Effect of soil saturation conditions and helical configurations on compression capacity of screw piles

Mahmood R Mahmood\textsuperscript{1,*}, Nahla M Salim\textsuperscript{1}, Ammar A Al-Gezzy\textsuperscript{1}
\textsuperscript{1}Civil Eng. Dept University of Technology-Iraq.
Email: 40079@uotechnology.edu.iq

Abstract. Helical piles provide many advantages over other conventional piles system. Most studies focuses on the performance of these piles in the dry and fully saturated soils. Rare studies are curried out to evaluate the performance of helical piles in partially saturated soils. Small scale models of steel piles of 600mm length with single, double, and triple helices have been embedded in cohesion less soil a depth of 400mm, the inner pipe diameter (d) was 20 mm and the helix diameter (D) was 50mm with spacing between helices of 3D, (i.e wing ratio (S/D) of 3). The models were tested using different soil saturations conditions (dry, fully saturated, and partially saturated soils). A pipe pile model was tested as a reference for bearing capacity improvement ratio. The results showed that the helical pile models and the pipe pile in fully saturation condition have less ultimate capacity compared to other soil conditions. The increment of bearing capacity increased for partially saturated soils than that of fully saturated soil by 1.5 to 1.8 times. The percentage of improvement of bearing capacity for additional helices single double and triple, embedded within fully saturation soil were 33.3%, 45.0% and 108.3% respectively, than shaft pile only.

1. Introduction
Helical piles are used since 170 years ago. They have high resistance to uplift and compression and used in different soil conditions for various applications [1]. Usually the traditional pile installation is a weight placement at a certain height that affects the pile and creates vibration and noise hitting the surrounding environment and adjacent structures [2]. Helical piles are installed by applying a vertical load called an overload by torque machine, which facilitates installation [3]. Although overloading may allow some piles to reach the required depths, some of them do not exceed the torque capacity [4]. Installation of screw piles are typically accomplished using a torque head affixed to the arm of a backhoe or a trailer-mounted hydraulic boom, the recommended penetration rate is equal to one stage for each revolution [5]. The torque in most cases is provided with a pit head (a hydraulic rotating motor) that attaches to the pile head [6]. The estimation of the maximum capacity of piles depends on the helix spacing, pile installation and soil conditions. Based on the requirement conditions, the helical piles can be classified as a deep or a shallow [7]. This description illustrates a discussion of the importance of the inclusion depth in spiral lint design and the spacing ratio (S/D), which is the spacing between two adjacent helices divided by the average diameter of these helices [8]. The spacing ratio represents the failure conditions (i.e. cylindrical shear failure or of individual bearing failure). Rao et al. [9] confirms that the change period from the cylindrical shear method to the individual loading method occurs with a spacing ratio (S/D) of between 2 to 3. This is why Livneh and Naggar [10] adopt the use of at least 4D spiral spacing to ensure failure mechanisms do not overlap. A series of experiments are performed by Spagnol et al. [11] to investigate the effect of the ratio of helix (or helical plates) to shaft diameter, and helix diameter
on the pull-out capacity of helical piles. The results. They suggest that the optimum pile design has a helix-to-shaft diameter (defined as wing ratio) between 1.5 and 2.0. Larger helical plates are significantly harder to install, whereas smaller helical plates provided little resistance to vertical loads.

In partially saturated soil, the complex relationship between soil and water has attracted the attention of many researchers to verify many of relationship. The complete behavior of this type of soil is not the same as that of dry or fully saturated soils. The soil suction is created within partially saturated soil mainly has two components such as matric and osmotic suction [12]. Suction is explained as the water potential in a soil-water system [13]. The suction is controlled by three components as described by [14], the first component is the capillary, the second component is surface charges on mineral surface, and the third component is a chemistry of the soil-water. Installation of the helical pile in partially saturated soil presents new challenges and this varies significantly from the same helical pile in saturation or dry soils. The main objective of the present work is to study the effect of saturation conditions and helical configuration on the performance of screw pile under compression.

2. Experimental work
The experimental work consisted of performing laboratory model tests to verify the ultimate bearing capacity of the helical pile models, which are embedded in cohesion less soil at a relative density of 50% and subjected to compression load in various saturation conditions dry, fully saturated, and partially saturated of different matric suctions.

2.1 Soil properties
Sandy soil was collected from Baghdad-Abu Nawas area. The standard tests to specify engineering and physical properties were performed and their results are shown in Table 1. Figure 1 shows the grain size distribution of the used soil, which was classified as SP According to USCS. Specific gravity test was performed according ASTM D 854-06 [15].

| Index Property | Sand Properties | Specifications |
|----------------|-----------------|----------------|
| Analysis of Grain size | | ASTM D422-00[16] |
| D10 ,(mm) | 0.16 | |
| D30 ,(mm) | 0.21 | |
| D60 ,(mm) | 0.29 | |
| (Cu) | 1.71 | |
| (Cc) | 0.89 | |
| Soil classification (USCS) | SP | ASTM D854-00 |
| Specific gravity(Gs) | 2.65 | ASTM D4253-00[17] |
| Maximum dry unit weight (kN/m³) | 16.6 | ASTM D4254-00[18] |
| Minimum dry unit weight (kN/m³) | 14.8 | ASTM D4254-00[18] |
| Relative density(RD)% | 50% | |

2.2 Helical Pile models
Three helical piles of mild steel models were designed and manufactured with (single, double and triple helices), with the following specifications, inner pipe diameter, d, of 20mm, helix diameter, D, of 50mm, thickness of helix, 2mm spacing between helices, S, 3D. Figure 2 shows the used pile models in this study. Table 2 shows the dimensions and specifications of the pile models.
2.3 Testing Apparatus
The apparatus were shown in figure 3. They were used to perform all the tests of the helical pile models. It consisted of soil container, steel frame, (saturation, drainage) system, load cell, and load indicator. Figure 4 shows a schematic diagram for the testing apparatus. The load cell capacity is 1ton which used to measure the compression resistance load of the helical pile model. The applicable vertical load in compression is controlled by strain control screw jack, connected by a motor of different speeds that was controlled by AC. The rate of loading was 0.5 mm/min. Digital dial gage was programmed to measure displacement in uplift and settlement for compression.

2.4 Preparation of Soil Bed
2.4.1 Soil Container. Steel container of internal dimensions (600 x 600 x 700 mm height) was designed to simplify the process of saturation and desaturation of the soil sample based on the specification of the container. Four valves were installed at one side of the container. They used for saturation and dewatering. The soil container was mounted on a moving base for easy moving and provides restrictions to prevent lateral movements during the progress of the test. Figure 5 shows soil container with its various components.
2.4.2 Soil Deposit Preparation and testing Procedure. Placing a layer of fine gravel at the bottom of the soil container and placing perforated fiberglass sheet was curried out to allow water to rise in a regular flow. Then, placing sheet of geotextile fine mesh was applied at the top of the fiberglass to prevent soil entering through the holes. After that placing a filter material with two layers of 50mm of each compacted at a relative density of 60% covered with double sheet of geotextile fine mesh to avoid mixing between filter and the soil used. Nine layers of fine cohesion less soil compacted with a steel tamping hammer to obtain the required relative density of 50% for each layer. After all, the layers are finished; the soil surface is leveled by a sharp edge ruler to obtain a flat surface. Then, a holder was fixed on the container sides to keep the aliment of the screw pile during installation. The process of rotation begins manually to install the model inside the soil where the rate of descent of the model (40-60) mm, at each descent of the model was confirmed vertically. However, the soil should not be deformed during installation. After that pile model being tested under vertical load applied through screw jack. The loading was applied at a rate of 0.5mm/min, digital dial gauges was used to record settlement during testing and load is recorded by the load indicator.

2.5 Measurement of soil Suction
A direct method was used for measuring negative pore water pressure in this study by Tensiometers.

2.5.1 Tensiometer. Tensiometer gauge can be measure the matric suction of the soil with a rang 0-100 kPa. The manual vacuum pump with the Tensiometer gauge used at a vacuum pressure between 80-85 kPa to release the air trapped in the disc of the ceramic. The tip of the Tensiometer ceramic was completely saturated and air-free before the Tensiometer was inserted into the soil. Figure 6 shows the Tensiometers with all accessories. A strong vacuum was placed on the Tensiometer gauge using a manual vacuum pump. The filling cap was removed. The edge was immersed in wet sand, and this
pump is vigorously made until a reading of 80 to 85 appears on the scale, usually 5 or 6 rapid withdrawals as shown figure 7.

2.6 Saturation and Desaturation. A supply water tube was connected with a lower valve for saturation the flows through filtered soil layer and rises from the bottom in a laminar flow with interrupting all the air voids until the water reach soil surface then left for 24 hrs, to be fully saturated. To get partially saturation with different matric suctions, the upper first valve was opened for lowering water level 150 mm. the tensiometer fixed to a depth of 75 mm to measure matric suction after 24 hrs. Then the second valve at the middle was opened to reduce water level to 300 mm. the Tensiometer was fixed to a depth of 225 mm to measure suction matric at this depth. After 24 hrs the third valve was opened to reduce water level 450 mm and the Tensiometer was fixed to a depth of 375 below the soil surface. Figures 8 shows the installation of Tensiometer in the unsaturated soil and the recording of suction for each layer in different conditions of the unsaturated soil due to reduce water level.

![Figure 6. Three Tensiometers used with their accessories.](image1)

![Figure 7. Installed the Tensiometer and record the results.](image2)

![Figure 8. Profile suction of all stage.](image3)

3. Results and Discussion

3.1 Profiles for Model Matric Suction

The results obtained from the suction profile set that describe the matric suction to the water level table. Table 2 shows values of the average matric suction summary for all lowering water table stages.
Table 2. Summary for average matric suctions due to reduce water level.

| Soil conditions  | Water table lowering from soil surface in (mm) | Corresponding average matric suction in (kPa) |
|------------------|-----------------------------------------------|---------------------------------------------|
| Fully saturated  | 0                                             | 0                                           |
| Partially Saturated | 150                                         | 6.5                                         |
|                   | 300                                           | 7.3                                         |
|                   | 450                                           | 9.6                                         |

3.2. SWCC Curve Prediction by Tensiometers

Figures 9 and 10 show the SWCC soil curves as estimated by equations of Fredlund, Xing and Van Genuchten [19-20], respectively.

![Figure 9](image1.png)

**Figure 9.** The relationship of gravitational water content and matric suction using the soil vision program adopted by Fredlund and Xing equation.

![Figure 10](image2.png)

**Figure 10.** Gravitational water content and the matric suction relationship using soil vision software adopted by Van Genuchten equation.

At the slope of the soil curve there are two regions of SWCC changes [19], it was announced that changes in the slope determine the focal points for SWCC. The first point is the "air entry value", where the largest voids begin to saturate with increasing suction. The second point is called "residual conditions", and it is defined as the point where water is removed from the soil becoming noticeably more difficult. The changes in the SWCC slopes were divided into three regions, the boundary effect zone in the lower suction range, the transition zone between air intake value, residual value, and
"residual zone". From Figures 9 and 10, the appropriate curves are suggested by Fredlund Xing [20] and Van Genuchten [REF], the air enter value \((u_a - u_w)\) was \((2.35)\) kPa, and \((2.38)\) kPa, respectively.

3.3. Effect of Saturation Soil Conditions on Bearing Capacity of Helical Pile Models with different Helices.

Figures 11, 12, 13, and 14 represent the behavior of pipe pile and helical pile models (single, double, and triple helices) under the effect of compression load at different matric suction values (6.5, 7.3 and 9.6 kPa). The Figures show an increase in bearing capacity with the increments of matric suction. The maximum bearing capacity was at matric suction of 9.6 kPa which was more than that of dry condition. This may be due to the attraction forces introduced due to lowering water table in cohesion less soils.

**Figure 11.** Load settlement relationships under compression load for pipe pile at different saturation conditions.

**Figure 12.** Load settlement curve for helical pile (single helix), under compression load at different saturation conditions.

**Figure 13.** Load settlement curve for helical pile model of (double helix), in compression load at different saturation conditions.

**Figure 14.** Load settlement curve for helical pile model of (triple helices), in compression load at different saturation conditions.

Table 3 summarize the ultimate compression capacity of pipe pile, helical pile with single, double, and triple helices which are embedded in dry, fully, and partially saturated soil. They were determined from the load-settlement curves, according to Cerato and Lutenegge, 2007 [21].
According to Table 3, the ultimate compression capacities of helical piles (pipe, single helix, double, and triple helices) which were embedded in fully saturated soil have the lower values. While, partially saturated soils show greater values than those embedded in fully saturated and dry soil. Furthermore, unsaturated soil of 9.6 kPa matric suction have the highest bearing capacity compared to the helical piles that was embedded in unsaturated soils of 6.5 and 7.3 kPa matric suctions and dry soil. This increment in ultimate bearing capacity due to an increase in effective stress due to increase in matric suctions.

3.3.1 Improvement Ratios in Bearing Capacities Due to Partially Saturation soil Under Compression Capacity. Table 4, shows the increment ratios of ultimate bearing capacities of pipe pile and helical piles with different number of helices embedded in partially saturated soil of matric suctions 6.5, 7.3 and 9.6kPa times the bearing capacity of fully saturated soil.

Table 4. Increment ratios of ultimate bearing capacities of models embedded in different saturation conditions to that embedded in fully saturated soil.

| Type of pile | Soil Saturation Conditions | dry soil condit. | Unsaturated soil of 6.5 kPa Matric suction | Unsaturated soil of 7.3 kPa Matric suction | Unsaturated soil of 9.6 kPa Matric suction |
|--------------|---------------------------|-----------------|------------------------------------------|------------------------------------------|------------------------------------------|
| Pipe pile    |                           | 1.55            | 1.11                                     | 1.20                                     | 1.7                                      |
| Single helix |                           | 1.56            | 1.12                                     | 1.43                                     | 1.68                                     |
| Double helices |                        | 1.79            | 1.20                                     | 1.49                                     | 1.86                                     |
| Triple helices |                      | 1.40            | 1.16                                     | 1.28                                     | 1.84                                     |

The results shows that the increment rations of bearing capacity increases with increasing suction values and even more than that of dry condition for matric suction value of 9.6 kPa, this is as mentioned before due attraction forces introduced when lowering water table in cohesionless soils. Figure 15 shows the increment ratio of bearing capacity of helical pile models due to different saturation conditions of partially saturated soils times fully saturation condition.

3.4 Effect of Number of Helices on Ultimate Bearing Capacity of Helical Pile Models
Effect number of helices on ultimate bearing capacity for helical pile models embedded within different soil conditions (dry, saturation, and unsaturation) shown in figures (16, 17, 18, 19 and 20).

### 3.4.1 Bearing Capacity of Helical Pile Models in Fully Saturated Soil

Figure 16 shows the behavior of the helical pile models (pipe pile, single, double, and triple helix) embedded within fully saturation soil. The figure demonstrate that an increase in bearing capacity with increasing number of helices.

### 3.4.2 Bearing Capacity of Helical Pile Models in Dry Soil Conditions

Figure 17 shows the behavior of the helical pile models (pipe pile, single, double, and triple helices) embedded within dry soil. The figure demonstrate that an increase in bearing capacity with increasing number of helices.

### 3.4.3 Bearing Capacity of Helical Pile Models in Partially Saturated Condition

In this case, tests divided into three model tests of different partially saturation conditions. Figures 18, 19, and 20 shows the behavior of pile models (pipe pile, single, double, and triple helices) embedded within partially saturation soil of different matric suction of (6.5, 7.3 and 9.6 kPa) respectively. The figures show that the bearing capacity of helical pile models increases with increasing number of helices for all soil conditions but within different increment ratios for each case.

**Figure 15.** Load settlement behavior for helical pile models embedded within fully saturation soil.

**Figure 16.** Load settlement behavior for helical pile models embedded within dry soil.

**Figure 17.** Load settlement behavior for helical pile models embedded within partially saturation soil of 6.5kPa matric suction.

**Figure 18.** Load settlement behavior for helical pile models embedded within partially saturation soil of 7.3kPa matric suction.
Table 5 shows the increment ratio of the bearing capacity. This increment due to increase number of helices (single, double and triple helices) times than the bearing capacity of pipe pile model (shaft only) for different saturation conditions.

Table 5 shows the bearing capacity of the embedded helical piles in dry, fully saturation and partially saturation soil was increased with addition of helices. The percentages of the increment were different for the helices, double helices. They showed that lower increments than that single and triple helices. For embedded helical piles in fully saturation soil the percentage of increases in bearing capacity for the additional helices single double and triple. They were approximately 33.3%, 45.0% and 108.3% respectively, than shaft pile only. The increment percentage shows that as the number of helices caused an increase in their percentage at different rates. For embedded helical piles in dry soil the percentage of increases in bearing capacity for additional helices single double and triple at approximately about 34.4%, 67.7% and 88.1% respectively, than shaft pile. The increment percentages also increase as the number of helices increase but at different rates. For helical piles embedded within partially saturation soils which was divided into three different saturation conditions of 6.5, 7.3 and 9.6kPa matrix suction, the percent of increases in bearing capacity for additional helices single, double and triple approximately about 34.3%, 56.7% and 116.4% respectively for matrix suction of 6.5kPa, and 59.7%, 80.5% and 112.2% for matrix suction of 7.3kPa, and 32.3%, 58.8% and 125% for matrix suction of 9.6kPa than shaft pile only. The results show that the best increments percent at matrix suction of 7.3kPa. The reasons for increasing bearing capacitances with increase number helices by providing more bearing surface area and more compact soil sections. The use additional helices give high capacity in compression according to Lutenegger [1]. The increased load capacity can be attributed to the increased condensation of sand during the installation of the helices as the volume of soil displacement increases. Figure 21 shows the behavior of increment ratio in bearing capacities with increasing number of helices in various soil conditions.
Figure 19. Load settlement behavior for helical pile models embedded within partially saturation soil of 9.6kPa matric suction.

Figure 20. The increment ratio in bearing capacity due to increase number of helices than that of pipe pile only.

4. Conclusions

The main conclusions drawn using helical pile model subjected to compression load as follows:

1- The ultimate bearing capacities of helical pile models and pipe pile under compression in fully saturation conditions are less than others which were handled with saturation soil conditions.

2- The ultimate bearing capacities of embedded helical piles in partially saturated soils are shows greater values than those embedded in fully saturation soils and even from dry soil of high matric suction.

3- The increment values of ultimate bearing capacity for embedded pipe pile in a dry and partially saturation soil of matric suction 6.5, 7.3 and 9.6kPa times than that embedded within fully saturation soil are 1.55, 1.11, 1.20 and 1.70 respectively.

4- It is concluded that helical pile of double helices embedded within dry and partially saturation soil have high increment values than the other helical pile models embedded within fully saturation soil.

5- It is concluded that the ultimate bearing capacity of helical pile models increase as number of helices increases. The per cent of increments in ultimate bearing capacity for additional helices single double and triple, embedded within fully saturation soil than shaft pile only are 33.3%, 45.0% and 108.3% respectively, and within dry soil 34.4%, 67.7% and 88.1% respectively and within partially saturation soil at matric suction of 6.5kPa are 34.3%, 56.7% and 116.4% , and at matric suction of 7.3 kPa are 59.7%, 80.5% and 112.2%, and at matric suction 9.6kPa matric suction 32.3%, 58.8% and 125% respectively.

6- Helical piles embedded within partially saturation soil of matric suction 7.3kPa have high increment values more than the other helical pile models embedded within fully saturation soil.

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