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A Review of the Design and Axial Capacity Calculation Practices for Helical Piles

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Abstract. Helical pile is a type of deep foundation consisting of a steel shaft with round steel plates welded to it. Their applications have significantly increased since the late 1990s with the development of high torque generating machines. They are used in solar power plants, boardwalks, retrofitting works, transmission towers, transmission towers, and even residential buildings. Significant advancement has been made over the years using various laboratory tests, field tests and software simulations to improve the design and strength of helical piles. However, research is still in progress for upgrading their design and predicting their load-carrying capacities. Codes have also been developed by a few countries for their design such as AC358 (USA), BS 8004:2015 (UK), CFEM 2006 (Canada), AS-2159:2009 (Australia). Field practices have also been carried out based on design manuals formulated by companies manufacturing helical piles. Currently, no Indian Standard code is available for their application in Indian conditions. In this paper, the most critical design and calculation methods framed by various researchers and the codal provisions have been discussed and compared. An overview of the essential design parameters influencing the helical pile capacity and a design recommendation have been provided which will be helpful in the design practices of helical piles.

Keywords: Bearing capacity, Finite element analysis, Helical piles, Screw piles

1 Introduction

Helical piles are low displacement deep foundation component which are installed by screwing into the ground. Their utilization has increased over the last few decades because of their several advantages over conventional piles and the development of high torque generating machines (Perko 2009).

Traditionally, helical piles were used as foundation for transmission towers to resist uplift loads or to resist smaller compressive forces, e.g., from residential buildings. But when scaled-up, they can also be used to resist heavy loads. They are now widely used for residential buildings, machine foundation, telecommunication towers, and for boardwalks in environmentally sensitive areas. In addition, they are also used as foundation for resisting tensile and lateral loads, e.g., guy anchors in poles and towers, tie-backs for retaining walls, foundation tiedown, offshore structures, tilt-up braces, and for slope stabilization.

They have various advantages over conventional pile foundation systems. They are easy and quick to install, produce less vibration, can be used for remedial works, and can be loaded immediately after installation. Moreover, they are environmentally friendly as they do not require concrete, do not produce spoils of excavation, and can be removed, reused, and recycled.

This paper discusses the design aspects, failure mechanism and the various factors influencing the capacity of helical piles. The most common methods used for the prediction of axial capacity of helical piles has been presented. A 2D finite element analysis (FEA) has also been conducted on helical pile and the results have been compared with field test results obtained from the literature.

2 Typical helical pile model

Main components of helical piles:

A standard helical pile is made of 3 main sections:

- **Shaft:** the shaft provides resistance through skin friction and helps to transfer the superstructure load to the helix.
- **Termination:** the termination is comprised of the drive lugs which helps to screw the pile into the soil, a splicing collar or bracket.
- **Bearing elements**: they consist of helices, which are the most important component for providing load resistance in helical piles. (Fig. 1)

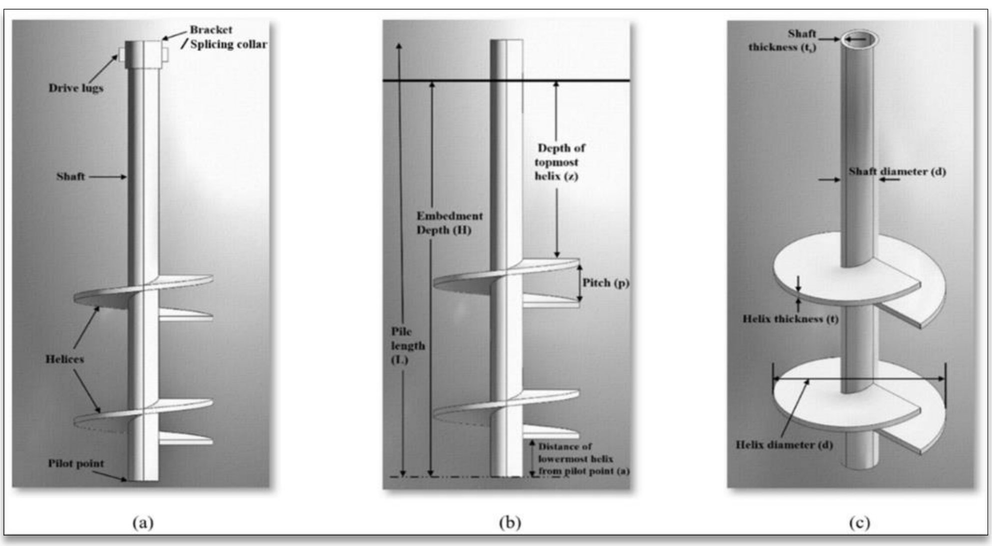

Fig. 1. Definitions and components of helical pile: (a) Main components of a typical helical pile; (b) and (c) Definitions of a typical helical pile

General specifications

The general design considerations and definitions conforming to the International Building Code (IBC 2009), Acceptance Criteria (AC358):2007, Chance Technical Design Manual (CTDM 2018), HAI engineering design manual (HEDM 2014), and some important studies, which are extensively followed for most research works and field practices, are listed below:

- *Steel Grade:* A wide variety of steel is used for manufacturing helical piles depending upon the project requirements. Generally, helical piles are manufactured using Grade 50 steel better.
- *Shaft wall thickness(t_s):* t_s is selected to resist loads without buckling or structural failure, depending upon the requirements of a project. t_s is typically taken between 5.5 mm and 9.5mm.
- *Shaft diameter (d):* Generally, round shaft helical pile diameters range from 73 mm to 305 mm. Square shaft are also used in cases where there is no problem of buckling or bracing.
- *Shaft length (L):* The shaft is manufactured in lengths ranging from 1 m to 6 m. Additional extension shafts can also be used to connect to the main shaft if the pile needs to be installed at greater depths.
- *Helix diameter (D):* Typically, helices of diameters 150 mm to 400 mm are manufactured. The helix diameter varies from 2 to 4 times the shaft diameter.
- *Helix Thickness (t):* The thickness varies from 5.5 mm to 25.4 mm depending on the project requirements (Schmidt & Nasr 2004).
- *Pitch (p):* Helical pile manufacturers use a standard pitch of 3 inches (76.2 mm).
- *Number of helices (n)*: Helical pile consists of a minimum of 1 helix. Additional helices may be welded to the shaft to increase the pile capacity. Practically, the maximum number of helix plates used is 5 in cohesive soils and 6 in cohesionless soils.
- *Helix spacing (s):* The distance between two helices is essential for determining the failure mechanism in helical piles. Helical pile manufacturers generally provide an optimum spacing of three times the diameter of the lower helix to avoid overlapping between the stress zones of the helices and incorporate individual failure mechanisms, maximize capacity, reduce shaft length, and enable the helices to be placed in the same layer, thus increasing the accuracy for bearing capacity calculations.
- *Embedment depth (H)*: The distance between the topmost helix and the ground surface is another determining factor for the failure mechanism in a helical pile. The minimum recommended embedment depth is five times the largest helix diameter (5D) as per CTDM (2018), and 6D as per HAI (2014) and Gavin et al. (2014) for compressive loading. For tensile loading, the minimum embedment depth is 12D.
- *Spacing between helical piles in the group (S):* The minimum recommended center-to-center spacing between adjacent helical piles is five times the diameter of the largest helix with spacing not less than 3 feet (0.91 m).
- *Speed of installation:* Usually a speed of one pitch per revolution is prescribed by helical pile manufacturers.
- *Installation torque (T):* T is directly proportional to the diameter of pile shaft (d). A maximum torque of 10000 Nm to 120000 Nm is recommended for pile having shaft diameters from 76.2 mm to 323.85 mm (Schmidt & Nasr 2004).
- *Factor of Safety (FOS):* A FOS of 2 and 1.5 for permanent and temporary structures, respectively is recommended. A FOS of 2 is considered for all allowable load

calculations according to AC358:2007 and IBC:2009. CFEM:2006 recommends the ultimate capacity to be multiplied by a geotechnical resistance factor of 0.4 for compressive loading and 0.3 for tensile loading.

3 Failure Mechanism and load distribution in helical piles

Helical pile may fail due to the collapse of any of its 4 main elements: Helix Capacity, Bracket Capacity, Shaft Capacity, and Soil Capacity (AC358:2007). According to IBC:2009, to avoid any failure each of the elements must conform to the minimum strength requirements to avoid failure.
From a geotechnical perspective, helical piles experience either deep failure or shallow failure. Deep failure develops locally near the helices in two ways: individual failure or cylindrical failure. In individual failure, the failure plane forms around each independent helix, while in cylindrical failure, the failure plane forms around the soil mass between the uppermost and the lowermost helix (Mitsch and Clemence 1985; Das 1990; Sakr 2009). In shallow failure, the failure plane reaches the soil surface. The factors that determine the type of failure occurring in helical piles are discussed in the following section.
Studies show that most of the resistance is provided by the helix (Zapata et al. 2015) and a very small part of the total resistance is offered by shaft friction, especially those having smaller shaft diameters. In their study, Clemence and Lutenegger (2015) found that resistance offered by shaft friction was not taken into consideration in over 80% of projects. The lowermost plate provides largest resistance under compression, while the uppermost plate provides maximum resistance under tension in multi-helix piles (Livneh and Nagger 2008; Sprince & Pakrastins 2009). It has been observed that the largest soil displacement takes place within a radial distance of 1.5 times the helix diameter from the axis of the shaft. According to different manuals, code books, and research papers, the failure of helical piles is generally considered to be the load at a pile head displacement of 5-10% of largest helix diameter (D_{max}) or average helix diameter (D_{avg}), provided no plunging failure develops (Livneh & Naggar 2008; Wang et al. 2013).

4 Factors influencing helical pile capacity

Bearing capacity of helical piles depends on several factors such as the type of connection, dimensions of the pile, soil properties, type of load applied, embedment depth, and soil-pile interaction. These factors which influence the load-carrying mechanism of a helical pile has been briefly described:

Embedment ratio (H/D)

The embedment ratio H/D, is defined as the ratio between embedment depth (i.e., the distance between ground surface and pilot point of shaft) and the helix diameter. Deep failure occurs when the embedment ratio is greater than the critical embedment ratio $(H/D)_{cr}$. Shallow failure occurs when H/D ratio is smaller than $(H/D)_{cr}$ (Merifield 2011;

Wang et al. 2013; Debnath and Singh 2022). Mittal & Mukherjee (2015) and Sprince & Pakrastins (2009) after performing parametric analyses using FEA concluded that the load carrying capacity in helical piles increases with the increase in H/D ratio under both tensile and compressive loading.

A helical pile is considered as deep if the depth of the top most helix (z) to its diameter (D) is greater than 5-7 (CTDM 2018). According to the uplift tests conducted by Trofimenkov and Maruipolshii (1965), $(H/D)_{cr}$ varied between 4 and 5 and between 5 and 6 for clay and sand, respectively. Narasimha Rao & Prasad (1993) suggest that shallow failure occurs at $H/D < 2$, a transition phase occours at H/D between 2 and 4 and deep failure occurs at $H/D > 4$, in clays.

Spacing ratio (s/D)

The spacing ratio is defined as the ratio of the distance between two adjoining helices to the diameter of the helix. The transition of failure mechanism from cylindrical to individual depends upon the spacing ratio and is almost independent of the diameter of helix and soil characteristics. Cylindrical failure occurs when the spacing ratio (s/D) is smaller than the critical spacing ratio $(s/D)_{cr}$ while individual failure occurs when the spacing ratio is greater than the critical spacing ratio value, i.e., $(s/D)>(s/D)_{cr}$. From the literature, it was found that the pile bearing capacity is directly proportional to spacing ratio upto a limiting value (i.e., s/D_{cr}) of 3.

Number of helices

Increase in the number of helices increases the helical pile capacity under both tensile and compressive loadings. Sakr (2009) and Polishchuk & Maksimov (2017) demonstrated in their finite element analyses that double helix pile had 40% and 30% higher bearing capacity, respectively, compared to a single helix pile. In another study, Papadopoulou et al. (2014) found that the pile capacity under compression increased by 40-55% in clayey soil but the tensile capacity remained unchanged. Thus, incorporating an additional helix can provide satisfactory increase in pile capacity at minimal cost.

Helix and shaft diameter

The most critical factor in determining the load-bearing capacity of helical pile is the diameter of its helix (D). D is directly proportional to the pile capacity. In contrast, diameter of shaft (d) has a relatively minor influence on the pile bearing capacity (Merifield 2011; George et al. 2017). Sprince & Pakrastins (2009) claim that the magnitude of the increase in pile capacity with helix diameter varies with the nature of soil.

Pitch

Pitch of the helix and inclination angle is useful during installation processes rather than for the determination of pile capacity. Finite element analyses by George et al. (2017) revealed that the compressive capacity of helical piles does not change with the variation of pitch but the tensile capacity reduces slightly.

Installation disturbance

The installation disturbance generated when helical piles are screwed into the ground, affects the pile capacity. This is because the soil properties in the immediate vicinity of the pile is altered. Therefore, the disturbance due to installation should be taken into account in designing of such piles (Nasr 2009; Wang et al. 2013). Spagnoli & Gavin (2015) in their finite element analyses and laboratory tests revealed that there was an increase in the uplift capacity. This increase was due to the compaction of the soil in the vicinity of the pile as a result of the installation effect. Mendoza et al. (2015) and Zapata et al. (2015) also found a higher pile capacity in their FEA when the installation disturbance was not considered. It can therefore be concluded that the pile capacity may increase in loose sand due to compaction. However, there might be a decrease in the pile capacity in stiff clay and dense sand due to reduction of soil stiffness after installation. It is also observed that installation disturbance generally affects the tensile capacities of helical piles and not their compressive capacities. This happens since the pile interacts with the disturbed soil above the bottom-most helix under uplift loading (Zhang et al. 1998).

5 Determination of axial capacity of helical piles

Trofimenkov & Maruipolshii (1965) proposed one of the first expression ((Eq. 1) for determination the axial load carrying capacity of single helix pile.

$$Q_u = R_u A_h + f P_s (L - D) \tag{1}$$

where, R_u=uplift resistance pressure, Q_u=ultimate uplift capacity, f=average specific pressure of soil, A_h=area of helix, P_s=perimeter of the shaft, D=diameter of helix, and L=length of shaft.

Analytical models based on cylindrical shear failure method

Mooney et al. (1985) proposed Eq. 2 for determining the bearing capacity of multi-helix pile in cohesive soil based on cylindrical failure mechanism:

$$Q_u = \square DLS_f c_u + A_h c_u N_c + \square\, d \square\, H_{eff} c_u \tag{2}$$

where c_u=undrained shear strength of soil, S_f =spacing factor, N_c=bearing capacity factor, H_{eff} =effective embedment depth, and α=adhesion factor.

Narasimha Rao & Prasad (1993) gave the following expressions (Eqs. 3a, 3b, and 3c) for estimating the value of S_f:

For s/D<1.5	$S_f = 1.0$	(3a)
For 1.5<s/D<3.5	$S_f = 0.863 + 0.069(3.5 - s/D)$	(3b)
For 3.5<s/D<4.6	$S_f = 0.700 + 0.148(4.6 - s/D)$	(3c)

For the determination of pile capacity under compression in cohesionless soil, the following equation (Eq. 4) was proposed by Mistch and Clemence (1985):

$$Q_u = \frac{1}{2}\pi D\gamma' \left(H_b^2 - H_t^2\right) K_0 \tan\Phi + \gamma' H A_h N_q + \frac{1}{2} P_s H_{eff}^2 \gamma' K_0 \tan\Phi \quad (4)$$

where, H_b and H_t=embedment depth of the topmost and bottom-most helices.

For determining the uplift capacity of a helical pile embedded in cohesionless soil, Mistch and Clemence (1985) gave the subsequent expressions (Eqs. 5 and 6):

For H/D<(H/D)$_{cr}$,

$$Q_u = \frac{1}{2}\pi \gamma' D\left(H_b^2 - H_t^2\right) K_0 \tan\Phi + \gamma' F_q H A_h \quad (5)$$

For H/D>(H/D)$_{cr}$,

$$Q_u = \frac{1}{2}\pi \gamma' D \left(H_b^2 - H_t^2\right) K_0 \tan\Phi + \gamma' F_q H A_h + \frac{1}{2} P_s H_{eff}^2 \gamma' K_0 \tan\Phi \quad (6)$$

where P_s and F_q are the perimeter of shaft and bearing capacity factor, respectively.

Narasimha Rao & Prasad (1993) presented the following equation (Eq. 7) for determining the uplift capacity in cohesive soils:

$$Q_u = W_a + \pi S_f D L c_u + A(c_u N_u + \gamma' H) + \pi d H_{eff} c_u \quad (7)$$

where W_a is the total weight of anchor.

Analytical models based on Individual shear failure method

Most of the codes and manuals recommend providing sufficient spacing between the helices so as to attain individual shear failure. This is done for achieving a greater efficiency and accurate prediction of the pile capacity. CFEM:2006 presents the following equation (Eq. 8) for calculation the load carrying capacity of helical pile in c-Φ soil when its helices are kept at a minimum spacing of $3D_{max}$:

$$Q_u = \Sigma Q_h + Q_s \quad (8)$$

Where, Q_h=individual bearing capacity for each helix expressed as (Eq. 9):

$$Q_h = A_h(N_c c_u + \gamma D N_q + 0.5\gamma B N_\gamma) \quad (9)$$

For a helical pile having a shaft diameter less than 100 mm, the shaft friction (Q_s) may be ignored. For pile having d>100 mm, Q_s can be calculated as (Eq.10) (CFEM:2006):

$$Q_s = \Sigma(\pi D f_s \Delta L_f) \quad (10)$$

Where, L_f is the pile length over which f_s and πD are constant and f_s is the sum of the adhesion friction between the pile and soil.

Empirical models for determining helical pile capacity

To calculate the load carrying capacity of pile using installation torque (T), Hoyt and Clemence (1989) presented the following equation (Eq. 11):

$$Q_t = K_T T \quad (11)$$

Where, T and K_T are the final installation torque (kNm) and resistance-to-torque ratio (m^{-1}), respectively. K_T is a is influenced by the shape of pile shaft, direction of loading (tension or compression), dimensions of the pile, and characteristics of the soil. Torque-capacity correlation is a quick method for helical pile capacity calculation and is commonly used as a verification tool as its results are not very reliable.

Numerical Modelling

The analytical pile load capacities are often validated against field load tests which are relatively time-consuming and expensive. Therefore, to study the behavior of helical piles in different design considerations, finite element method (FEM) is employed. FEM can simulate the actual geometry of a spatial structure such as the helical blade at a microlevel. For most of the previous FEA, the piles were considered to be wished-in-place into a soil body consisting of a meshed continuum. Although they give fairly accurate insights into the behavior and capacity of screw piles, they do not usually consider the installation effects of installation on the behaviour of the soil. In 2D FEM analysis, helix has mostly been considered as a plane plate for simplification purposes, which does not represent the actual geometry. The actual helix model can be designed and realized only in a 3-dimensional FEA. For FEM analysis on helical piles, a strength reduction factor (Rint) is used at the contact surfaces to simulate the decrease in the shear strength of the soil at the interface (Papadopoulou et al. 2014). Some other software studies on helical piles have also been carried out in applications such as LPile which is based on p-y analysis, Particle Flow Code (PFC) 3D which is based on discrete element analysis (DEM), etc. (Debnath and Singh 2022).

6 Case study

George et al. (2017) conducted a 3D FEA on helical piles in Plaxis 3D and validated it against field load test. A 2D FEM analysis was conducted on one of the problems presented in the paper. The results have been compared and presented in this paper. The details of the design and other considerations are provided in Table 2.

Table 2. Pile and soil properties considered for case study

Pile dimensions considered:	
Shaft diameter (d)	0.273 m
Helix diameter (D)	0.61 m
Embedment depth (H)	5.5 m
Model boundary:	
Width	10D (7m approximately)
Depth	5D (9m approximately)
Pile properties:	
E	200 GPa
μ	0.2
***Soil properties*:**	
Density	20 kN/m3
c	0
Φ	30°
E	80 MPa
μ	0.3
Rint	0.4
Constitutive model	Mohr-Coulomb

Maximum load	250 kN
Loading type	Compressive

To conduct the FEM, the pile and soil were first modelled in the Plaxis 2D. The model was then discretized into small elements, known as meshing. Material properties were then assigned and load was applied in the last step. The model was then analyzed by executing the calculation tool. Figs. 2 and 3 show the helical pile model and the mesh as designed in Plaxis 2D.

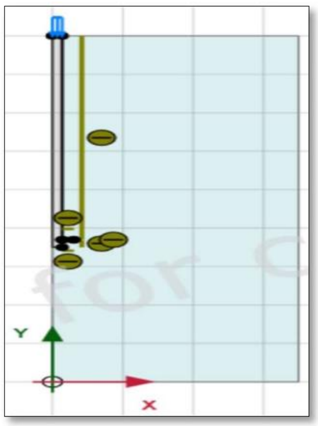

Fig. 2. Pile model created in Plaxis 2D

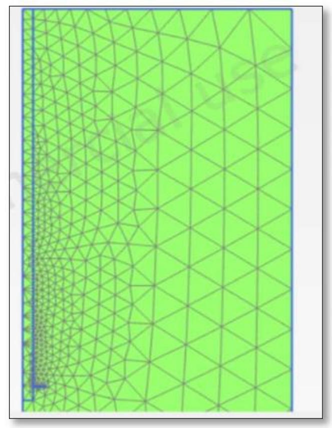

Fig. 3. Meshing of the model

After the analysis was complete, the results were studied and compared. Figs. 4a and 4b show the stress distribution developed around the pile. From the figures it is clear that the maximum stress developed in the soil body, occours around the helix and upto a distance of about 4D below the pile.

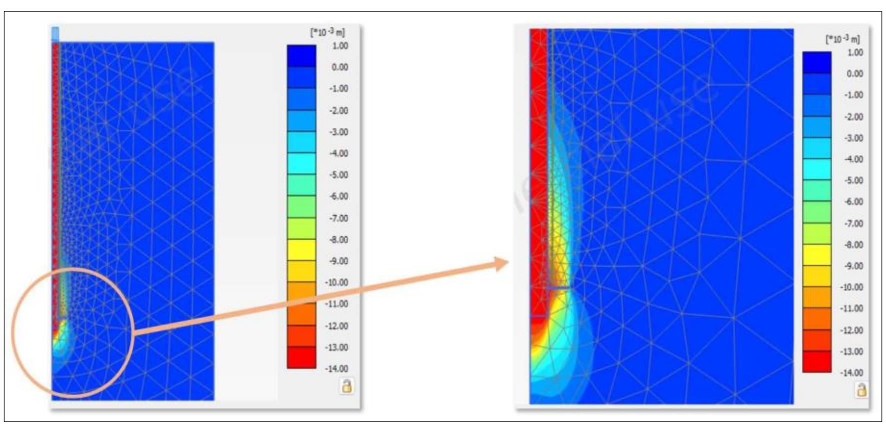

Fig. 4a. Stress zones developed after FEA

Fig. 4b. Magnified view of the stress zone

A load vs displacement graph was plotted from the results obtained after the analysis. Fig 5 shows a comparison of the load vs settlement graph obtained from the present study with the previous study.

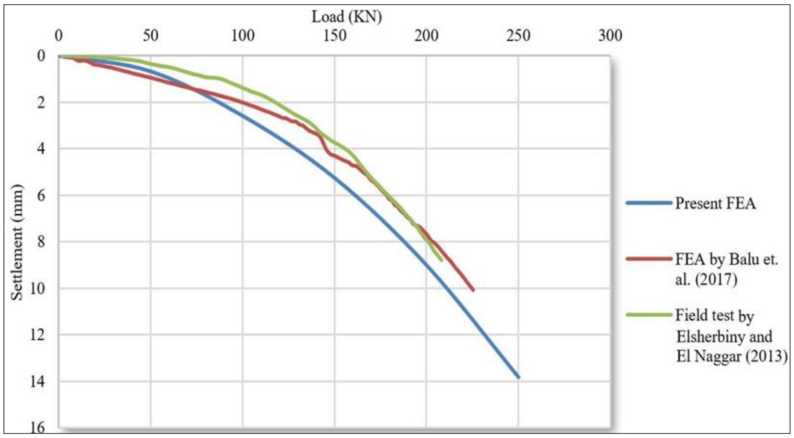

Fig. 5. Comparison of load vs settlement curves

The graph shows a similar trend and the ultimate capacity corresponding to 0.1D of settlement obtained from the FEA were within acceptable limits (Table 3). The results obtained using 2D FEA provided slightly lower capacity compared to the field tests and 3D analysis. This also shows that a 3D analysis provides a more accurate result compared to the 2D analysis, as the values were closer to field test results. This may be due to the fact that the actual helix design can accurately represented in a 3D model with proper pitch and inclination with respect to the shaft.

Table 3. Comparison of load capacity corresponding to 0.1D settlement

Calculation method	**FEA by George et al. (2017)**	**Present FEA study**	**Settlement by field load test (10% of D)**
Load at carrying Capacity (kN)	179	163	176

7. Conclusion

This paper presents an aggregated inference obtained from numerous studies, codes, and design manuals. The performance of helical piles under static compressive and tensile loadings has been discussed. From the discussion, the following conclusions can be drawn:

1. Embedment depth, helix spacing, and the soil properties are the main factors influencing the failure mechanism in helical piles.

2. In the absence of maximum allowable displacement, a pile head displacement between 5 to 10% of D may be considered as failure, provided no plunging failure occurs.

3. An analytical solution has been proposed for calculating the tensile and compressive capacity of helical pile embedded in both cohesionless and cohesive soils.
4. The different factors influencing the bearing capacity of helical piles have been discussed in detail and the following points can be concluded:
i. Critical embedment depth (H/D_{cr}) may be assumed to be 5.
ii. Critical spacing ratio s/D_{cr} may be considered as 3.
iii. Use of additional helices increases pile capacity at minimal cost.
iv. The bearing capacity of the pile increases as the helix and shaft diameters increase. The lowermost and the uppermost helices are the primary contributor to the compression and tensile resistance, respectively.
v. For helical piles, installation disturbance should be taken into consideration, particularly for stiff soils under tensile loading, as the soil above the bottom most helix will be disturbed.
5. Shaft resistance may be neglected if the diameter of the shaft is less than 100 mm.
6. The 2D FEA conducted on single helix pile showed lower bearing capacity compared to the 3D analysis and field tests. But the results were similar and the difference in bearing capacity was within acceptable range.

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