University of Baghdad
College of Engineering
JOURNAL OF ENGINEERING

Journal of Engineering

journal homepage: www.jcoeng.edu.iq

Volume 31 Number 6 June 2025

The Axial Uplift Capacity of Screw Piles: A Review

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ABSTRACT

There is a continuous demand in geotechnical engineering to find more economical footing. Screw piles provide acceptable or even much more bearing against tensile, compression, lateral, and overturning moment loads with less impact on the environment and surrounding buildings. Screw piles may be utilized either as shallow footing or deep footing, and can be installed in various types of soils except the soils that contain gravel or stiff clay. A screw pile is generally made of high-quality steel shaft with a single helix plate or multiple helixes plates attached to the lower end of the shaft at specified spacing utilized by the designer. The current study highlighted the various theoretical and field methods that were utilized in literature to estimate the uplift capacity of screw piles and pointed out several field, laboratory scale, and numerical simulation studies that investigated the most important parameters during installation and uplift loading of the screw piles. The former investigations revealed that installing the screw piles with torque rotation speed (v) of 1 (p/r) provides higher uplift capacities as well as increasing the embedment depth, the helix diameter, and the number of helical plates welded to the screw pile shaft. In general, the the decrease in the spacing ratio (S/D) gave higher uplift capacity in almost all the soils used by researchers this case can also be said to the decrease in the (L/D) ratio. Finally, increasing the undrained shear strength of clayey soil and the relative density of sandy soil gave a higher uplift capacity.

Keywords: Screw piles, Uplift capacity, Collapsible soils, Soft clay soils, Expansive soils.

1. INTRODUCTION

Screw piles footing systems also known as helical piles, helical piles, screw piles or helical anchors **(John et al., 2009; Al-Baghdadi, 2018)** are idealistic footing options for expansive soil, weak soil, hillsides, bay mud, creek sides, and high water-table projects. Screw piles have been vastly utilized to provide structural stability in engineering applications to resist

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Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2025.06.06

Article received: 26/10/2024
Article revised: 12/03/2025
Article accepted: 27/03/2025
Article published: 01/06/2025

uplift tension, axial compression, and lateral force in addition to overturning moment **(Abdel-Rahim et al., 2013; Ibrahim and Karkush, 2023)**. Screw pile composed of single or multiple circular helix plates at various intervals fixed to a central galvanized steel shaft along with a sharp end for effortless insertion into the ground surface by the application of torque to the top end of the shaft and as a result, the helix plates will enter the soil with a spiral movement without forming spoil or generating vibration **(Abbas, 2017; Jebur et al., 2020; Jamill and Abbas, 2021**). The primary elements of this type of pile are illustrated in **Fig. 1.**

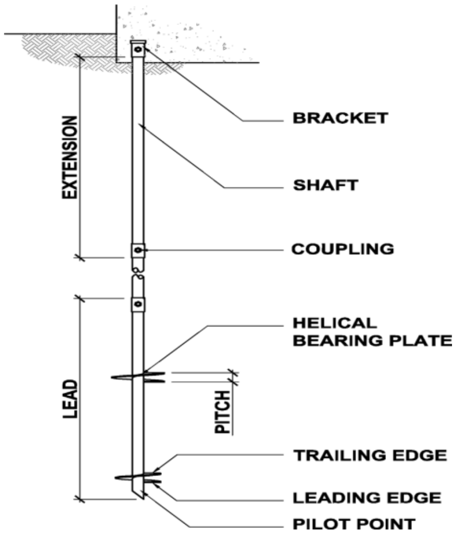

Figure 1. The primary elements of a screw pile **(Perko, 2009).**

A Screw pile footing provides sufficiently high bearing capacity, and decreases pile sliding, Moreover, it provides a good economic performance as a result of the smaller amount of steel required **(Lin et al., 2022)**. There are several factors that impact the behaviour of screw piles such as the spacing between helices, the shaft and helix diameters, and the spacing between screw piles **(Livneh and ElNaggar, 2008; Guo and Deng, 2017)**. Screw piles is frequently used in clay, silt and sand however screw pile footing system is not suitable in soil containing gravel nor stiff clay due to the damage that may happen to the helix plates during the driving process **(Abbas, 2017; Ali and Abbas, 2019)**. In recent years advanced nations such as Canada plus USA adopted screw pile, as a modernistic footing practice in the construction of structures like wind turbines, light house, solar panels, electric transmission, furthermore they used screw pile as tunnel support system and as a bracer in excavation **(Perko, 2009; Vignesh and Mayakrishnan, 2020; Ibrahim and Karkush, 2024)**. Currently screw pile usage has been expanded to include medium and heavily loaded structures despite its first usage as a footing for lightly loaded structures **(Vito and Cook, 2011)**. Screw piles were regarded as a suitable footing approach that can used for short-span bridges as well as middle span, In city areas **(Sakr, 2010)**.

The present study centers on defining, exploring applications, and examining methods for calculating the bearing capacity of screw piles under both compression and pullout loads across various soil types. Additionally, it involves a comprehensive review of prior experimental and numerical research conducted in this area.

2. TYPES OF SOILS

The screw piles can be used as deep foundation in several types of soil such as:

2.1 Cohesionless Soils

These soils consist of minerals that demonstrate grainy properties in which the soil grains stays separated from one another in a way that there will be no formation of lump of soil nor holding with each other to form accumulation of particles. Soils with this kind of attributes tend to have high level of liquid seepage between soil particles in addition to the high shear strength that originated from the friction among the soil particles that has no cohesion objections. cohesionless soils can involves sandy loam when the silt-sized soil particles were non-plastic nor non-sticky. It also includes sand and loamy sand as stated by the soil classification system that has been chosen and agreed as mentioned by **(Keaton, 2018).**
In civil engineering gypseous soils are known as very problematic because of the solubility of gypsum when structures were built on gypseous soils there were several problems that have been observed such as the increment of leakage of water through the soil, collapsing of the soil in addition to the attack of sulphate on concrete. These problems are the result of the slow and continuous dissolution of gypsum particles through the seepage of water throughout the soil that's containing gypsum **(Mahdy, 2004; Karkush et al., 2008)**. Gypseous soils can be found in different regions around the world and In Iraq these soils occupies around 30% of the country land space **(Al-Dulaimi, 2004)**. **(Seleam, 2006)** declared that either the initial void ratio (e) or the bulk unite weight (γ_t) or a combonation of both characteristics along with the initial water content ($w_{initial}$ %) were the main soil properties that influence collapsibility of gypsifereous soils in the land of Iraq whereas the other properties such as the plasticity index and the soil gypsum content appear to have lesser effect. Leaching strain increases in the soils containing high amount of gypsum content as a result to the increased percentage of dissolved gypsum in leaching water **(Karkush et al., 2008)**.

2.2 Cohesive Soils

Are the soils that contains fine grain particles that consist of silt and clay. Cohesive soils particles have the capability to adhesion but it also can be deformed without difficulty. Soil is stated to be cohesive when the quantity of fine materials which includes silt and clay soil particles is greater than the total mass of soil by 50 %. Moreover, cohesive soils are the soils that demonstrate plasticity and noticeable cohesive strength among the soil particles. The cohesion originates from three significant sources which are the cementation, the electrostatic as well as electromagnetic attraction, and finally the fundamental adherence along with valence bonding. these soils include organic clay, clayey silt, and sandy clay, in addition to silty clay as stated by **(Mitchell and Soga, 2005; Gautam, 2018; Karkush et al., 2022).** The current study will highlight several studies that deal with the uplift capacity of screw piles installed in cohesionless as well as cohesive soils including several problematic soils In geotechnical engineering a lot of soils can prove problematic cause they collapse, disperse, expand, and soluble, have distinct lack of strength in addition to the soils that undergo excessive settlement. These characteristics may be as a result of their composition, fabric, and mineralogy or may be resulting from the nature of their pore fluids **(Driscoll and Chown, 2001)**. Among many types of problematic soils, The definition of collapsible gypseous soil, expansive clay and soft clay and several problems associated with them are stated below:

2.2.1 Expansive Clay

(Al-Jorany and Noori, 2013) stated that the problems associated with expansive soils happen when the water reach out the soil particles and consequently cause them to separate. The swelling pressure will cause severe structural damage to the footing of light loaded structure. The cost related to damage from swelling soil is more than twice as much as the cost related to damages from tornados, hurricanes, earthquake, flooding and others so to avoid the danger of swelling soil pile footing is utilized to anchor down the structure to a desired depth where the variation of moisture content is negligible. Expansive soils can be found in Turkey, China, Canada , USA (United State of America) and others. In general, these soils could be found in arid zones in addition to semi-arid zones.

2.2.2 Soft Clay

(Ahmed and Adkel, 2017) stated that soft clay soils are a recent alluvial deposit that likely formed throughout the last millennium. These soils identified by their low shear strength (c_u<40 kPa) and high compressibility (Cc values ranges from 0.19 to 0.44). Generally, at the dry state soft clay soil are stiff however, at the wet state these soils loose it stiffness property. The rains and the absence of evaporation because of the pavement and buildings in addition to the floods and leakage in sewer lines are the common reasons of the increment of moisture content in clayey soils. In geotechnical engineering soils with such attributes can cause major problems relating to the settlement and stability. In Iraq several locations were investigated and the scanning reports indicate that soft clay soils do exist in some regions. The majority of these sites were concentrated in the middle part of Iraq land in addition to the southern part of the country **(Karkush, 2016)**.

3. DESIGN METHODS TO PREDICT THE UPLIFT CAPACITY OF SCREW PILES

(Pack, 2003) declared that even though the details relating to the design of screw pile were available in literature, their comprehensive details relating to their performance observation, examination, and quality assurance (QA) were limited. **(Mohajerani et al., 2016; Safdar et al., 2021)** stated that there were various design procedures utilized in literature to estimate the uplift capacity of screw piles which involves theoretical techniques approaches and empirical techniques approaches. **(Buhler and Cerato, 2010; Mohajerani et al., 2016)** informed that both of the individual bearing method as well as the cylindrical shear method were considered as theoretical techniques. **(Buhler and Cerato, 2010; Wang et al., 2013)** stated that the theoretical techniques employ several equations that can be different based on type of load subjected to the screw pile and whether the soil was cohesionless or cohesive. Therefore by utilizing a specific equation the screw pile ultimate capacity can be determined. And additionally mentioned an empirical technique that differ with the properties of used screw pile and soil conditions. This empirical technique is related to the torque applied on the screw pile during its installation. **(Tappenden and Sego, 2007; Safdar et al., 2021)** mentioned a direct technique that depends on the field cone penetration test (CPT) this technique is called “LCPC direct pile design method” which was discussed elaborately by **(Tappenden and Sego, 2007)**. In present time, the empirical and numerical methods were employed as a field conformation tool **(Buhler and Cerato, 2010; Wang et al., 2013).**

3.1 Cylindrical Shear Method

(Karkush and Mukhlef, 2021; Karkush and Hussein, 2021) stated that cylindrical shear failure zone supposed that the screw pile and soil above the helixes will fail like a cylindrical block with a length equivalent to the installation depth along with width equivalent to the diameter of helix plates of pile as shown in **Fig. 2.**

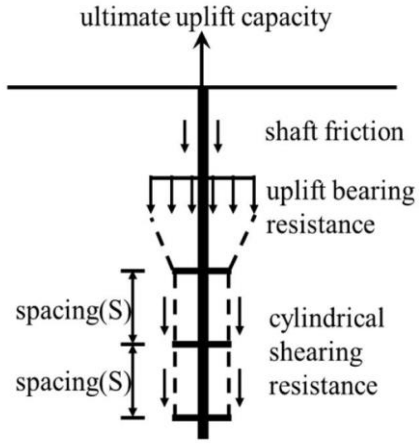

Figure 2. Cylindrical shear failure mode of screw pile with multiple-helix configuration **(Yuan et al., 2023).**

3.1.1 Cohesionless Soils

(Meyerhof and Adams, 1968) explained and derive an equation to estimate footing ultimate uplift and later **(Mitsch and Clemence, 1985)** represent an uplift capacity equation assuming a cylindrical shear failure zone for a screw pile with a multiple-helix plates composition fixed in non-cohesive soil at deep footing condition when $(H/D > (H/D)_{cr})$ **(Karkush and Mukhlef, 2021)** will be as follows:

$$Q_t = Q_{helix} + Q_{bearing} + Q_{shaft} \quad (1)$$

Where;

$$Q_{helix} = 0.5\,\pi\,D_a\,\gamma'\left(H_b^2 - H_t^2\right) K_u \tan\varphi \quad (2)$$

$$Q_{bearing} = \gamma'\,H\,A_H\,F_q^* \quad (3)$$

$$Q_{shaft} = 0.5\,\gamma'\,P_s\,H_{eff}^2\,K_u\,tan\varphi \quad (4)$$

$$H_{eff} = (H - D) \quad (5)$$

Thus;

$$Q_t = 0.5\,\pi\,D_a\,\gamma'\left(H_b^2 - H_t^2\right)K_u\tan\varphi + \gamma' H A_H F_q^* + 0.5\,\gamma' P_s H_{eff}^2 K_u \tan\varphi \quad (6)$$

Where
Q_t = Screw pile ultimate uplift capacity (kN);
Q_{helix} = shearing resistance activated throughout the length of cylindrical shear failure surface;
$Q_{bearing}$ = the uppermost helix end bearing;
Q_{shaft} = the steel shaft resistance;
A_H = The helix area (m^2);
D = Helix plate diameter (m);
D_a = the average helix diameter (m);
F_q^* = The breakout factor for deep screw piles;
H = The depth from the soil surface to the topmost helical plate (m);
H_b = the depth from the soil surface to lowermost helical plate (m);
H_{eff} = effective shaft length (m);
H_t = the depth from the soil surface to the uppermost helical plate (m);
K_u = lateral soil pressure coefficient under uplift loading (dimensionless);
P_s = the perimeter of the screw pile shaft (m);
γ' = the soil effective unit weight (kN/m^3);
φ = the soil friction angle (degree).

For shallow footing condition when ($H/D < (H/D)_{cr}$) supposing a cylindrical shear failure zone, the uplift capacity equation for a screw pile with a multiple helix plates configuration installed in cohesionless soil will be reduced as follows **(Karkush and Mukhlef, 2021)**:

$$Q_t = Q_{helix} + Q_{bearing} \quad (7)$$

Thus;

$$Q_t = 0.5\,\pi\,D_a\,\gamma'\,(H_b^2 - H_t^2)\,K_u\,tan\varphi + \gamma' H A_H F_q \quad (8)$$

Where F_q = The breakout factor for shallow screw piles.

3.1.2 Cohesive Soils

(Mooney et al., 1985) implemented the ideas and principles of cylindrical shear failure on the helical piles installed in silt in addition to clay soils. The formulated equations of this method rely on soil conditions, the spacing within helical plates, the geometry of helical pile, and the number of helical plates utilized **(Mohajerani et al., 2016; Vignesh and Mayakrishnan, 2020; Safdar et al., 2021). (Rao and Prasad, 1993)** gave the subsequent equation to calculate screw pile uplift capacity when installed in cohesive soil as follows:

$$Q_t = S_f(\pi\,D\,L_c)c_u + A_H(c_u N_u + \gamma' H) + \pi\,d\,H_{eff}\,\alpha\,c_u \quad (9)$$

Where L_c = The distance between uppermost and lowermost helix plates (m); N_u = Uplift bearing capacity factor; and α = soil adhesion factor. The screw pile foundation is considered a shallow foundation when the embedment ratio (H/D) is less than 3 and as a result, the shaft friction above the uppermost helix will be insignificant **(Safdar et al., 2021)**, so the uplift capacity in Eq. (13) will be reduced and became as:

$$Q_t = S_f(\pi\ D\ L_c)c_u + A_H(c_u N_u + \gamma' H) \quad (10)$$

Where S_f = The factor of spacing ratio.

(Lutenegger, 2009) supposed that no disturbances might be induced to the soil although soil structure could be disturbed during the installation of screw piles and by taking into account the undrained shear strength of the helical pile installed in clay. **(Lutenegger, 2009)** suggested an equation for the cylindrical shear method which was as follows:

$$Q_u = Q_s + Q_e + W_s + W_a \quad (11)$$

$$Q_S = (\pi\ D\ L_c)c_u \quad (12)$$

$$Q_e = A_H\ 9\ c_u \quad (13)$$

Where
Q_S = Cylindrical shear strength;
Q_e = uppermost helix plate end bearing;
W_s = the weight of the steel (kN);
W_a = the weight of the soil among helical plates (kN);

3.2 The Individual Bearing Method

(Adam and Klym, 1972) declared that when the spacing among each helix plate is sufficiently big this will cause every helix plate to behave separately from each other as mentioned by **(Mohajerani et al., 2016; Vignesh and Mayakrishnan, 2020; Safdar et al., 2021)**. The total uplift capacity of the screw pile is determined by the sum of the shaft resistances as well as the bearing capacity of each separate helix plate **(Livneh and ElNaggar, 2008; Kim et al., 2018)** as illustrated in **Fig. 3.**

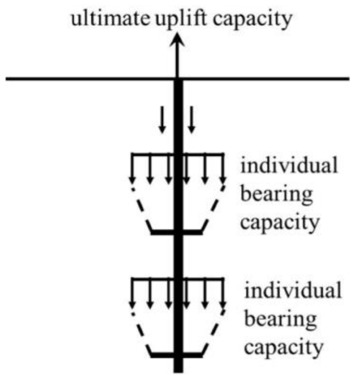

Figure 3. Screw pile with multiple-helix configuration having individual bearing failure mode **(Yuan et al., 2023)**.

The soil disturbed on top of the helical plate and the bearing area of the helical plate are the parameters that will influence the bearing capacity of the screw pile when it is subjected to uplift load **(Mohajerani et al., 2016; Safdar et al., 2021). (Chance Company, 1992)** introduced the following expression to calculate the screw pile uplift capacity when installed in cohesive in addition to cohesionless soils as shown in Eq. (14).

$$Q_t = \sum Q_{bearing} \quad (14)$$

Where;

$$Q_{bearing} = A_H\left(9c_u + q\,N_q\right) \le Q_s \quad (15)$$

For cohesive soil employ the following equation:

$$Q_{bearing} = A_H 9\,c_u \quad (16)$$

In the case of cohesionless soil utilze the following equation:

$$Q_{bearing} = q\,A_h\,N_q \quad (17)$$

Where c_u = soil undrained shear strength (kN/m^2) and d = screw pile shaft diameter (m);

By observing the previous expressions the influence of screw pile shaft skin friction while subjected to uplift load was not taken into consideration by **(Chance Company, 1992)**. **(Nasr, 2009)** proposed the following expression to determine screw pile uplift capacity shown in Eq. (18).

$$Q_t = \sum Q_{bearing} + Q_{shaft} \quad (18)$$

(Lutenegger, 2009) supposed if the shaft used in the screw pile was square the shaft friction is insignificant and gave the following expression for the uplift capacity in cohesive soil using individual bearing method.

$$Q_t = n\,Q_b + W_s + W_a \quad (19)$$

Where Q_b = same as Eq. 16

The notations of these terms based on **(Mohajerani et al., 2016; Vignesh and Mayakrishnan, 2020; Safdar et al., 2021)** were as follows $Q_{bearing}$ = Individual helix plate bearing capacity (kN); Q_s = The helix strength; c_u = The soil undrained shear strength (kN/m^2); q = The soil effective vertical stress (kN/m^2); Nq = factor of capacity for cohesionless soils; W_a = The weight of the screw pile; and W_s = The weight of the soil between helixes.

3.3 Empirical Relationship Between Uplift Capacity and Installation Torque

(Hoyt and Clemence, 1989) were the first researchers in the geotechnical literature to publish an empirical relationship that relates the installation torque to the uplift capacity of screw piles they introduced Eq. (20):

$$Q_u = K_T\,.T \quad (20)$$

(Hoyt and Clemence, 1989) considered (K_T) as a constant that differs with the screw pile shaft diameter The notations of these terms based on **(Hoyt and Clemence, 1989; Mosquera et al., 2015)** are as follows: Q_u= the ultimate uplift capacity; K_T= is a torque factor, T = the final torque applied during the installation of screw pile.

3.4 The LCPC Method

(Bustamante and Ganeselli, 1982) were the first to document this method and was further elaborated in the CFEM (Canadian Foundation Engineering Manual) in 2006 as mentioned by **(Tappenden et al., 2009; Perko, 2009)**. The Laboratories Central des Ponts et Chausees in Paris/France, which is referred to as the LCPC method uses the field cone penetration test (CPT) results data to determine the bearing capacity. **(Perko, 2009)** stated that the data obtained from the CPT can be utilized as an approach to determine the side shear strength in addition to the soil's ultimate bearing capacity and that the LCPC method is practical in complicated stratified soil sites with loose or soft soils inter-disbursed with cobbles, semi cemented layers or other compact material where it is highly random to predict the soil shear strength and the factors of bearing capacity. Moreover, by using the data acquired from the CPT the LCPC method can be utilized in both of the theoretical techniques to find the capacity of screw piles. The soil's ultimate bearing capacity on the basis of this approach is determined by the following equation:

$$q_{ult} = q_{ca}\, k_c \tag{21}$$

(Tappenden and Sego, 2007) utilized k_c value equal to 0.45 for the determination of screw piles. The side shear strength based on LCPC method is given by the following :

$$T = q_s \tag{22}$$

The notationts of these terms based on **(Safdar et al., 2021)** were as follows “q_{ca} = the equivalent cone tip resistance at the helix plate depth; k_c = bearing capacity factor for the penetrometer, T= the side shear strength; q_s = the unit side friction obtained from CPT”.

3.5 Uplift Capacity Determination from Pile Load Testing

In the literature there are many ways to find out the ultimate uplift capacity of a pile from the load-displacement curve resulted from pile load testing, several of these approaches were pointed out in references **(Zhang, 1999; Yttrup and Abramsson, 2003; Sakr, 2009, 2011; Nasr, 2009; Tappenden et al., 2009; Mohajerani et al., 2016)** which may include the L1-L2 methodology, ISSMFE which stated that the ultimate load is the load responsible for a screw pile movement equal to 10% of the helical plate diameter, Federal Highway Administration (FHWA) declared that the ultimate load is the load causing a displacement equivalent to 5% of the helical plate diameter, Brinch Hansen criterion, and Davisson criterion**.** Furthermore, **(Lutenegger, 2009)** stated that several authors defined the ultimate load as the accountable load for a displacement equal to 20% of the helical plate diameter.

4. UPLIFT CAPACITY OF SCREW PILES

(Meyerhof and Adams, 1968) suggested a critical ratio to decide whether the footing were considered as shallow or deep footing this ratio is called the critical embedment ratio $(H/D)_{cr}$. **(Meyerhof and Adams, 1968)** declared that when the shallow and deep footings were analysed the fundamental differences were within the failure mechanisms. **(Mitsch and Clemence, 1985)** declared that the soil conditions, the internal spacing among helix plates, and the embedment depth were the factors that the determination of the screw pile ultimate uplift capacity was reliant on when it was installed in sand. **(Rao et al., 1993)** declared that when the screw piles were installed in soft to medium clays and were subjected to uplift loadings the observed failure pattern of the screw pile after testing indicated that their failure surface was almost shaped as cylindrical if the spacing ratio (S/D) remains between (1–1.5). **(Rao et al., 1993)** showed that the bearing zone will be the whole area beneath the soil surface during the uplift of helical piles with several helical plates at deep footing conditions while the bearing zone will be only from the uppermost helical plate to the soil during the uplift of helical piles with several helical plates at shallow footing conditions.

(Zhang et al., 2007) found that the ultimate screw pile capacity is dependent on the spacing ratio (S/D) in addition to the embedment ratio (H/D). **(Zhang et al., 2007)** declared that when the embedment ratio (H/D) is exceeding 5 the screw piles under the influence of tensile or compression stresses were considered as deep footing. **(Lutenegger, 2009)** declared that the cylindrical shear failure was controlling the screw pile behaviour at a spacing ratio (S/D) ≤ 2.25 while the individual bearing failure was in control when the spacing ratio (S/D) exceed 2.25 after testing several screw piles with multiple helix plates embedded in clay soil. **(Nasr, 2009)** Stated that the ultimate screw pile uplift capacity can be better predicted using the individual bearing method when the spacing ratio exceeds (2). **(Tsuha and Aoki, 2011)** used the installation torque as a tool for quality control on site for the screw pile inserted in cohesionless soil which was sandy soil by comparing the resulting field and laboratory-measured magnitudes of (K_T) documented in the literature to the magnitudes of (K_T) gained from their investigation. Their analysis showed that increasing the soil friction angle (φ) as well as the pile dimensions caused a reduction in the value of (K_T). **(Abbas, 2017)** used square screw piles laboratory models and installed these models in sandy soil with 14% gypsum content. The test results showed that if there was an increase in the embedment depth, the helix plate diameter, the soil relative density and the number of helix plates then the square screw piles uplift capacity will also increase and the performance against uplift loads of square screw piles models was better than ordinary piles. Finally, from the results obtained by (**Abbas, 2017)**, its clear that increasing (L/D) ratio provides higher uplift capacity as shown in **Fig. 4**.

(Perez et al., 2017) performed several laboratory scale experiments and numerical simulation studies regarding the influence of installation effects on the performance of screw piles with single helix installed in cohesionless soil with a relative density of 99% and subjected to tensile loading. Different helix diameter was utilized for the screw piles models they used laboratory setup, FLAC 3D software for the numerical simulation and used Microtomographic imaging to compare their experimental findings to the numerical ones. The tomographic test analysis showed that installing the helical pile loosened the dense sand due to the helical plate penetrating the sand. Furthermore, the simulation in the numerical software showed there was a reduction in the soil angle of internal friction in the disturbed sand above the helix and around the screw pile. Furthermore, there was lesser disturbance happening to the soil around the helical pile and higher ditrubance to the soil above the helix plate. Finally, the load-displacement curve of the uplift test from the numerical study indicated that the resulted uplift capacity was overestimated when not including the effect of installation as shown in **Fig. 5**.

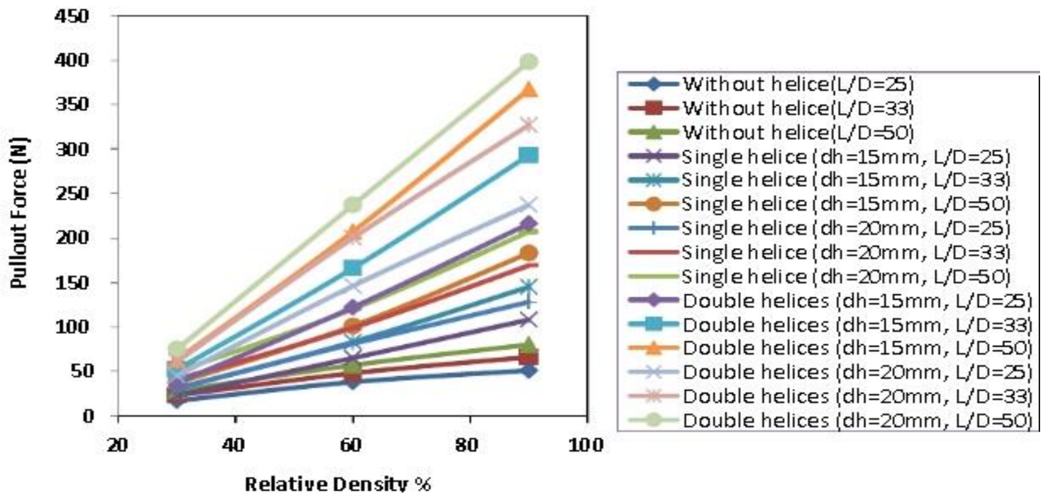

Figure 4. Uplift capacity vs. relative density for various screw piles and ordinary pile models **(Abbas, 2017)**.

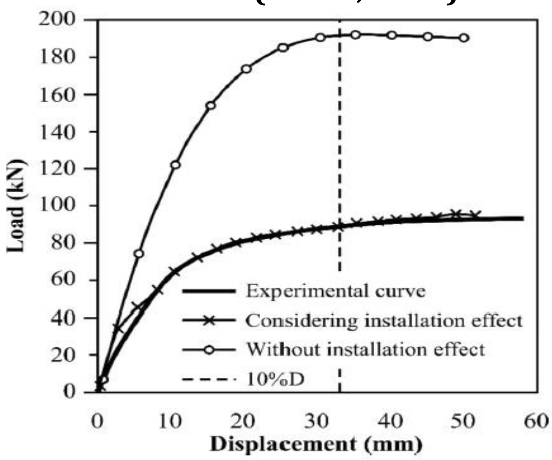

Figure 5. Comparison of the load–displacement curves obtained with and without considering the installation effect **(Perez et al., 2017).**

(Salem and Hussein, 2017) performed a numerical as well as field investigations regarding the uplift capacity performance of screw piles with a spacing ratio (S/D) equal to 2.5, the screw piles were embedded in cohesionless and cohesive soils. The outcome of their investigations were that the number of the helix plates, the soil strength, and screw pile embedment depth were the dominant parameters that have impacted the screw piles uplift capacity performance on the screw pile uplift capacity. **(Ashni and Janani, 2017)** investigate the uplift capacity of screw piles when installed in medium stiff consistency clay and declared that if there was an increase in the screw pile parameters such as the number of helix plates, internal spacing among helixes and the embedment depth then the screw piles uplift capacities will also increase.

(Aouadi et al., 2020) studied the effect of helical surface area on the uplift performance of multi-helix screw piles embedded in different types of soils as follows: Well-graded sand (S1), Silty gravel (S2) Sandy Clay (S3), and Organic peat (S4). The study was done by conducting experiments on screw pile models with perforations in the helix plates and comparing them with ordinary screw pile models without perforations in the helix plates the outcome of the experiment showed there was an improvement in the ease of installation for the screw pile with perforation used due to the reduction of the screw pile weight however, despite the uplift performance of the screw pile models with perforations was above the target value but their uplift capacity was lesser when compared to the ordinary screw pile model, as shown in **Fig. 6**.

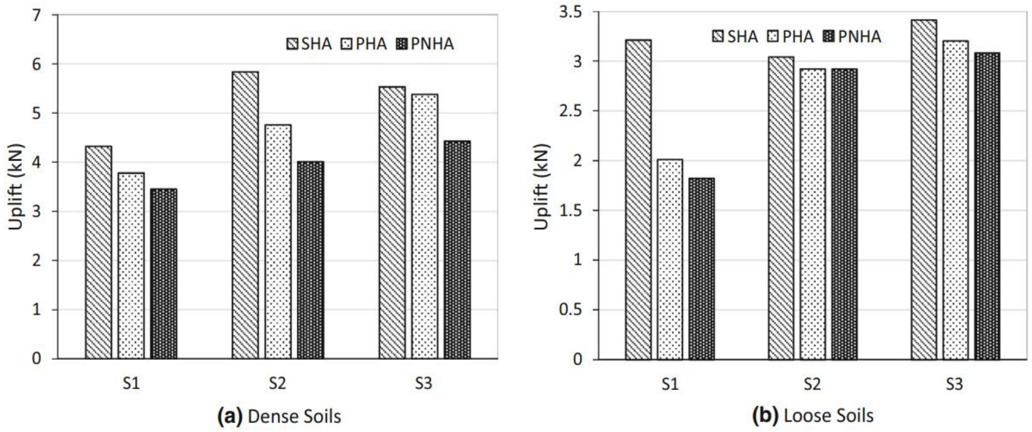

Figure 6. Uplift capacities of Solid Helical Anchor (SHA), Perforated Helix Anchor (PHA), and Perforated and Notched Helices Anchor (PNHA) **(Aouadi et al., 2020)**.

(Wang et al., 2020) studied the effect of installation for several screw pile models with various single helix plate diameters on its uplift capacities when installed in shallow dense sand and found that when the outer helix plate diameter increased the installation torque also increased. The uplift capacities of screw piles were barely altered when the installation speed (v) were ≤ 0.5 p/r while higher uplift capacities were observed when utilizing installation speed (v) of 1 p/r. Finally, for all installation speeds utilized the uplift capacity was higher when the helix plate gets bigger as shown in **Fig. 7**.

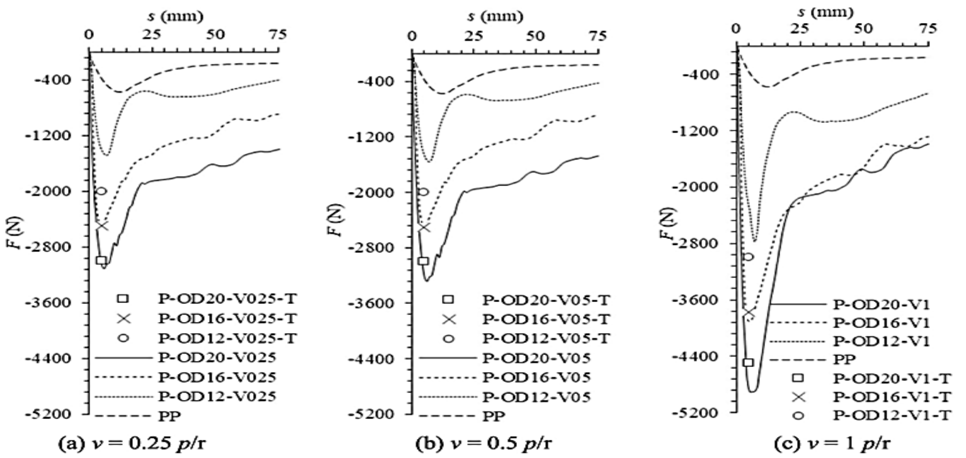

Figure 7. The uplift capacities of various single helix plate screw piles models at various installation speeds **(Wang et al., 2020)**.

(Mulyanda et al., 2020) showed that increasing the helix diameter gave higher uplift capacity for the screw piles embedded in clay soil with an average plasticity index of 40%. They also found that increasing the spacing ratio (S/D) will result in lower uplift capacities. Furthermore, the non-uniform tapered screw pile with helix plates positioned at the top of the pile in the sequence of biggest to lowest diameter had high uplift capacity than most of the uniform helical plates screw pile models as shown in **Fig. 8.**

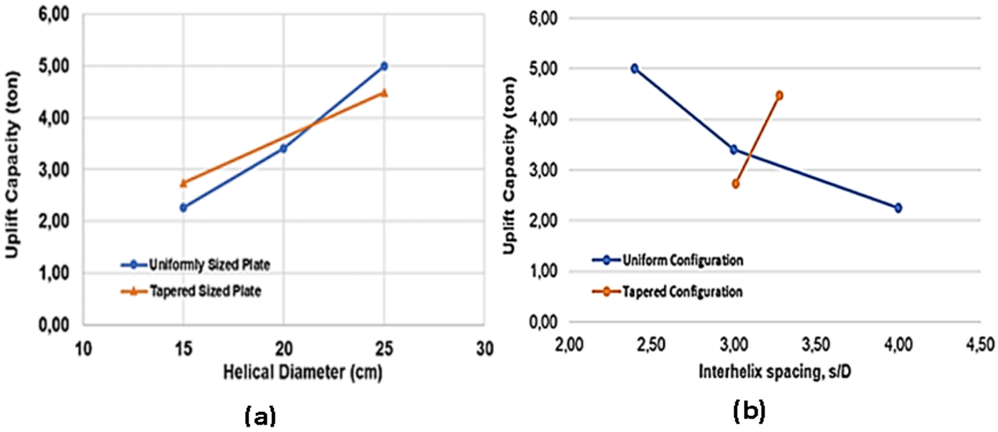

Figure 8. (a) The uplift capacity vs. the upper helix diameter adopted for uniform and tapered screw piles configurations, (b) the uplift capacity vs. the utilized space ratio (S/D) **(Mulyanda et al., 2020)**.

(Karkush and Hussien, 2021; Hussien and Karkush, 2022) investigated the uplift performance of laboratory screw pile models with continuous helixes along the embedment depth of 40 cm. The screw pile models used were with constant (shaft to helix) diameter ratio installed in soft clay which was prepared in layers inside a metal box. The obtained results showed that increasing the helix plate diameter resulted in a higher uplift capacity. Therefore reducing the ratio of screw pile embedded length to helix plate diameter (L/D) gave a higher uplift capacity as shown in **Fig. 9**.

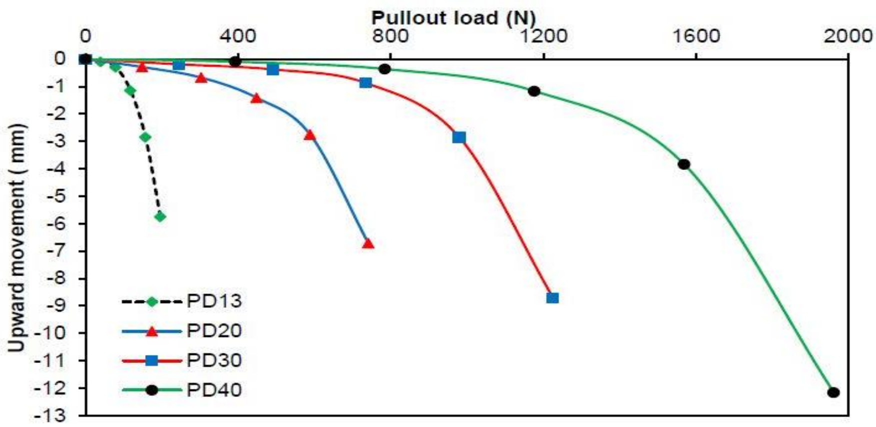

Figure 9. The uplift capacity of screw pile models and ordinary pile vs. the corresponding displacement **(Hussien and Karkush, 2022)**.

(Mukhlef et al., 2020; Karkush and Mukhlef, 2021) investigated the uplift capacity of laboratory models screw pile with continuous helixes along the embedment depth of 40 cm in gypseous soil with gypsum content of 40% which was achieved by using the raining technique inside a metal box, the ratio of (shaft to helix plate) diameter was constant for all screw piles models. The experiments were conducted in the dry condition as well as soaking condition after 24 hr to study the effect of dissolved gypsum content on the ultimate uplift capacity. The test results revealed that decreasing the ratio of screw pile embedded length to helix plate diameter (L/D) results in higher ultimate uplift capacity consequently, increasing the helix plate diameter will produce higher ultimate uplift capacity in addition to lowering the upward movement for both conditions. The ultimate uplift capacity at the soaking condition was reduced by (26, 10, and 1.8) % for the screw pile models with (L/D) ratios equal to (20, 13.33, and 10) respectively, due to the dissolution of gypsum after soaking for 24 hrs, as shown in **Fig. 10**.

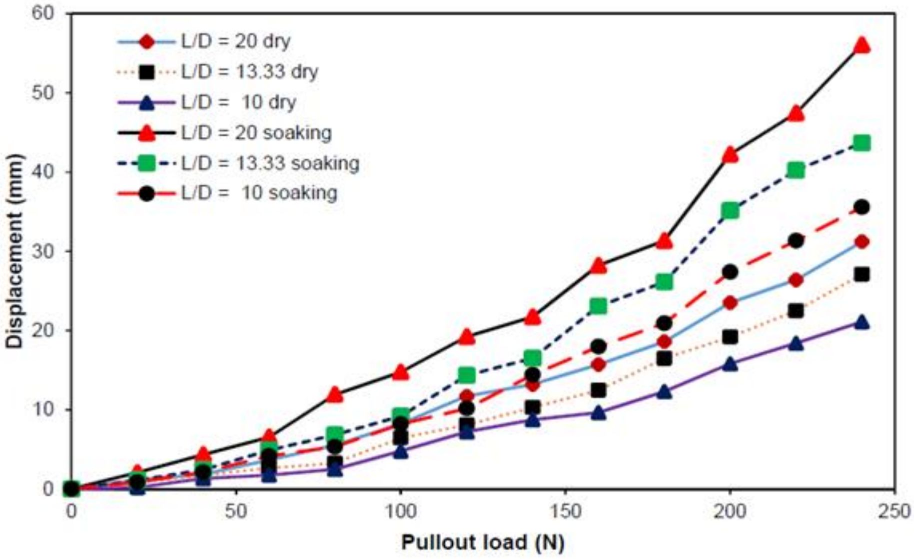

Figure 10. Effect of soaking on the uplift capacity of screw piles models with different (L/D) ratios installed in gypsiferous soil **(Karkush and Mukhlef, 2021)**.

(Mahmood et al., 2021) inspected the ultimate uplift capacity of different screw pile laboratory models with different helix number configurations and compare them to an ordinary pile model, all the models were with same shaft specifications. Each one of these pile models was inserted in cohesionless soil with a relative density of 50% then the tests were done at various soil saturation states including fully saturated, and partially saturated at various water levels, in addition to the soil dry state. The partially saturated soil water levels were achieved by utilizing several valves at different heights along the metal box and the corresponding average matric suction was recorded after 24 hours for every achieved water level by a Tensiometer. They found that increasing the number of helixes result in higher ultimate uplift capacity and the ordinary pile ultimate uplift capacity was significantly lower than all the screw pile models at all soil saturation states, Furthermore, all the screw pile models used in the tests have the highest ultimate uplift capacities when the soil state was partially saturated regardless of the various matric suctions while at the fully saturated soil state, the ultimate uplift capacities of screw pile models get reduced and were the lowest at dry soil states. lastly, the ultimate uplift capacity of the ordinary pile model was highest at partially saturated soil while its ultimate uplift capacity was reduced in the fully saturated soil state to be the lowest when compared to the dry soil state as shown in **Fig. 11**.

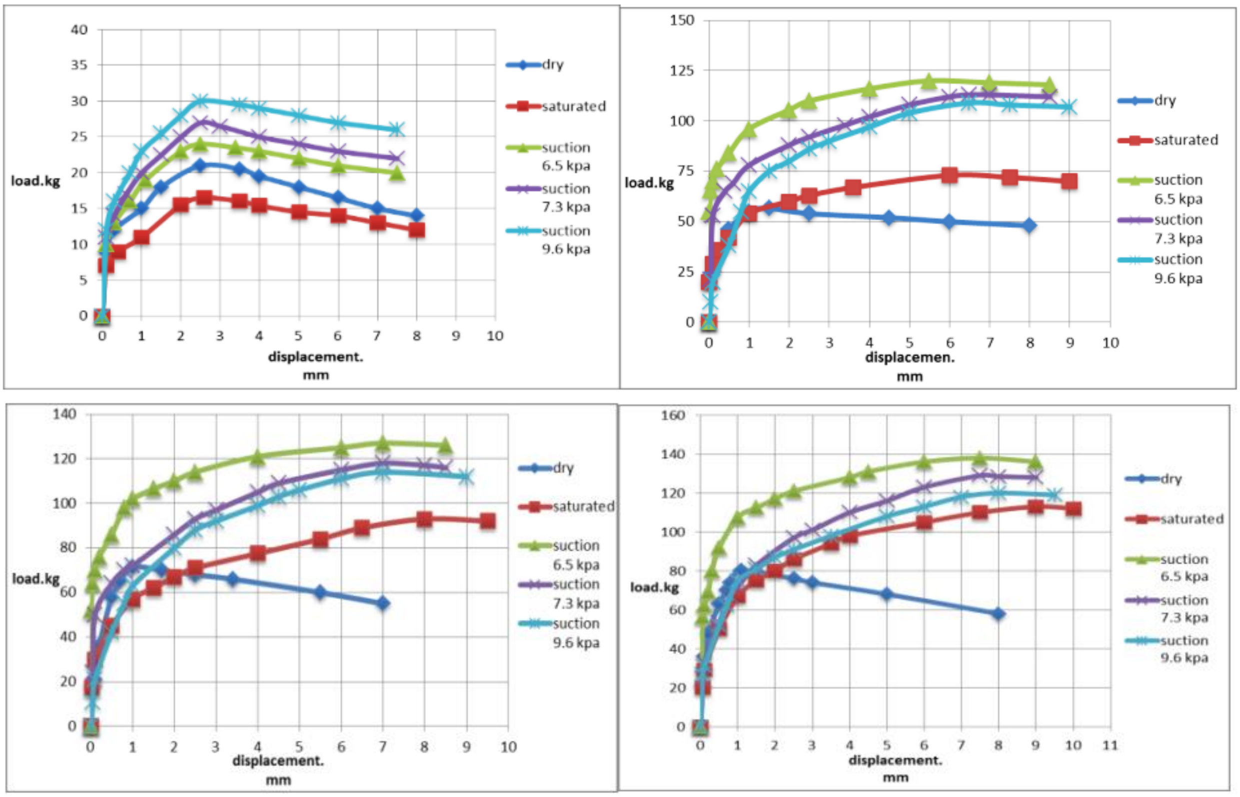

Figure 11. The uplift capacity and the displacement of : (a) ordinary pile, (b) single helix screw pile, (c) double helix screw pile, and (d) triple helix screw pile **(Mahmood et al., 2021).**

(Al-Ani, 2021) evaluated the uplift capacity of two laboratory screw pile models with continuous helixes along the embedment depth of 40 cm. The screw pile models used were with constant (shaft to helix) diameter ratio installed in expansive soil which was treated by clean water and proceeded by the electro-osmotic flow (RO). The study also showed the impact of the screw pile models uplift capacity performance when the same clean water treated previously was circulated in magnetic fields with several levels ≤ 2000 Gauss and then used to treat the expansive soil. The soil was inside a cylindrical container and was prepared and compacted in layers. The test results obtained showed that reducing (L/D) ratio results in higher uplift capacity thus, increasing the diameter of the helix plate results in higher uplift capacity. Furthermore, the uplift capacity of screw pile models installed in the soil treated with clean water treated previously by (RO) and circulated in magnetic fields with several levels ≤ 2000 Gauss was higher than the ones embedded in the soil only treated by clean water proceed by (RO) as illustrated in **Fig. 12**.

(Alkaby and Karkush, 2022; Karkush and Alkaby, 2023) investigated the uplift capacity performance of screw pile models subjected to seismic loading. The studies were done By utilizing numerical modelling simulation software called PLAXIS 3D. The screw pile models were with various number of helixes configurations and each one was installed in soil with multiple layers. The soil's upper layer was sandy silt while the bottom layer was silty clay The tests showed that the spacing ratio (S/D) controls the failure mechanism. When the spacing ratio (S/D) adopted was equal to 2 the cylindrical shear failure was in control and when the (S/D) adopted was equal to 3 the individual bearing failure was in control.

Increasing the number of helix plates attached to the shaft from one helix to four helixes results in higher uplift capacity by about 58% and the failure load of screw piles can be assumed to be the uplift load that causes an upward movement equal to 5% of the helix diameter. Furthermore, when the soil undrained shear strength (c_u) increased the uplift capacity also increased as shown in the **Fig. 13**.

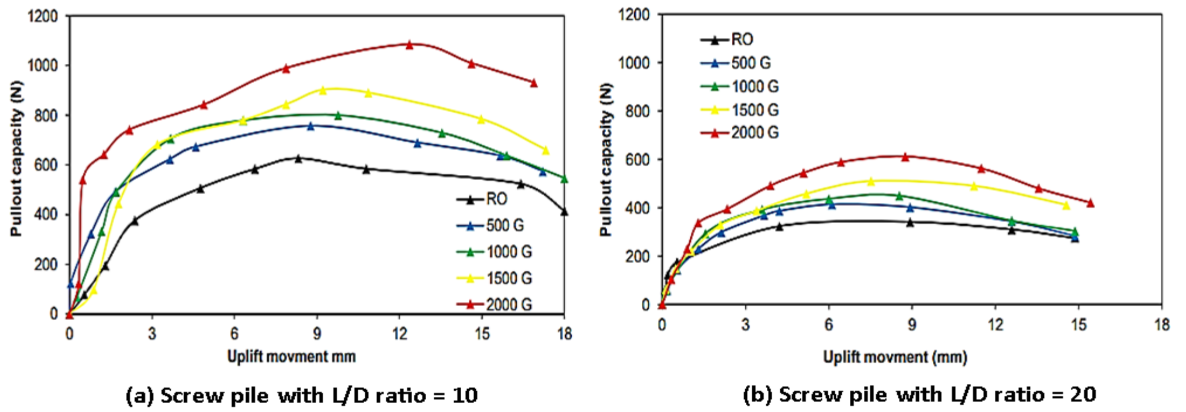

Figure 12. Uplift capacity and coressponding displacement for screw pile models with different (L/D) ratio **(Al-Ani, 2021).**

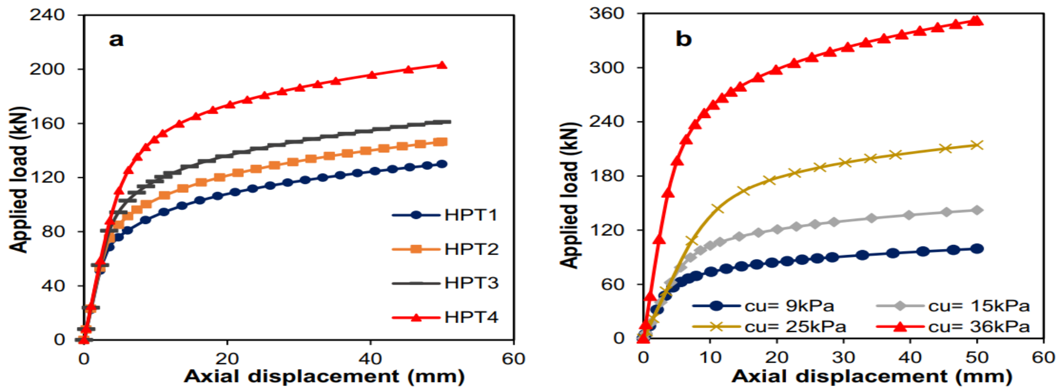

Figure 13. Uplift load vs. upward movement of screw piles: a) screw piles embedded in soil with two layers) and b) Screw pile with 3 helixes (HPT3) installed in one layer of soil having various cohesion (**Karkush and Alkaby, 2023)**.

5. CONCLUSIONS

Screw piles, also known as helical piles, serve as deep foundations and have a wide range of applications in geotechnical engineering, particularly for supporting compression and pullout loads. Additionally, they are effective in the rehabilitation of structures. Based on the numerical and experimental studies discussed earlier, it is clear that:

- The Uplift capacity of helical piles increased with the increase of the helix size, embedment depth, and number of helixes.
- The upward displacement decreased with the increase of embedment depth, the diameter of the helical plate, and the number of helical plates.
- In almost all types of soil, decreasing the spacing ratio (S/D) produces higher uplift capacity.
- Installing the helical pile with rotation speed (v) equals 1 p/r giving higher uplift capacity.

- Reducing (L/D) ratio will increase the uplift capacity of helical piles with continous helix plates along the embedded depth when installed in gypseous soil, soft caly and expansive soils.
- The most effective parameters in all the studies were the embedment depth, the helix plate diameter, the number of helical plates, and the internal spacing among helical plates.
- Increasing the moisture content or raising the groundwater table in cohesionless soils can affect the uplift capacities of helical piles significantly, the uplift capacities of helical piles were higher in the case of partially saturated soil rather than the fully saturated and dry soil states, respectively.
- Increasing the sand's relative density, and the undrained shear strength (c_u) in clayey soil gave higher uplift capacities.
- Despite the uplift performance of perforated Screw piles being less than ordinary screw piles but their performance was above the target value and their installation was easier.
- Screw pile installation in dense sand modifies the soil density and decreases the angle of internal friction of the soil.

NOMENCLATURE

Symbol	**Definition**	**Symbol**	**Definition**
A_H	The helix area (m^2)	Ps	The perimeter of the screw pile shaft (m)
Cc	Compression index	q	The soil effective vertical stress (kN/m^2
CPT	Cone peneteration test	QA	Quality assurance
c_u	Undrained shear strength of soil (kN/m^2)	$Q_{bearing}$	The uppermost helix end bearing
D	Helix plate diameter (m)	q_{ca}	The equivalent cone tip resistance at the helix plate depth
d	Screw pile shaft diameter (m)	Q_e	uppermost helix plate end bearing
Da	The average helix diameter (m)	Q_{helix}	Shearing resistance activated throughout the length of cylindrical shear failure surface
e	Initial viod ratio	Q_s	Cylindrical shear strength
FHWA	Federal Highway Administration	q_s	The unit side friction obtained from CPT
F_q	The breakout factor for shallow screw piles.	Q_{shaft}	The steel shaft resistance
F_q^*	The breakout factor for deep screw piles	Q_t	Screw pile ultimate uplift capacity (kN)
H	The depth from the soil surface to the topmost helical plate (m)	Qu	The ultimate uplift capacity
H_b	The depth from the soil surface to lowermost helical plate (m)	S/D	Spacing ratio
H_{eff}	Effective shaft length (m)	S_f	The factor of spacing ratio
H_t	The depth from the soil surface to the uppermost helical plate (m)	T	The final torque applied during the installation of screw pile

Symbol	Definition	Symbol	Definition
k_c	Bearing capacity factor for the penetrometer	v	Torque rotation speed
K_T	The torque factor	W_a	The weight of the soil among helical plates (kN)
Ku	Lateral soil pressure coefficient under uplift loading (dimensionless)	W_s	The weight of the steel (kN)
L/D	Selenderness ratio	γ'	The soil effective unit weight (kN/m^3)
L_c	The distance between uppermost and lowermost helix plates (m)	γ_t	Bulk unite wieght
LCPC	Direct pile design method	α	Soil adhesion factor
Nq	Factor of capacity for cohesionless soils	φ	The soil friction angle (degree)
N_u	Uplift bearing capacity factor	$\omega_{initial}$	Initial water content

Credit Authorship Contribution Statement

Ibrahim W. Ibrahim: Project Administration, Methodology, Validation,Writing – Review & Editing. Mahdi Karkush: Conceptualization, Methodology, Supervision, Writing – Review & Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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قابلية تحمل الركائز الحلزونية لحمل الشد: دراسة مراجعة

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قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد، بغداد، العراق.

الخلاصة

هناك طلب مستمر في الهندسة الجيوتقنية لإيجاد أساس يكون ذا تكلفة اقل و يوفر قدرة تحمل مقبولة أو حتى أكثر بكثير ضد احمال السحب، والانضغاط، والاحمال الجانبية، بالإضافة الى احمال عزم الدوران. وكل ذلك يكون بتأثير أقل على البيئة والمباني المحيطة. وقد تم استخدام الركائز الحلزونية على نطاق واسع في هذا الصدد. يمكن استخدام الركائز الحلزونية كأساس عميق أو ضحل في أنواع مختلفة من الترب عدا الترب التي تحتوي على الحصى أو الطين الصلب. الركيزة الحلزونية بصورة عامة تكون مصنوعة من عمود فولاذي عالي الجودة مع لوح حلزوني واحد أو ألواح حلزونية متعددة متصلة بالطرف السفلي من العمود بمسافات محددة من قبل المصمم. سلطت الدراسة الحالية الضوء على الطرق الميدانية والنظرية المختلفة التي تم استخدمت في حساب قابيلة تحمل الركائز الحلزونية لحمل السحب. تمت الاشارة إلى العديد من الدراسات الحقلية والمختبرية ودراسات المحاكاة العددية التي تبحث في أكثر المحددات تاثيرا على قابيلة تحمل هذه الركائز لحمل السحب أثناء تثبيت الركائز الحلزونية في التربة واثناءعملية تسليط قوى السحب. أظهرت الدراسات ان تثبيت الركائز بسرعة دوران مكافئة الى 1 دورة لكل ادخال ينتج ركائز ذات تحمل اعلى لقوى السحب بالإضافة الى زيادة العمق الدفن لاعلى لوح حلزوني، قطر الصفيحة الحلزونة، وعدد الصفائح الحلزونية الملحومة على عمود الركيزة الحلزونية. وبصورة عامة تقليل نسبة (S/D) تعطي قابيلة تحمل اكثر لحمل السحب لاغلب الترب المستخدمة من قبل الباحثين ونفس الشئ يمكن ان يقال عند تقليل نسبة (L/D). وأخيرا زيادة الكثافة النسبية للتربة الرملية وزيادة قوة القص غير المصرفة (c_u) في التربة الطينية يؤدي الى زيادة قابيلة تحمل الركائز الحلزونية لحمل السحب.

الكلمات المفتاحية: الركائز الحلزونية، قابلية السحب، الترب الانهيارية، الترب الطينية الضعيفة، الترب الانتفاخية.