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Contemporary conceptual models for predicting carrying capacity of multi helices screw piles

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Abstract. Contemporary civil constructions are based on foundation systems consisting mainly of shallow, semi deep and deep foundations. The screw pile resembles essentially to a large screw that is inserted into the ground by a special machine. Basically, it acts as a foundation or an anchor. In general, it is composed of a central shaft and one or more graded steel helices. Screw piles have made great progress in recent decades, particularly when it comes to their axial capabilities and installation processes. Using screw piles for anchoring and supporting structures is advancing rapidly. Despite this, screw piles are still lacking design methods that require further research. This study consists on developing three conceptual models to predict the carrying capacity of a screw pile of multi helices. The first analytical model takes into account shaft friction, grooves' geometry, and configuration of helices' assembly. The second analytical model is based on the observed failure surface of screw piles proclaimed in literature. Whereas, the third empirical model considers the existing correlation between the torsional resistance generated during screw pile installation and its carrying capacity. The three models were validated against some actual testing results and some experimental data reported in literature. It was noted that the first analytical model underestimate the compressive carrying capacity of screw piles by about 5 to 15%. For the second model, a reasonable agreement was noted between the calculated and the measured results when the ratio $L/B \geq 10$. However, in the opposite, the model overestimates the ultimate capacity of screw piles by about 15.3%. Likewise, the empirical model (third model) overestimates the tensile carrying capacity of screw piles by 10 to 20% with an average of 12.4%.

Introduction and Background

Foundations that are deep (such as piles and shafts) play an important role in transmitting loads or stresses from superstructures to the ground beneath them. When the soils are problematic or have mediocre properties, their use can be crucial. Construction of any type relies heavily on the foundations because they support the entire structure. It is therefore essential to choose a foundation that best suits the requirements and the various essential parameters.

In the construction industry, screw piles (Fig. 1) are one of the most commonly used types of piled foundations. They are made from circular hollow sections of steel that have one or more helices welded to the shaft to provide self-tapping properties during installation. Upon installation, the hollow stem may be filled with reinforced concrete, and it is structurally connected to the building substructure. Depending on capacity requirements, shaft diameters range from 50 mm to 600 mm, and helices' diameters range from 150 mm to 1200 mm. Compared to other pile types, screw piles can provide significant advantages in terms of speed and ease of installation. As well as providing a high bearing capacity and a wide range of applications, they are also quick to form piles, have a flexible size, do not vibrate or make noise, and are of low unit cost. They have been widely used in foundations of high-rise buildings [1, 2, 3]. A multitude of constraints can be overcome with screw piles, including the following: excavation is not possible, unstable ground, underpinning (cracked and collapsing foundations), work schedules are limited by weather or climate, soil is contaminated, soil has low bearing capacity, access to the work site is restricted, and there are environmental restrictions When screw piles are installed, they can be loaded immediately after installation, making them a unique type of foundation. A screw pile does not require waiting for excess pore water pressures to subside, nor does concrete or grout need to harden. This can be important, for example, emergency response projects may require fast foundation installation if the construction schedule is short and the rest of the project is dependent on it. Screw piles are galvanized steel supports or anchors that are highly corrosion-resistant. In comparison to formwork tubes or poured concrete foundations, they are much more cost-effective.

A screw pile's capacity is affected by ground conditions and its structural design. The capacity of piles depends on many factors, such as the type of soil, shaft size, number of helices, helical size and spacing, concrete in-filling, helix-to-shaft weld, pile spacing and installation angle, and installation torque. The bearing properties and failure mechanism of screw piles under compressive, tensile and lateral loading conditions were examined through numerical analyses, laboratory tests, and field load tests [4,5,6,7,8,9,10,11, 12]. A screwed pile is shown to have a higher ultimate carrying capacity than a circular pile due to occlusion effects between the screw or helices and soil.

Recent advances have been made in enhancing the axial capacities of screw piles and their installation processes [13,14,15]. The design methods for screw piles, however, are still lacking, which calls for further investigation [16]. As a result, it is evident that screw piling requires further research to continue to evolve and become a common engineering practice. Different design methods related to screw piles are reported in the literature. They consist of the cylindrical shear method, the individual bearing method and a relationship between the installation torque and the bearing capacity [17]. In spite of this, screw piles are designed so most of the capacity of the pile is generated through the bearing of the helix plates against the soil rather than shaft friction.

This study consists on developing three conceptual models to predict the carrying capacity of a screw pile of multi helices. The first analytical model takes into account shaft friction, grooves' geometry, and configuration of helices' assembly. The second analytical model is based on the observed failure surface of screw piles proclaimed in literature. Whereas, the third empirical model consider the existing correlation between the torsional resistance generated during screw pile installation and its carrying capacity. The three models are validated against some actual testing results and some experimental data reported in literature.

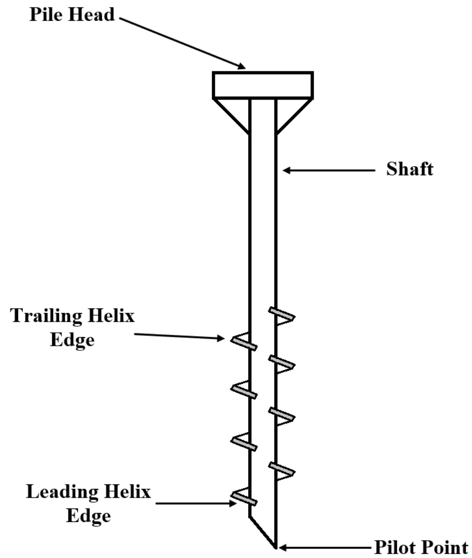

Figure 1. Structural elements of a screw pile

Theoretical Developments

The lack of knowledge about screw piles and the minute data that supports their capabilities has led foundation designers to follow conventional foundation techniques [18]. Despite improvements in screw pile practice, guidelines for helical piles have not been widely adopted yet, though further efforts are needed [15]. As such, this section aims to further enlighten the design of screw piles in a contemporary context, thereby raising awareness and improving the effectiveness of screw piles during construction.

Prediction of Compressive Carrying Capacity of Screw Piles:

A screw pile of multi helices derives its load-carrying capacity by friction or adhesion along the pile shaft with surrounding soil, by compressive resistance at the contact of the pile base with underlying soil, and by passive resistance of soil at the contact of pile grooves (Fig. 2).

The load Q_u at the head of a single screw pile can be expressed as the sum of the bearing load (Q_p) carried at the base, the friction load (Q_s) carried by the shaft of the pile, and the bearing load carried by the helices (Q_g), as follows:

$$Q_u = Q_p + Q_s + Q_g \tag{1}$$

Where:
Q_u = Ultimate carrying capacity.
Q_p = Pointe bearing capacity of screw pile.
Q_s = Skin resistance (friction) of screw pile.
Q_g = Resistance of helices' grooves.

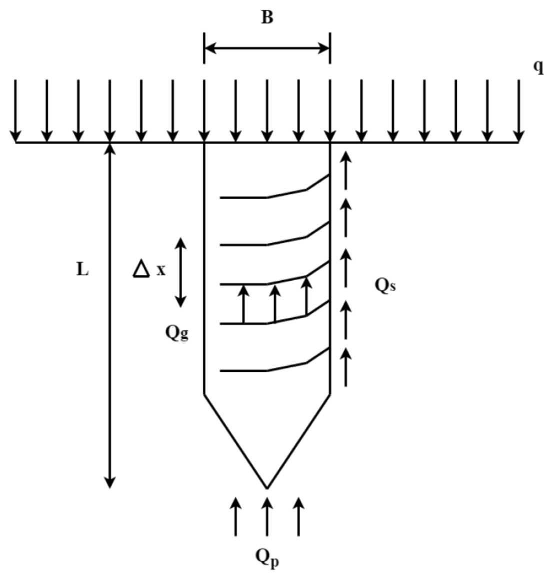

Figure 2. Components of pile's resistances

For an embedment depth L greater than L_o, the point bearing capacity (Q_p) of the screw pile can be determined by the following expression:

$$Q_p = q_p \times A_p \tag{2}$$

$$q_p = (\gamma L + q)N_q^* + 1.3cN_c^* \tag{3}$$

$$A_p = \frac{\pi B^2}{4\cos\beta} \tag{4}$$

$$L_o = \frac{B}{4} N_q^{2/3} \tag{5}$$

$$N_q = \tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) e^{\pi \tan\varphi} \tag{6}$$

Where:
B = Diameter of screw pile
L = Embedment depth (i.e. length) of the screw pile
β= Angle of inclination of screw pile's tip
A_p = Cross-section of screw pile's shaft
γ= Soil unit weight
c = Soil cohesion
φ = Soil shearing resistance
q = Applied surcharge (if any)
N_q^* and N_q^* = Bearing capacity factor determined from Meyerhof chart [19]

Likewise, the shaft friction or the positive skin friction on shaft of a screw pile can be determined by the following expression:

$$Q_s = \pi B\left(cD + k_o\left(\frac{1}{2}\gamma D^2 + qD\right)\tan\varphi\right) \tag{7}$$

Where:
k_o = Coefficient of earth pressure at rest $\left(k_o = 1 - \sin\varphi\right)$
D = length of the pile's shaft (i.e. the distance between the pile's head and the helices).

Concerning the resistance of the helices' grooves (i.e. the third term of Eq. 1), it can be assumed that all the grooves form circular ring foundations. Then, the helices' grooves resistance can be determined by the following expression:

$$q_g = \sum_{i=1}^{n} q_{gi} = \left[1.3cN_c + 0.3\gamma(B_{ext} - B_{\text{int}})N_\gamma\right]n + \sum_{i=1}^{n}(\gamma D_i + q)N_q \tag{8}$$

Where:

$$\begin{aligned}
&\sum_{i=1}^{n}(\gamma D_i + q)N_q = (\gamma D_1 + q)N_q + (\gamma D_2 + q)N_q + ... + (\gamma D_n + q)N_q \\
&\sum_{i=1}^{n}(\gamma D_i + q)N_q = N_q\left[(\gamma D_1 + q) + (\gamma D_2 + q) + ... + (\gamma D_n + q)\right] \\
&\sum_{i=1}^{n}(\gamma D_i + q)N_q = N_q\left[\gamma(D_1 + D_2 + ... + D_n) + nq)\right] \\
&\sum_{i=1}^{n}(\gamma D_i + q)N_q = N_q\left[\gamma\sum_{i=1}^{n} Di + n.q\right] \\
&\sum_{i=1}^{n} D_i = D_1 + D_2 + ... + D_n \\
&\sum_{i-1}^{n} D_i = (\Delta x_1 + e) + (\Delta x_2 + 2e) + ... + (\Delta x_n + ne)
\end{aligned} \tag{9}$$

$$\begin{aligned}
&But, \\
&\Delta x_{i+1} = 2\Delta x_i
\end{aligned} \tag{10}$$

$$\begin{aligned}
&Therefore, \\
&\sum_{i=1}^{n} D_i = (\Delta x_1 + e) + 2(\Delta x_1 + e) + ... + n(\Delta x_1 + e) \\
&\sum_{i=1}^{n} D_i = (\Delta x_1 + e)(1 + 2 + ... + n)
\end{aligned}$$

This implies:

$$\sum_{i=1}^{n} D_i = (\Delta x_1 + e)\frac{n(n+1)}{2} \tag{11}$$

It can be written that:

$$Q_g = q_g.\pi.\frac{(B_{ext} - B_{\text{int}})^2}{4} \tag{12}$$

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Therefore,

$$Q_g = \left[\left(1.3cN_c + 0.3\gamma(B_{ext} - B_{\text{int}})N_\gamma\right)n + \left(\gamma(\Delta x_1 + e)\frac{n(n+1)}{2} + nq \right)N_q \right] . \frac{\pi(B_{ext} - B_{\text{int}})^2}{4} \qquad (13)$$

Finally, the ultimate carrying capacity of screw piles can be determined as follows:

$$Q_u = \left[(\gamma L + q)N_q^* + 1.3cN_c^*\right]A_p + \left[\pi B \left(cD + k_o \left(\frac{1}{2}\gamma D^2 + qD \right) \tan\varphi \right) \right] + \left[\left(1.3cN_c + 0.3\gamma(B_{ext} - B_{\text{int}})N_\gamma\right)n + \left(\gamma(\Delta x_1 + e)\frac{n(n+1)}{2} + nq \right)N_q \right] . \frac{\pi(B_{ext} - B_{\text{int}})^2}{4} \qquad (14)$$

It is worthy to note that, this equation is applicable in case: $L \geq L_o$. However, in case of $L < L_o$, the parameters N_q^* and N_q^* should be replaced by the N_q and N_c.

Where:
D_i = Distance between pile's head and helice "*i*".
B_{ext} = External diameter of helices.
B_{int} = Internal diameter of helices.
Δx = Distance between two successive grooves.
e =Thickness of grooves.
n = Number of grooves.

Prediction of Tensile Carrying Capacity of the Screw Piles:
In this section, an analytical model to predict the tensile carrying capacity of a screw pile of multi helices is proposed. The model was developed based on the failure mechanism (i.e. the failure surface) reported in literature [20]. A conical failure surface was observed during the pull-out of a screw pile in a homogeneous soil. Cone pull-out failure occurs when shear forces are reduced to zero along the failure plane. At this critical point the pile and some surrounding soil is pulled out in the shape of a truncated inverted cone or pyramid (Fig. 3). The angle of pull-out will vary depending on soil type and is typically between 0.45φ to 0.55φ (φ is the soil angle of shearing resistance). The ultimate tensile carrying capacity mobilized along the truncated inverted cone failure surface can be computed as follows:

$$Q_u = \int_0^L pdz\left[k_p(c + \gamma z \tan\varphi)\right] = p\int_0^L \left[k_p(c + \gamma z \tan\varphi)\right]dz \qquad (15)$$

$$Q_u = pk_p\left(cL + \frac{\gamma L^2}{2}\tan\varphi \right) \qquad (16)$$

$$Q_u = k_p\left(\frac{\pi B + \pi(B + 2L\tan\alpha)}{2} \right)\left(cL + \frac{\gamma L^2}{2}\tan\varphi \right) \qquad (17)$$

$$Q_u = \tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2} \right)(\pi B + \pi L\tan\alpha)\left(cL + \frac{\gamma L^2}{2}\tan\varphi \right) \qquad (18)$$

The failure plane angle (α) depends mainly on the soil shearing resistance angle (φ) and the number of the helices (n). It can be apparoximated by the following expression:

$$\tan\alpha = \tan(0.01n + 0.44\varphi) \tag{19}$$

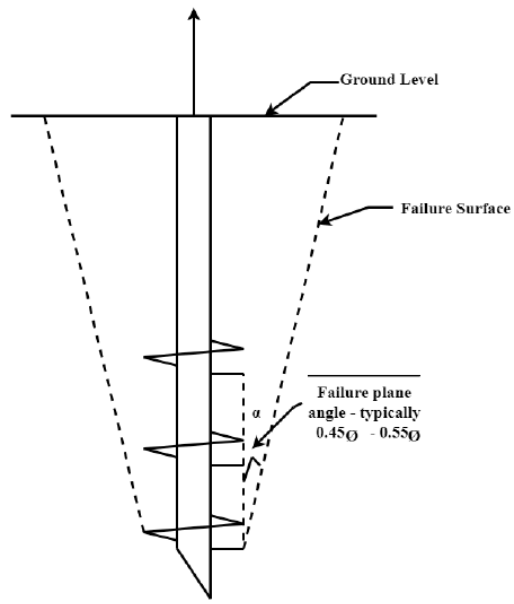

Figure 3. Cone Pull out Failure Surface of Screw Pile [20]

Prediction of Compressive Carrying Capacity of Screw Piles Based on Installation Torque: An attempt was conducted to correlate the compressive carrying capacity of screw piles and the installation torque. It was reported in literature that a straight line could approximate the relationship between the ultimate capacity of screw piles and the installation torque [20, 21]. The torsional resistance generated during screw pile installation is an indication of soil shear strength and provides an alternative (empirical) way to find the capacity of a screw pile. According to the proclaimed observation in literature, the following expression can be used to predict the compressive carrying capacity of screw piles:

$$Q_u = aT \tag{20}$$

Where:
a = Parameter which depend mainly on soil type and pile shaft diameter (1/m)
T = Installation torque (kN.m)
Q_u = Ultimate capacity of screw piles (kN)

In order to calibrate the parameter (a), an analogy between a screw pile in soil and a bolt and its nut was adopted in this investigation. Similarly, a torque is simply a measure of the twisting force required to spin the nut up along the threads of a bolt. In this case, the relationship between the torque and the desired clamp load tension is given by the following formula [22]:

$$T = \frac{KBP}{12} \tag{21}$$

Therefore, for a screw pile in the ground, it can be written that:

$$Q_u = \frac{12}{KB}T \tag{22}$$

So,

$$a = \frac{12}{KB} \tag{23}$$

Where:
T = Torque (lbs.ft)
B = Nominal diameter (in.)
Q_u= Ultimate carrying of screw piles (lbs)
K = Torque coefficient (dimensionless)
a = Parameter depending on soil type (1/in.)

The K coefficient can vary depending on the condition of the soil. The following coefficient range can be adopted (the different values of K were deduced by an analogy applied between pile/soil and bolt/nut): K = 0.10 for soft clay or loose sand, K = 0.20 for medium stiff clay or medium-to-dense sand, and K = 0.30 for firm clay or dense/very dense sand.

Validation of the Analytical Model

To validate the analytical models described previously in sections 2.1 and 2.2 (i.e. Eqs. 14 and 18), a small scale testing program was conducted in laboratory. Whereas, the third model, purported in section 2.3 (Eq. 22), was endorsed against some experimental data reported in literature. The laboratory testing program consisted on loading in a test rig three types of steel screw piles of different lengths, diameters and distances between grooves. The diameters adopted were 8, 10 and 12 mm; while, the piles' lengths used were 50, 100 and 150 mm. The soil bed was dense uniform sand with an angle of shearing resistance $\varphi = 38^o$.

The results of the different comparisons are summarized in Tables 1, 2 and 3. According to the data grouped in Table 1, it can be deduced that the first analytical model, represented by Eq. 14, underestimates the compressive carrying capacity of screw piles by about 5 to 15%. For the second model, a reasonable agreement was noted between the calculated and the measured results when the ratio $L/B \geq 10$. However, in the opposite, the model overestimates the ultimate capacity of screw piles by about 15.3%. Likewise, the empirical model (Eq. 22), overestimates the tensile carrying capacity of screw piles by 10 to 20% with an average of 12.4%. In consequence, Eq. 22 was revised in order to reduce or eliminate this discrepancy. The revised equation was obtained by multiplying the parameter (a) by 0.847. Accordingly, the current equation representing the empirical model is given as follows:

$$Q_u = \frac{10}{KB}T \tag{24}$$

Table 1. *Comparison between Theoretical (Eq. 14) and Present Laboratory Results*

Screw Piles Characteristics			**Compressive Carrying Capacity, Q_u(N)**	
B **(mm)**	***L*** **(mm)**	**Δx(mm)**	**Theoretical (Eq. 14)**	**Experimental**
8	50	0	22.97	25.18
	100		34.97	37.57
	150		40.29	43.33
10	50	0	23.82	26.67
		2	27.22	29.10
		3.5	32.14	36.67
		5	33.71	37.95
	100	0	34.72	37.39
		2	36.73	41.48
		3.5	37.93	42.50
		5	37.79	44.00
	150	0	47.03	55.00
		2	50.83	59.60
		3.5	57.64	64.35
		5	59.29	67.72
12	50	0	39.72	45.33
		2	41.02	47.38
		3.5	44.77	50.00
		5	49.62	57.87
	100	0	39.94	46.90
		2	42.25	48.73
		3.5	48.12	50.66
		5	53.28	62.07
	150	0	65.34	76.08
		2	68.05	78.67
		3.5	78.97	84.61
		5	75.53	88.31

Table 2. *Comparison between Theoretical (Eq. 18) and Present Laboratory Results*

Screw Piles Characteristics			**Compressive Carrying Capacity, Q_u(N)**	
B **(mm)**	***L*** **(mm)**	**φ(°)**	**Theoretical (Eq. 18)**	**Experimental**
10	100	38	51.31	44.00
	150		73.42	64.35
12	50	38	48.85	50.00
	100		46.46	48.73
	150		85.71	88.31

Table 3. *Comparison between Theoretical Results (Eq. 22) and Experimental Data Reported in Literature*

Screw Piles Characteristics			**Tensile Carrying Capacity, Q_u, kN**(lbs)	
***B*, mm** (in.)	***Soil State* (*K*)**	***T*, kN.m** (lbs.ft×10^3)	**Theoretical (Eq. 22)**	**Experimental [23]**
114 (4.49)	0.1	**15** (11.06)	**179.42** (40.33×10^3)	**150** (33.72×10^3)
	0.2	**20** (14.75)	**222.14** (49.94×10^3)	**200** (44.96×10^3)
140 (5.51)	0.1	**25** (18.44)	**281.61** (63.31×10^3)	**255** (57.32×10^3)
	0.2	**35** (25.81)	**342.58** (77.01×10^3)	**310** (69.69×10^3)
	0.3	**50** (36.88)	**468.37** (105.29×10^3)	**425** (95.54×10^3)

Definitely, in geomechanical and geomaterial design a variability of the ultimate capacity parameters of 5 – 20% is fairly frequent and acceptable [24]. Furthermore, the calculated values for the mean and the standard deviation of the results grouped in Tables 1, 2 and 3 are 11.3, 12.4 and 15.3% (for the mean), and 3.03, 4.06 and 1.7 (for the standard deviation), respectively. In addition, the coefficient of variation, defined as the ratio of the standard deviation to the mean (which is a measure of the dispersion of a data set), is less than one, indicating a relatively low variation in the results.

Conclusion

Significant advances are being made toward the utilisation of screw piles as anchors and foundations of structures. Nonetheless, there is still a lack of design methods related to screw piles which require continued investigation. The main conclusions drawn from this investigation are summarized as follows:

1- Three conceptual models to predict the carrying capacity of a screw pile of multi helices were developed.
2- The first analytical model takes into account shaft friction, grooves' geometry, and configuration of helices' assembly (Eq. 14). It was noted that this analytical model underestimate the compressive carrying capacity of screw piles by about 5 to 15%.
3- The second analytical model is based on the observed failure surface of screw piles proclaimed in literature (Eq. 18). For this model, a reasonable agreement was noted between the calculated and the measured results when the ratio $L/B \geq 10$. However, in the opposite, the model overestimates the ultimate capacity of screw piles by less than 15.3%.
4- The third empirical model considered the existing correlation between the torsional resistance generated during screw pile installation and its carrying capacity (Eq. 22). Likewise, the empirical model overestimates the tensile carrying capacity of screw piles by 10 to 20% with an average of 12.4%.

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