The Performance of Taper Helical Pile Embedded in Loose Sand Under Uplift Static and Cyclic Load Using 3D-Finite Element Analysis

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Abstract. Piles with helices are a kind of foundation that is capable of withstanding compression, tension, and lateral loads. However, for almost 25 years, this kind of Pile was widely used across the world. Its behaviour is unpredictable and terrifying, especially in Iraq. The present study analysed this kind of Pile using the finite element method. It was recommended that the helical pile geometry be modeled by numerical model technique and the computer program Plaxis 3D. The plaxis 3D software is a well-known geotechnical engineering tool that numerically analyses soil and simulates experimental work in terms of curve matching and outcomes. Furthermore, an analysis of variables was conducted. The primary variable research investigates the influence of the number of helices and the tapered helix distance under static and cyclic load. The final finding is that the more helices in a pile, the smaller the displacement (or amplitude) in comparison to one helix under the effect of uplift static and cyclic load. As a result that the effect of helix number on soil behaviour is more than the effect of changing the distances between helix.

Keywords: Helical pile, Numerical model, Uplift static, load Uplift cyclic load, helix of diameter, Effect placement of a helix

1. Introduction

Over the past two decades, helical piles have gained appeal as a deep foundation alternative for onshore and offshore structures [1]. Helical piles are a one-of-a-kind method for enlarging existing foundation systems [2]. They were developed in 1836 by Alexander Mitchell, an Irish civil engineer, to strengthen the foundations of buildings. They have been utilized in the United Kingdom since 1853 and were widely employed in the United States between 1850 and 1890 as a foundation for light structures. Following this, until 1985, helical piles were similarly employed as anchoring [3]. It was meant to include helix plates with a diameter larger than the diameter of the hollow shaft, as well as comparable helix plates with end bearing capacity in addition to the shaft's skin friction capacity [3]. The Bearing Capacity of Hexagonal Joint Helical Piles was studied by Kim et al. [3]. They discovered that the cylindrical or individual mode of failure is utilized to determine a helical pile's bearing capacity. As is
the case with cylindrical structures, the bearing capacity of all helices is calculated simultaneously. Individual mode enables each helix to function independently, whereas end bearing is equal to the total of the end bearings of each helix. Sharma and Guner [4] studied a system-level modelling technique for simulating the interaction of the cup of the pile, pile with helices group, and soil under uplift stresses. They introduced that Due to their high tensile capabilities, minimal impact on the surrounding environment, and appropriateness for building sites with restricted access or space, helical piles are becoming more often utilized in practice to withstand the uplift influences of inclined loads [4]. [4] Found that the simulations are carried out under three different embedment depth settings inside the concrete pile cap, as shown in figure 1a. The resulting system-level uplift capabilities are shown in the figure. 1b. The increase in embedded depth from the bottom to the centre of the pile cap improves the uplift capacity by 25% [4]. Rawat and Kumar [5] studied Numerical modelling of the pullout of the helical soil nail. They illustrated that the increase in the pullout of helical soil nails associated with nail head movement may be due to helical plates increase bearing capacity as a result of the increased overburden on helical plates. Chiavon et al. [6] studied physical modelling of cyclic loading on a one-helix anchor in sand soil. They introduced that The result showed that to impose a pre-tensile load after the installation is completed, The vertical displacements of the anchor model head at model scale were 5.4 mm in Test 1, 5.0 mm in Test 2, and 4.8 mm in Test 3. Each test was subjected to cyclic stress following anchor placement. The model anchor was not loaded before the cycle test (except the pre-tensile load). Three distinct cyclic loading amplitudes were examined, with that same value for pre-load (Qpre). As a result of a setup error in the programming of the servo-controlling system, the cyclic loading began earlier than intended, resulting in a slope of the applied load for the first twelve cycles of Test 2 and fifty cycles of Test 3. Fig. 2. illustrates that the anchor's three distinct load-displacement responses under cyclic loading. The displacements recorded in the first cycle are greater and considerably different from those observed in subsequent cycles. The initial cycle is different because it corresponds to the very first loading of disturbed sand above the helix. This finding demonstrates that the initial stiffness of the anchor is lowered as a result of the sand disturbance induced by the anchor placement [6]. G. Spagnoli and C. de Hollanda Cavalcanti Tsuha[7] studied the influence of piles with helices as an alternative to conventional offshore foundations. They found that in comparison to compressive capacity, tension capacity is highly variable and harder to estimate since the soil that helps tension loads is the soil that is located above the helices, which was deformed during pile installation. The shaft resists contribution to the axial capacity of piles with helices increases as the diameter of the helix decreases, ultimately approaching that of ordinary straight-shaft piles (Kwon et al. 2019)[7]. Trofimenkov and Maruipolshii (1965)[7] presented the primary eq.(1) for calculating the ultimate upward pressure associated with the helix of a one helix pile as a function of without dimension factors affecting load, comparable to the Terzaghi load capacity eq. According to these authors, the uplift capacity of a one helix pile is described as the summation of the ultimate upward pressure associated with the soil located above the helix and the resistance of the shaft [7]:

\[
Qu, \text{ tens} = Ru, \text{ tens.AH} + f.U.Lp
\]

(1)

Where Ru, tens is the ultimate upward pressure associated with the helix, AH is the helix's working conditions, f is the soil's average specific pressure on the side surface, The pile shaft's perimeter is denoted by the letter U, and Lp is the pile shaft's design length, which is L D. (where L is the length of the pile embedded and D is the diameter of the helix) as a result of the disturbed zone above the helix being compacted [7].

This research aims to study the influence of pile with helices via the use of 3D plaxis program (2020 ), The effect of a number of helices, and the influence of the spacing of helix under static & cyclic load and comparison of results.
2. Program Verification

The experimental work was compared to the numerical model by simulation of two helices embedded in medium sand under uplift load at saturation conditions. The displacement that results from the load (Uz) for two of these studies is shown in Fig. 3. According to this figure, there is an excellent agreement between these studies in terms of the shape and results of values. It was discovered that the displacement values were extremely comparable, indicating that the software produces excellent results that are accurately similar to the experimental work. (the experimental work based on) Khidear, 2020) [8, 10]
Figure 3: Simulation of experimental work with numerical model

3. Methodology and Model of Preparation

The study makes use of three-dimensional finite element software (PLAXIS). The following components comprise the model’s structural characteristics for this parametric study:

- A cup of the helical pile has a diameter of 0.325 m
- A helical pile of ten meters in length
- The shaft has a diameter of 0.325 meters and a thickness of 9.5 mm.
- Helix diameter: 0.762 m, thickness: 25 mm
- Loose sand of soil with dimensions 20*20 m², 35 m depth.
- A static load of 115 kN is applied in the case of the number of helix and 120 kN in the case of changing the distances between the helices.
- The cyclic load applied on the pile with helices as shown in Fig. (4) and according to (Yasser Abdelghany and M. Hesham El Naggar) [9].

Figure 4: The pile with helices is subjected to a cyclic load according to (Yasser Abdelghany and M. Hesham El Naggar) [9].

This program is a specialist 3D finite element analysis for studying displacement, rigidity and movement in a wide range of solutions in geotechnical engineering. The software has an intuitive geometric
experiment interface that enables users to produce a three-dimensional geometric model and finite element mesh quickly.

The following Table 1 summarizes the soil characteristics. Helices and round shafts are shown similarly to materials for plates. To represent the materials, two parametric models were employed. "Elasticity" assumption was applied for the piles and helices described in Fig. (5). A mohr-coulomb soil model was used to simulate the sand. Laboratory findings were used to calibrate the numerical model's parameters. According to (Yasser Abdelghany and M. Hesham El Naggar), a perpendicular cyclic force is given to the pile with helices as dynamic surface forces [9].

Fig. illustrates the finite element model (5). It provides the numerical model’s mesh, the soil's dimension, and the helical pile. Figure (6) depicts a helical pile in several configurations, including one without a helix, one with 1 helix, 2 helices, and 3 helices, all with varying distances between the helices. The distances of the three helices are based on the distance (D), which represents the diameter of one hex

![Figure 5: Model soil mesh generated numerically using dimension soil and pile with helices](image)

| Properties                      | Medium Sand          |
|---------------------------------|----------------------|
| Model                           | Mohr-Coulomb         |
| Unit Weight 𝑦(𝐾𝑁/𝐌³)           | 18.5                 |
| 𝐸(𝐾𝑁/𝐌³)                       | 16760                |
| 𝑣                               | 0.3                  |
| 𝐸𝑜𝑒𝑑_ref(𝐾𝑁/𝐌²)                | 22560                |
| Frictional Angle 𝛾               | 28                   |
| Angle of Dilatancy Ψ             | 0                    |
| Rinter                           | 0.7                  |
Three different diameters of helix were used in this study, where as the depth of the Pile increases, the diameter of the helix reduces, as shown in Figure 7. The different diameters that were used are 0.762m, 0.712m, and finally, 0.662m.

Figure 6: a (no helix)  Figure 6: b (1 helix)  Figure 6: c (2 helices s=3.5d)

Figure 6: d (3 helices s=0.5D)  Figure 6: e (3 helices S=3.5D)  Figure 6: f (3 helices with varying diameter helix)

Figure 7: Tapered helices
4. Result and Discussion

4.1. Effect of Number of Helices under Static and Cyclic Loading

Figure (8) illustrates the uplift static load-displacement relationship (in the z-direction) for several conditions (one helix, two helices, three-helices and four-helices). According to figure (8), displacement decreases by 96 % and decreases by 94 % when three helices with \( s=2D \). Finally, displacement decreased by 91.65 % when four helices were used. All of the above-mentioned instances were compared to the condition of one helix.

![Uplift static load-displacement relationship](image)

**Figure**: 8 load-displacement relationship under uplift static load in one helix, two helices, three helices and with four helices

Table 2. Shows the value of displacement in each case as shown in figure (8)

| Type of Helix       | Displacement(z)(mm) |
|--------------------|---------------------|
| One helix          | 7.163               |
| Two helices        | 6.879               |
| Three helices      | 6.751               |
| Four helices       | 6.565               |

The cyclic load has an effect on the soil’s behaviour. As shown in Fig. (9), increasing the number of helices in a pile substantially decreased the danger of cyclic loading. This figure depicts the dynamic time-displacement (with z-direction) for several conditions (1 helix, 2 helices, 3 helices and 4 helices). According to Fig. (9), the displacement amplitude is reduced by 94.85 % in the case of a two-helix. The displacement amplitude reduced by 92.7 % in the case of three helices and by 89.94 % in the case of
four helices. All these mentioned cases were compared to the condition of one helix. The explanation for this is that the more helices in the soil, the higher its bearing capacity for the stresses applied, and this resistance reduced the impact of cyclic loading by reducing the amplitude of soil displacement. This finding explains why an increase in the number of helices results in a reduction in the amplitude of the cyclic loading.

![Dynamic time-displacement under cyclic uplift load with one helix, two helices, three helices, and four helices](image)

**Figure 9:** Dynamic time-displacement under cyclic uplift load with one helix, two helices, three helices, and four helices

4.2. The Effect of Helical Spacing under Static and Cyclic Loading

Figure (10) illustrates a comparison of various spacing between tapered helices using three tapered helices with spacing of 0.5 D, 1D, 1.5D, 2D, 2.5 D, 3D and 3.5 D under uplift static load. According to this Fig., the value of displacement (in the direction of z) with spacing 1D decreases by 97.9% when compared to the value of displacement (in the direction of z) with spacing 0.5 D, while the percentage return 100% with spacing 1.5 D, and then decreased by 97.8% with spacing 2 D. The values continue to decrease by a very small percentage until it reaches 96.63% with spacing 3.5 D. All these mentioned cases were compared to the condition of distancing 0.5 D. The reason for returning the space ratio of 1.5D to 100% is as a result of this distance not having an effect on reducing the displacement. In comparative Figures (8) and (10), it was discovered that altering the number of helices had a greater impact than altering the space between helices. In figure (8), the change in displacement amplitude is obvious, while the difference in displacement amplitude in figure (10) is small as compared to figure (8). The reason for this is because the presence of helix in a pile has a significant effect on the behaviour of the soil as shown by the findings.
Table 3. The value of displacement in each case, as shown in figure (10)

| Spacing | Displacement(z)(mm) |
|---------|---------------------|
| 0.5 D   | 7.228               |
| 1 D     | 7.079               |
| 1.5 D   | 7.228               |
| 2 D     | 7.069               |
| 2.5 D   | 7.049               |
| 3 D     | 7.026               |
| 3.5 D   | 6.985               |

Figure (11) compares three tapered helices with a spacing of 0.5 D, 1D, 1.5D, 2D, 2.5D, 3D, and 3.5D under uplift cyclic load. According to this figure, the displacement amplitude was reduced by 97.73 percent at a spacing of 1 D. With a distance of 2 D, the displacement amplitude was reduced by 97.56 percent. With a spacing of 3 D, the displacement amplitude dropped by 96.83 percent, while the ratio decreased by 96.25 percent with a spacing of 3.5D. All of the above-mentioned cases were compared to the Pile with a spacing of 0.5 D. This is because the greater the spacing between helices, the greater the bearing capacity of the soil for the applied stresses, and this resistance mitigated the effect of cyclic loading by decreasing the amplitude of soil displacement. Comparing Figures (9) and (11), it was discovered that altering the number of helixes had a greater impact than altering the space between helices. In figure (9), the change in displacement amplitude is obvious, while the difference in displacement amplitude in figure (11) is small as compared to figure (9). The reason for this is because the presence of helix in a pile has a significant effect on the behaviour of the soil, as shown by the findings.

Fig.10: load-displacement using static load with 3 tapered helices for varying spacing.
Figure 11: Dynamic time - displacement under uplift cyclic load with three tapered helices for different spacing.

5. Conclusions

The following conclusions can be made as a result of this research: Under the influence of uplift static load, the greater the number of helices, the smaller the displacement in the soil as a result of the increase in the uplift helical pile capacity with the increase in the number of helices. Under the influence of cyclic uplift load, the more helices in a pile, the lower the amplitude of displacement (in the direction of z) in comparison to one helix. Under the influence of uplift static load, in the instance of three tapered helices, the higher the spacing between the helices gives a few percentages, and therefore its effect is not clear in reducing the displacement value compared to the number of helices. Under the influence of cyclic uplift load in the instance of three helices, the higher the spacing between them, the smaller the displacement amplitude (in the direction of z) with a few percentages. As a final result, increasing the number of helices in a pile has a greater effect in reducing the amplitude of displacement more than increasing the distances between the helices under the effect of uplift static and cyclic load.

6. References

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