate of 100 mm/revolution. At least 80% of perfect installation pitch is generally recommended to minimize soil disturbance and improve in-service pile performance (Perko, 2009; Tsuha et al. 2012). The high initial AR shown on Fig. 5 is due to the helix failing in grabbing the soil and providing torsional resistance and is consistent with the torque measurements. Apart from the first 0.7 m, the AR varies from about 30 to 60 which is higher that the perfect pitch. This is likely to be because the thrust application was kept to a minimum during installation.

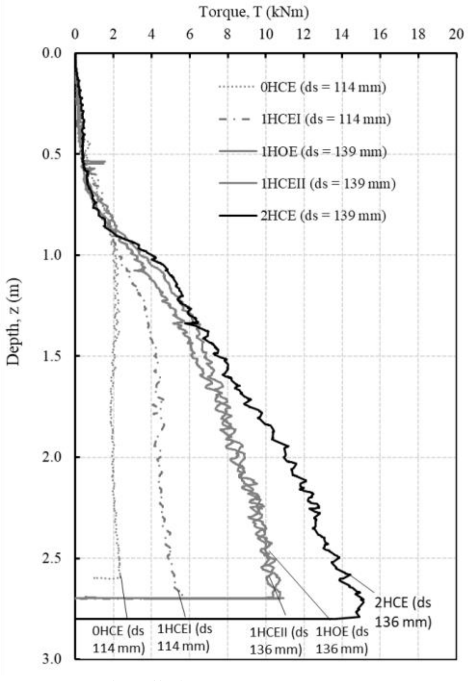


Figure 3. Torque installation measurements

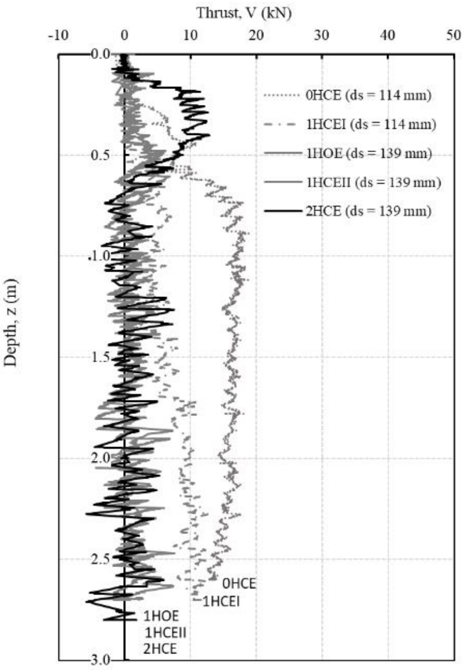


Figure 4. Thrust installation measurements

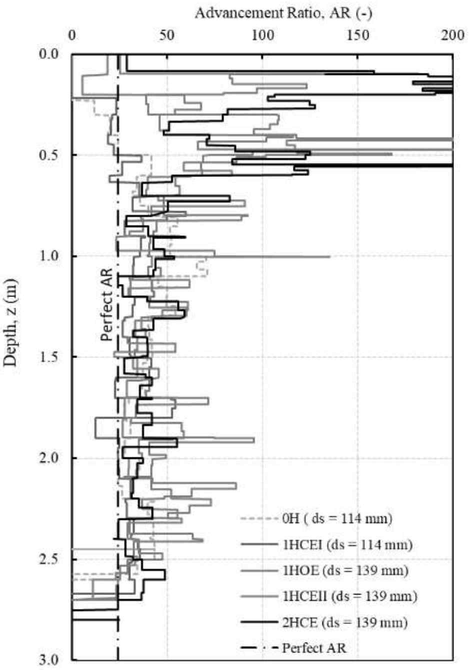


Figure 5. Advancement ratio measurements during installation

3.2 *Tension Load Tests Results*

The load displacement responses measured during static tension tests are plotted in Fig. 6. The pile with no helix mobilized an uplift capacity of 59 kN whereas the single helix pile with the same diameter (1HCEI) showed a softer initial stiffness but attained a capacity of 110 kN at a pile head displacement of 38 mm (10% of the helix diameter). Piles 1HCO and 1HCEII gave almost identical uplift capacities (138 kN and 140 kN respectively) confirming, as suggested by the torque measurements, that the pile end condition did not affect the uplift capacity of these screw piles. The double helix screw pile (2HCE) mobilized an axial resistance of 178 kN indicating that the addition of a second helix increases the uplift capacity by about 27%.

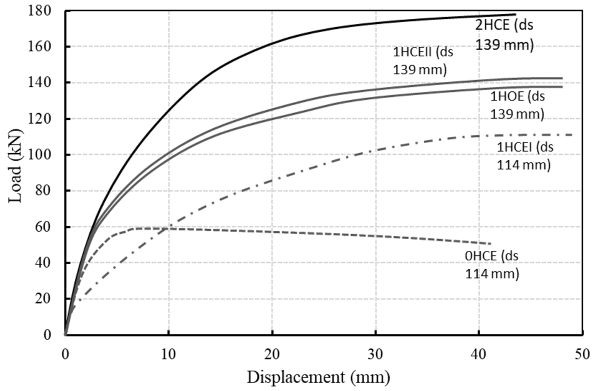


Figure 6. Tension test load displacements

In an attempt to estimate the shaft and helix contribution of these screw piles separately, the shaft friction (τ_s) of the piles was estimated from the shaft capacity of the pile with no helix (0HCE). This calculation indicated a τ_s value of 51.7 kPa which, interestingly, is about double the shaft friction generated by equivalent driven piles at Shenton Park (Bittar et al 2020). Table 1 illustrates the shaft and helix load estimations for each test pile based on this τ_s value and the effective length (L_{eff}) calculation for screw piles recommended by Zhang (1999).

Table 1. Shaft and helix load estimations from total capacities

Pile	**L (m)**	**d_s (m)**	**D_h (m)**	**Q_s (kN)**	**Q_h* (kN)**	**Q_u (kN)**
0HCE	2.6	0.114	0.384	59.0		59.0
1HCEI	2.7	0.114	0.384	46.7	63.3	110.0
1HOE	2.7	0.114	0.384	57.0	81.0	138.0
1HCEII	2.7	0.114	0.384	57.0	83.0	140.0
2HCE	2.8	0.114	0.384	54.8	123.2	178.0

*Q_h is the uplift capacity of a single helix determined from Q_u and Q_s

4 DISCUSSION

The relationship between the final torque (T) and the uplift capacity of the piles (Q_u) tested for this study is presented in Fig. 6. Assuming that Q_u is zero when the torque is zero, this plot indicates that Q_u varies approximately with T raised to the power of 0.6 i.e. Q_u does not increase linearly with T as indicated in Equation (1).

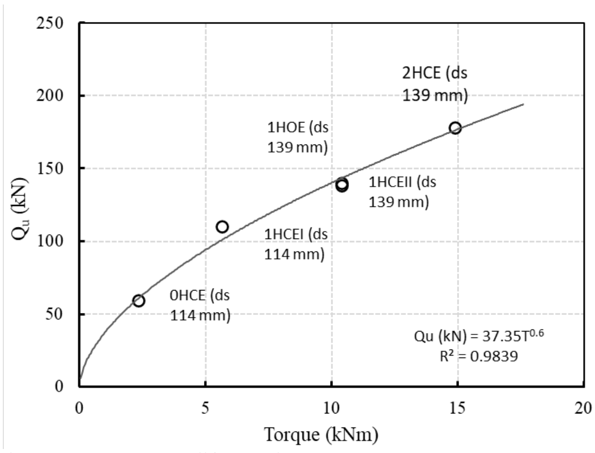


Figure 6. Torque vs. uplift capacity

Perko (2009) collected Qu and T data from over 600 single helix screw piles and correlated them by a linear regression (Fig. 7). The data were from tests performed on piles with helix diameters up to 350 mm and lengths up to 8 m (Spagnoli 2017). However, the torque measurements in most of this database were less than 30 kNm and the Qu vs T relationship is highly scattered in this region. As a consequence, Spagnoli (2017) suggests no unique Qu - T correlation exist.

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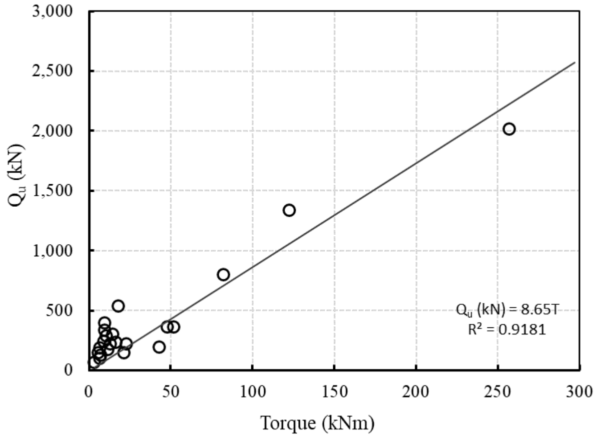

Figure 7. Torque vs. uplift capacity (modified after Perko 2009)

Results from the present study were evaluated against torque-capacity prediction methods. In contrast to the trend shown on Fig. 6, Hoyt & Clemence (1989) assume a direct proportional relationship between Qu and T via an empirical factor, K_t :

$$Q_u(kN) \;=\; K_t\ (m^{-1}).\ T\ (kNm) \tag{1}$$

The same authors proposes a range of Kt values which depend on the pile shaft diameter. Perko (2009) developed the following equation from backanalysis of 300 load tests which relates Kt with the shaft diameter of screw piles :

$$K_t(m^{-1}) = \frac{1433}{[d_s(mm)]^{0.92}} \tag{2}$$

Ghaly & Hanna (1991) correlated the installation torque and the pile uplift capacity based on laboratory investigation on small-model screw piles. Their proposed relationship is :

$$\left(\frac{Q_u}{\gamma A_h H}\right) = 2\left(\frac{T}{\gamma A_h H p}\right)^{1.1} \tag{3}$$

where γ is the unit weight of sand, A_h is the surface area of the helical plate, H is the installation depth and p is the helix pitch.

Tsuha & Aoki (2010) developed a torque model where the torque is linked to the uplift resistance of the pile through the following expression:

$$T = \frac{Q_s d_s}{2} + \frac{Q_h d_c(\theta + \delta_r)}{2} \tag{4}$$

$$\mathrm{d}_c = \frac{2}{3}\left(\frac{D_h^3 - d_s^3}{D_h^2 - d_s^2}\right) \tag{5}$$

$$\theta = tan^{-1}\left(\frac{p}{\pi d_c}\right) \tag{6}$$

where θ is the helix angle, and δ_r is the ultimate interface friction angle between the sand and the pile shaft, taken as

29°. The method was originally developed to estimate the installation torque from different capacity methods presented in the geotechnical literature.

Table 2 summarises the torques calculated from the selected uplift capacity prediction methods and compares these with the measured torques. In general, it is seen that the Perko method gives a reasonable estimation of torques from measured uplift capacities for both single and double helix screw piles. It is important to mention that the Perko method did not contemplate double helix piles in its development, and, despite this, the method produced a good estimation of the torsional resistance of the double helix screw pile.

The application of the Tsuha & Aoki (2010) method requires estimation of Q_h, which was derived by backanalysis of the actual measured ultimate capacity. Therefore, although the agreement between the predicted and measured torques indicated in Table 2 is simply confirmation of the form of Equation (4), the fact that backfigured Q_h values are relatively constant and Q_s values are consistent with a constant τ_s value (see Table 1) indicates that this equation may provide a way forward for derivation of rational relationship between Q_u and T.

The Ghaly & Hanna method underestimates the torque of all the screw piles. A similar trend was observed by Tappenden (2007) who concluded that Ghaly & Hanna's method consistently overestimated the pile ultimate capacity by between 130% to 850% and is not suitable for field scale helical pile capacity predictions. In the case of the pile with no helix, only the method presented by Tsuha & Aoki (2010) proposes an expression to estimate the torque generate purely by the pile shaft; this method overestimated the measured torque by about 60%.

Table 2. Measured and calculated torques

Pile	Measured Torque	Calculated Torque		
		Perko	Ghaly & Hanna	Tsuha & Aoki*
0HCE	2.35	-	-	3.71
1HCEI	5.70	6.98	4.42	8.18
1HOE	10.40	10.53	5.43	11.18
1HCEII	10.40	10.68	5.50	11.37
2HCE	14.90	13.58	7.26	15.00

* Derived using Q_h and Q_s values inferred from load tests

Although Table 2 shows that reasonable predictions were obtained using the Perko and Tsuha & Aoki methods. This result is encouraging although it should be noted that various authors assert that these methods may not be valid for a wide range of screw pile configurations. Harnish& El Naggar (2017) and Spagnoli (2017), for example, recommend a better understanding and evaluation is required for the prediction of the performance of large-diameter screw piles.

5 CONCLUSIONS

A series of field scale experiments using a variety of different screw pile configurations was performed at a medium dense sand site at Shenton Park, Perth, Australia. The piles were typically 2.7m long with a helix diameter of 384mm and shaft diameters of either 114mm or 140mm.The experiments showed that:

(i) The Shenton Park tests indicate that the uplift capacity (Q_u) does not vary in direct proportion with the torsional resistance (T). However, despite this observation, the empirical correlation proposed by Perko (2009), which assumes that Q_u varies directly with T, provides excellent predictions for these tests. It is likely that this finding arises because the Shenton Park test piles had a size and geometry comparable to that of piles in Perko's database. Consequently, application of the Perko formulation to large scale screw piles currently being contemplated for offshore installation is questionable.

(ii) Torque increments are more sensitive to shaft surface augmentation than helix addition. Enlarging the shaft diameter by 22% produced a torque gain of 84% whereas adding an extra helix added only 43%.

(iii) The relationship proposed by Tsuha & Aoki (2010) between torque and the torsional shaft resistance (Q_s) and helix uplift resistance (Q_h) is seen to lead to a comparable relationship between uplift capacity and torque indicated by the field tests. Relating Q_s and Q_h with the CPT qc value may therefore provide a practical and rational approach for the design of these piles.

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