LINKING THE INSTALLATION RESPONSE OF SCREW PILES TO SOIL STRENGTH AND ULTIMATE CAPACITY

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ABSTRACT

A perceived advantage of screw-type foundations is the ability infer aspects of foundation performance from quantities measured or observed during installation, especially the installation torque. A particular concept widely used in practice is to correlate installation torque to ultimate capacity. This notion has proven useful as a field verification technique despite the absence of validated models that relate key variables of interest, such as installation torque, axial (crowd) force, geometrical parameters, and soil strength. This paper considers previous work by the co-authors and collaborators on analytical, numerical, and physical modelling of screw piles to relate the quantities measured or controlled during installation (e.g., installation torque) to the ultimate capacity and soil strength. Attention is given to saturated clay as a particular soil type amenable to simplified analysis. An analytical model for a single-helix pile is considered as a means of directly relating the ultimate capacity and undrained shear strength to the installation torque, crowd force, plate pitch, plate diameter, shaft diameter, installation depth, and surface roughness. The connection between the installation variables and ultimate capacity—and the sensitivity to crowd force in particular, a quantity that is typically not measured during field installations—is also discussed. The theoretical predictions are compared against data obtained from small-scale laboratory experiments that suggest the installation torque relates to the remolded strength of the soil.

Keywords: screw piles, helical anchors, installation, torque-capacity correlation, modeling, experiments

INTRODUCTION

Screw piles are deep foundations that are twisted into the ground through an applied torque. Advantages over driven piles or drilled foundations include the relative silence of the installation, with low ground vibrations, and the possibility of being easily decommissioned by reversing the direction of twisting. Screw piles are now routinely encountered as a flexible, low-cost solution for numerous applications (Figs. 1 and 2), and they are also being considered for applications in offshore energy production due to limitations being imposed with respect to decommissioning and underwater noise.

Also known as "screw anchors," "helical piles", or "helical anchors," screw piles consist of helices or helical plate elements attached to a central shaft. Figure 3a shows the components of a single-helix pile and key variables. The diameters of the shaft and helix are denoted by d and D, respectively, and p is the pitch of the helix. Variable H denotes depth of the helical plate, and T and N denote the torque and axial (crowd) force applied during installation. In typical applications, the pile includes multiple helical plates, and the shaft is composed of segments that allow for it to extend to large depths into the soil.

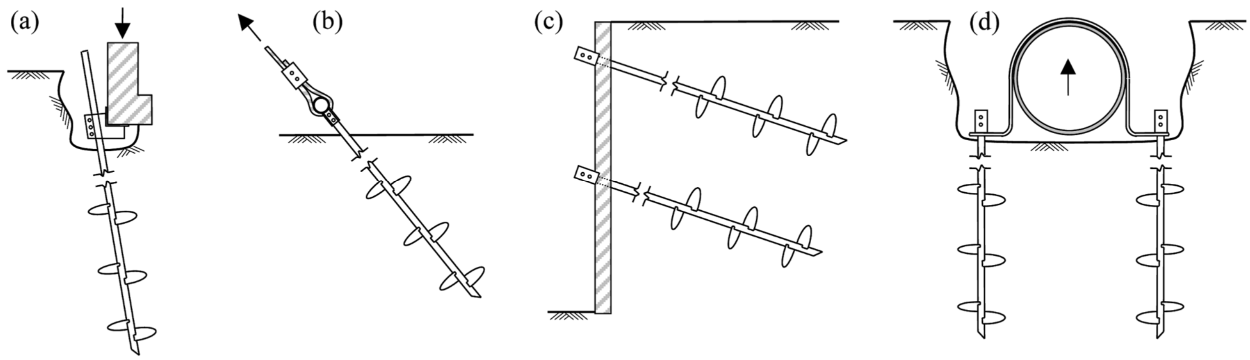

Fig. 1. Selected applications for helical anchors: (a) underpinning of shallow foundations; (b); ground anchorage; (c) tiebacks; (d) control of buoyancy for buried and underwater pipelines (Hambleton et al. 2014; reproduced with permission from the Australian Geomechanics Society)

Fig. 2. Installation of screw piles (helical anchors) to be used as tiebacks in a slope stabilization project

A compelling concept utilized widely in practice is that the installation torque should, in principle, relate to the ultimate capacity of the pile. In other words, a larger installation torque implies a larger capacity. This concept of "torque-capacity correlation" is embodied in the following formula (Hoyt and Clemence 1989):

$$F_{\max} = KT \quad [1]$$

where $F_{\max}$ is the ultimate axial capacity of the pile in tension or compression and K is the "capacity-to-torque ratio." Perko (2009) ascertained the following empirical expression for K based on numerous field measurements:

$$K = 1433d^{-0.92} \quad [2]$$

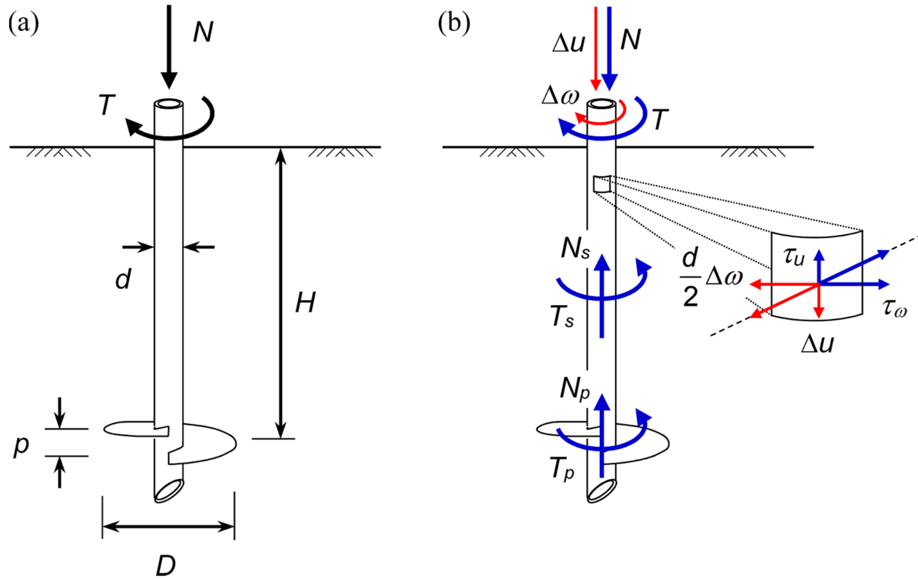

Fig. 3. Schematic of a single-helix screw pile: (a) key variables; (b) stresses and resultant forces generated on the shaft and helical plate during installation (Hambleton et al. 2014; reproduced with permission from the Australian Geomechanics Society)

In Eq. [2], K and d have units of m^{-1} and mm, respectively, such that $F_{\max}$ and T in Eq. [1] have units of N and N·m. Standard practice is to assume that Eqs. [1] and [2] apply to the ultimate capacity in both tension and compression, and this is supported by data showing that K is only slightly higher in compression compared to tension (Perko 2009). The equations above are assumed to hold regardless of the soil type.

A concept explored in this paper specifically is that the installation torque should relate to the strength of the soil. This concept has not received prior attention in large part due to the absence of theoretical or empirical models that involve soil strength as a variable, as evidenced by Eqs. [1] and [2]. Provided installation torque can be related to soil strength, a record of installation torque with depth could potentially be interpreted to determine a soil strength profile in much the same way as a cone penetration test is used to infer soil strength from tip resistance.

This paper considers the theoretical model proposed by Hambleton et al. (2014) as a means of understanding the merits and limitations of torque-capacity correlation and, by relating the installation response to soil strength, the possibility of regarding the installation process as a form of *in situ* testing. Attention is limited to the case of installation and ultimate loading under undrained conditions (e.g., saturated clay), and focus is exclusively on the single-helix configuration shown in Figure 3. The analysis highlights the fact that the capacity-to-torque ratio in Eq. [1] depends on not only the shaft diameter but also the crowd force and undrained shear strength of the soil among other variables.

ANALYTICAL MODEL FOR SCREW PILE INSTALLATION IN CLAY

Hambleton et al. (2014) developed a theoretical formula that predicts the installation torque for a single-helix pile installed in undrained conditions (e.g., saturated clay). As illustrated in Fig. 3b, the underlying analysis considers the total installation torque T as the torque mobilized along the shaft (T_s) and at the helical plate (T_p). Similarly, the axial (crowd) force N is the summation of resistance along the shaft (N_s) and the plate (N_p).

Upon assuming that the displacement rate Δu and rotation rate $\Delta\omega$ are determined by the helix pitch p (so-called neutral rotation with $\Delta\omega/\Delta u = 2\pi/p$), T_s and N_s are determined by assuming that the shear stresses mobilized along the shaft are co-axial with the incremental axial displacement and rotation of the pile, as shown in Fig. 3b. The shear stresses are assumed to be uniform along the shaft and given by $\tau = \alpha s_u$, where α is the so-called adhesion coefficient ($0 \leq \alpha \leq 1$) and $\tau = (\tau_\omega^2 + \tau_u^2)^{1/2}$. The case $\alpha = 0$ corresponds to a perfectly smooth (frictionless) shaft or no contact, and the case $\alpha = 1$ corresponds to perfect adhesion between the shaft and the soil, such that the undrained shear strength s_u is fully mobilized along the interface.

The torque and axial force at the plate, T_p and N_p, are determined based on the following yield envelope, determined from a large number of finite element simulations for a single deeply embedded helical plate subjected to combined torque and axial force (Todeshkejoei et al. 2014):

$$\left(\frac{N_p}{N_{p,\max}}\right)^q + \left(\frac{T_p}{T_{p,\max}}\right)^r = 1 \qquad [3]$$

where

$$q = 1.07, \quad r = 5.16 - 8.02\frac{p}{D}$$

$$N_{p,\max} = 10.82 s_u D^2\left[1-\left(\frac{d}{D}\right)^2\right]\left[1+\left(\frac{p}{D}\right)^2\right]^{-\frac{1}{2}}, \quad T_{p,\max} = s_u D^3\left[0.74 + 0.33\frac{p}{D}\right] \qquad [4]$$

The relationships given in Eq. [4] are valid for $0.16 \leq p/D \leq 0.48$ and $0 \leq d/D \leq 0.4$, and they are based on the assumptions of perfect adhesion between the shaft and soil, as well as plate thickness $t = 0.05D$. In Eqs. [3] and [4], $N_{p,\max}$ is the ultimately capacity of the plate under pure axial loading ($T_p = 0$), which for all values of p/D and d/D remains close to the theoretical capacity of $12.42 s_u D^2$ for a deeply embedded circular plate (Martin and Randolph 2001).

The final formula derived by Hambleton et al. (2014) can be expressed as

$$T = \frac{\pi^2 \alpha s_u d^3 H}{2\sqrt{p^2+\pi^2 d^2}} + T_{p,\max}\left\{1 - \mathrm{sign}\left(N - \frac{\pi\alpha s_u dHp}{\sqrt{p^2+\pi^2 d^2}}\right)\left[\frac{1}{N_{p,\max}}\left|N - \frac{\pi\alpha s_u dHp}{\sqrt{p^2+\pi^2 d^2}}\right|\right]^q\right\}^{\frac{1}{r}} \qquad [5]$$

where q, r, $N_{p,\max}$ and $T_{p,\max}$ are given by Eq. [4]. Equation [5] is slightly adapted from the original expression given by Hambleton et al. (2014) to allow for the case when crowd N is insufficient to overcome the resistance along the shaft, such that the force generated on the pile by the soil must be directed downward ($N_p < 0$). In Eq. [5], the function sign(x) assumes values of sign(x) = 0 for $x \leq 0$ and sign(x) = 1 for $x > 0$, and the function $|x|$ gives the absolute value of x.

Despite its apparent complexity, Eq. [5] provides a straightforward way of relating the torque T, crowd force N, undrained shear strength s_u, shaft roughness α, embedment depth H, and the parameters that define the pile configuration (d, D, and p). The formula can be easily programmed into a spreadsheet, which can then also be used to solve for any variable as a function of the others. The Appendix shows an example completed with an Excel spreadsheet available for download on the first author's website: https://sites.northwestern.edu/hambleton/resources/.

Figure 4 plots the torque T computed using Eq. [5] for a typical set of parameters: d = 50 mm, D = 250 mm, p = 70 mm, H = 1.5 m, s_u = 40 kPa, and α = 1 (full shaft adhesion). The torque is plotted as a function of the crowd force N to highlight two particularly important features. First and foremost, it can be observed that Eq. [5] directly provides a prediction of the pile's axial capacity by considering the particular case T = 0 and solving for the axial force N. This point corresponding to the maximum axial force is indicated as "pile capacity" in Fig. 4. This value is somewhat larger than the capacity of the plate alone due to resistance generated along the shaft, which is also responsible for reversing the direction of the axial force on the plate ($N_p < 0$) at low values of the crowd force, as indicated in the plot. The second important feature to recognize is that the installation torque T is a function of the crowd force N, a fact that is notable due to the absence of any consideration for the crowd force in empirical torque-capacity correlations such as Eqs. [1] and [2]. Indeed, guidance pertaining to how much crowd force should be applied during installation is limited (Perko 2009), and unlike installation torque, crowd force is typically not measured during construction.

Figure 4 includes the value of torque obtained from the empirical torque-capacity correlation given by Perko (2009) and encapsulated in Eqs. [1] and [2], assuming $F_{\max}$ is given by the plate capacity $N_{p,\max}$. This value of 638 N·m determined using the empirical formulas agrees surprisingly well with the value of 611 N·m predicted for zero crowd force using Eq. [5]. However, the discrepancy between the constant value obtained using the empirical formula and the values obtained using the theoretical model grows as the crowd force increases.

RELATIONSHIP BETWEEN TORQUE AND ULTIMATE CAPACITY

The analytical model presented in the previous section suggests that the installation torque is indeed directly related to ultimate capacity. However, the model also suggests that the capacity-to-torque ratio K commonly used in torque-capacity correlation is not in fact a constant that depends only on the shaft diameter but rather a function that depends on crowd force, soil strength, shaft roughness, embedment depth, and other parameters defining the pile configuration. The simplest means of obtaining a theoretical prediction of K is to assume, as commonly done in practice, that the ultimate capacity of the pile $F_{\max}$ is identical to the plate capacity, which is given in Eq. [5] by the variable $N_{p,\max}$. Upon equating $F_{\max} = N_{p,\max}$, Eq. [5] can be used to compute the capacity-to-torque ratio K directly.

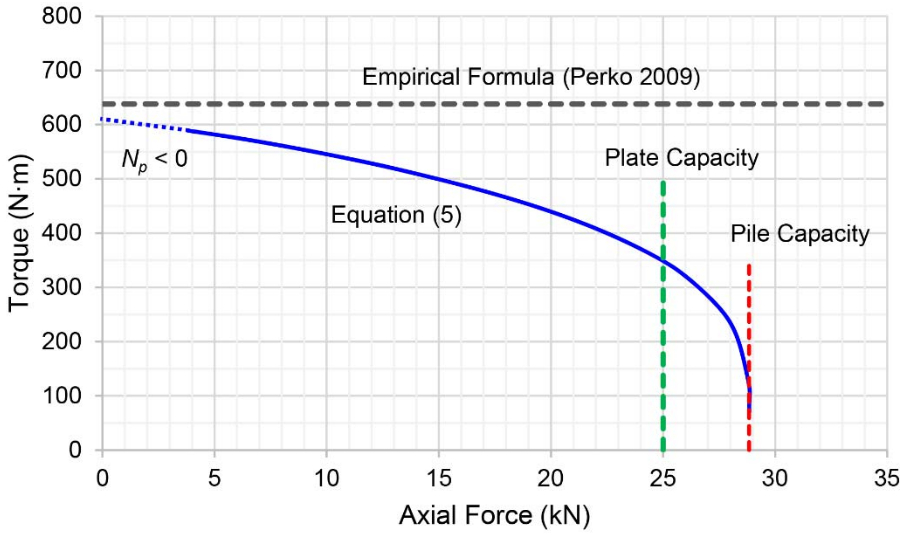

Fig. 4. Predictions of installation torque *T* from Eq. [5], plotted against axial (crowd) force *N*, for assumed parameters d = 50 mm, D = 250 mm, p = 70 mm, H = 1.5 m, s_u = 40 kPa, and α = 1 (rough shaft)

Figure 5 shows theoretically predicted values of the capacity-to-torque ratio K in comparison to the empirical values obtained using Eq. [2]. The theoretical predictions, totaling roughly 100 in Fig. 5, are obtained using Eq. [5] with randomized parameters that fall into the following ranges: 50 mm $\leq d \leq$ 400 mm, 250 mm $\leq D \leq$ 750 mm, 30 mm $\leq p \leq$ 140 mm, 1 m $\leq H \leq$ 4 m, and 10 kPa $\leq s_u \leq$ 100 kPa. The adhesion coefficient α was set to $\alpha = 1$ for all calculations. The figure shows that the theory tends to follow the empirical relationship overall but that significant deviations are present as a result of variations in the capacity-to-torque ration produced by changes in individual parameters. It must be emphasized that these deviations are not random but rather variations that are predicted by the theoretical model of Eq. [5]. This scatter is rather remarkable in comparison to the deviations evident in the data compiled by Perko (2009) and reproduced in Fig. 5, which has been heretofore tacitly attributed to random error and unattributed to the effects of any particular parameters.

RELATIONSHIP BETWEEN TORQUE AND SOIL STRENGTH

An overlooked feature of screw piles is the possibility of inferring soil strength from the measured response during installation. This is directly reflected in Eq. [5], which in principle can be solved to determine the undrained shear strength s_u as a function of all other variables. While the equation does not lend itself being solved with respect to s_u explicitly, s_u can be computed numerically. A spreadsheet for computing s_u, when all other quantities are known, can be downloaded from the first author's website: https://sites.northwestern.edu/hambleton/resources/ (see also Appendix).

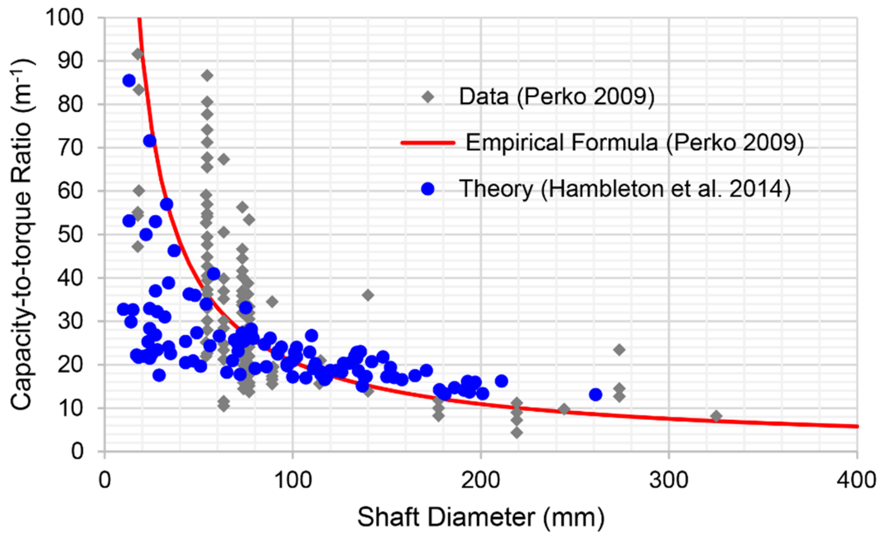

Fig. 5. Relationship between the capacity-torque ratio *K* and the shaft diameter *d* as predicted by the theoretical model of Eq. [5] for randomized inputs compared against the values obtained using the empirical formula of Eq. (2) (Perko 2009)

Data obtained by Todeshkejoei (2019) from small-scale laboratory tests is used to illustrate how soil strength can be assessed from measured torque and axial (crowd) force. Todeshkejoei's tests were completed on kaolin samples using a model screw pile with shaft diameter $d = 10$ mm, plate diameter $D = 40$ mm, and pitch $p = 8.5$ mm. Piles were tested in various configurations and under a range of loading protocols, but here only the data corresponding to neutral installation of a single-helix pile is considered. While the pile was instrumented with strain gauges to measure torque and axial force at various locations along the shaft, only the measurements corresponding to the top of the shaft, which correspond to the total installation torque and total axial (crowd) force, as might be measured during a field installation, are presented and discussed here. The clay samples were prepared by mixing kaolin with a high water content to form a slurry, and then consolidating the mixture in a press. The reader is referred to the thesis by Todeshkejoei (2019) for additional details.

Figure 6 shows the data collected by Todeshkejoei (2019) for the two tests completed by installing the pile through "neutral rotation," such that the advance rate of the pile per revolution is equal to the pitch ($\Delta\omega/\Delta u = 2\pi/p$). It should be emphasized that the smooth curves plotted in Fig. 6 were obtained by digitizing and replotting the data from Todeshkejoei's thesis, which results effectively in some filtering that does not in any substantive way obfuscate the trends in the original data. The curves were slightly adjusted, using some degree of judgement, such that all curves originate from the origin. The two tests plotted in Fig. 6 correspond to the same test completed at different locations across the clay sample, indicating a high degree of repeatability.

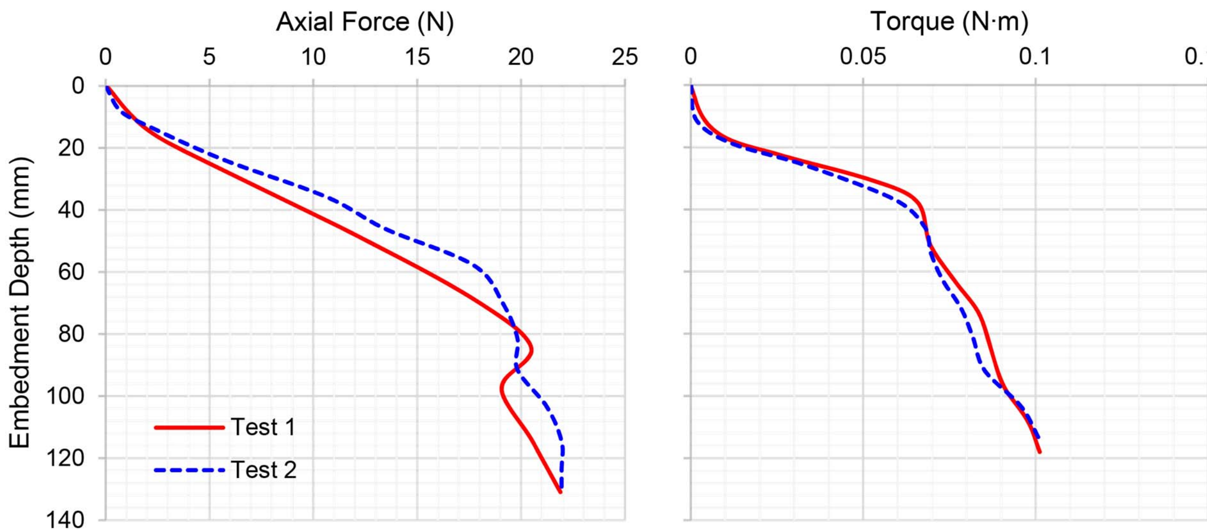

Fig. 6. Axial (crowd) force and torque measured by Todeshkejoei (2019) for a single-helix pile installed in clay

Figure 7 shows the values of undrained shear strength s_u back-calculated from the data plotted in Fig. 6 using Eq. [5]. Only the data for "Test 1" is considered in the back-calculation. An adhesion coefficient of $\alpha = 1$ is assumed, but all other parameters are measured or otherwise known quantities. Figure 7 also shows the intact strength measured using a T-bar, as well as the remolded strength obtained by dividing the intact strength by the measured sensitivity of $s_{u,intact}/s_{u,remolded} = 3$ (Todeshkejoei 2019). It can be observed that the back-calculated values of the undrained shear strength deviate from the remolded strength at small embedment depth but match the remolded strength closely as the embedment depth increases. The source of the discrepancy at small embedment depth is unknown but not unexpected given the complex deformation induced as the screw pile first comes into contact with the soil. Similarly, the strong correlation between the measured installation response and the remolded strength is as one might expect, given the large shear deformations produced as the screw pile is twisted into the ground.

CONCLUDING REMARKS

The analysis considered in this paper casts new light on the concept of torque-capacity correlation and provides some evidence to suggest that soil strength can be inferred by measuring the installation response of screw piles in much the same way that strength is inferred from other types of *in situ* tests (e.g., cone penetration or T-bar). The paper shows that the theoretical relationship derived by Hambleton et al. (2014) for a single-helix pile in clay can be used as the basis for computing capacity-to-torque ratios that include dependence on key parameters such as crowd force, soil strength, shaft roughness, embedment depth, shaft diameter, plate diameter, and helix pitch. Moreover, the analysis reveals that the capacity-to-torque ratio should not be considered a constant but rather a function of the numerous parameters involved. The analysis presented in this paper considering experimental data from small-scale testing on saturated clay further suggests that one can potentially infer the remolded strength of fine-grained soil from measured installation torque and axial (crowd) force. These conclusions require validation from carefully completed full-scale testing.

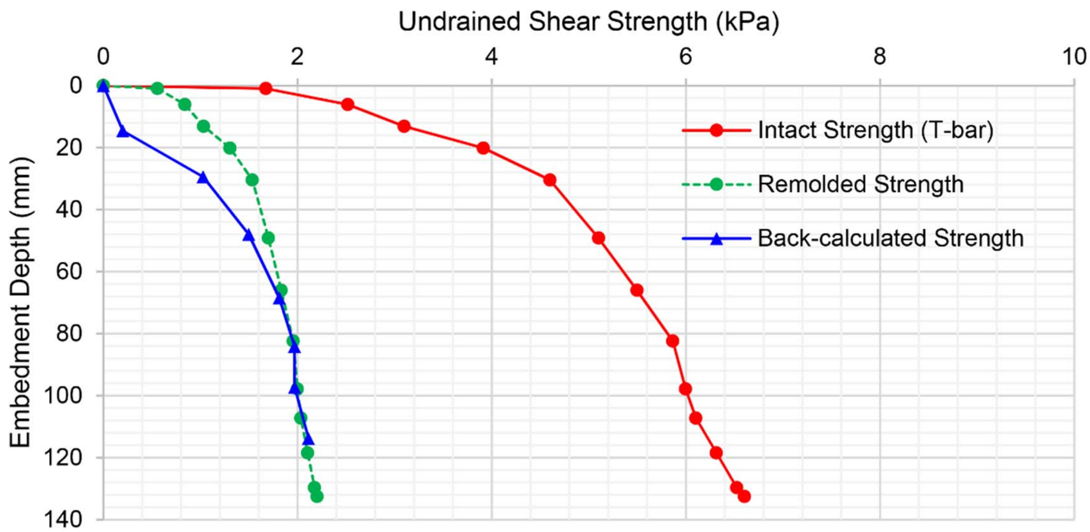

Fig. 7. Comparison of back-calculated and measured strengths from installation data collected by Todeshkejoei (2019) for a single-helix pile installed in clay ("Test 1" only)

This paper considers only a limited subset of the possible configurations and soil types encountered in applications. In addition to validating and refining the model described in this paper, extensions to multi-helix systems and other soils types, particularly sand, represents areas of future work.

APPENDIX: SPREADSHEETS

Spreadsheets for computing torque and shear strength using the theory described in this paper can be downloaded on the first author's website: https://sites.northwestern.edu/hambleton/resources/. Figure 8 shows an example calculation of installation torque.

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	A	B	C	D
1	Calculator for single-helix screw piles in clay			
2	Reference: Hambleton, J. P., Stanier, S. A., Gaudin, C., & Todeshkejoei, K. (2014). Analysis of installation forces for helical piles in clay. Australian Geomechanics, 49(4), 73-79.			
3				
4	**Variable**	**Value**	**Units**	**Description**
5	***Primary Inputs***			
6	s_u	50000	N/m^2	Undrained shear strength
7	α	1	-	Coefficient of adhesion for shaft (varies from 0 for smooth to 1 to rough)
8	D	0.25	m	Helix diameter
9	p	0.07	m	Helix pitch
10	d	0.05	m	Shaft diameter
11	H	1.5	m	Embedment depth
12	N	15628.91	N	Axial (crowd) force
13	***Calculated Inputs and Secondary Inputs***			
14	q	1.07	-	Exponent in Eq. (4) of Hambleton et al. (2014)
15	r	2.9144	-	Exponent in Eq. (4) of Hambleton et al. (2014)
16	$T_{p,max}$	650.3125	N·m	Ultimate torque computed for plate
17	$N_{p,max}$	31257.81	N	Ultimate force computed based on bearing capacity of plate
18	***Computed Torque***			
19	T	654.8191	N·m	Installation torque computed from Eq. (9) in Hambleton et al. (2014)

Fig. 8. Spreadsheet for computing installation torque *T* for specified values of undrained shear strength s_u, adhesion factor *α*, helix diameter *D*, helix pitch *p*, shaft diameter *d*, embedment depth *H*, and axial (crowd) force *N* based on Eq. [5]

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