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The Performance of Helical Pile under Cyclic Load Using 3D-Finite Element Analysis

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HIGHLIGHTS

- As a final result, increasing the number of helices in a pile has a greater effect on reducing displacement amplitude than increasing the distances between the helixes.

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ABSTRACT

Helical piles are a kind of foundation that can withstand compression, tension, and lateral stresses. However, this kind of pile was utilized extensively globally for almost 25 years. Its behavior, particularly in Iraq, is uncertain and frightening. The current research used the finite element technique to analyze this kind of pile. The helical pile geometry was suggested to be modeled using the finite element method using the computer software Plaxis 3D The soil used is medium sandy soil. Additionally, parametric analyses were conducted. The primary parametric research examines the impact of helix number, helix spacing, helix diameter, and helix configuration under cyclic load. The main results are more helices in a pile, the lower the amplitude of settlement (in the direction of z) compared to a pile without helices. As a result, the amplitude of settlement in the case of two helices decreased by 81.6 %, while the amplitude of settlement in the case of three-helix decreased by 77.74 %. In the case of three helices, the higher spacing between the helices, the lower the value of the amplitude of settlement (in the direction of z). The effect of the number of helices in the hardening soil model is more than the effect of the number of helices in the Mohr-Coulomb. As a final result, increasing the number of helices in a pile has a more significant effect in reducing the amplitude of settlement than increasing the between the helices.

1. Introduction

Helical piles have risen in popularity as a deep foundation option for onshore and offshore buildings over the last two decades [1]. Helical piles are a unique technique for increasing the size of existing

foundation systems [2]. To accomplish the bearing capacity, it was intended to contain helix plates with a diameter more significant than the diameter of the hollow shaft and equivalent helix plates with end bearing capacity in addition to the shaft's skin friction capacity [3]. Kim et al. [3] investigated the bearing capacity of hexagonal joint helical piles. He found that the cylindrical or individual failure mode is used to assess the bearing capacity of a helical pile. As with a cylindrical structure, the bearing capacity of all helices is determined in unison. Individual mode allows each helix to operate independently, and end bearing equals the sum of each helix's end bearings. Alexander Mitchell, an Irish civil engineer, invented helical piles in 1836 to reinforce the foundations of structures. Helical piles have been used in the United Kingdom since 1853 and were commonly used as a foundation for pastel buildings in the United States between 1850 and 1890. Following this, helical piles were similarly used as anchors until 1985 [3]. Basack and Nibalkar[4] investigated the Numerical Solution of a Single Pile Under Cyclic Torsion. They discovered that pilings are frequently employed to support large structures such as offshore platforms, wind turbine foundations, broad buildings, bridges, and granular railway embankments. These structures are commonly subjected to significant cyclic stresses (axial, lateral, and torsional) due to wave action, collisions with ships, or moving trains [4]. Hailmarian and Wuttke[5] investigated the cyclic mechanical behavior of two sandy soils used for heat storage. As a result, it was concluded that their mechanical stability, both static and cyclic mechanical loading, is caused by artificial structures and natural hazards such as earthquakes. They should be carefully evaluated at elevated temperatures before their design and operation using appropriate mechanical tests [5]. Jahed et al. [6] reported an experimental evaluation of helical piles' dynamic response in dry sand using 1g shaking Table tests. In addition, it was also concluded that previous research on the dynamic behavior of helix

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piers examined the post-cyclic or post-dynamic axial capacity of helix piers while accounting for a variety of parameters such as helix number, helix size, shaft diameter, and helical pile type. The helical pile types included reinforced and unreinforced grouted pulldown micro-piles (El Naggar and Abdelghany 2007a, b, Abdelghany 2008, Cerato and Victor 2008, 2009). Schiavon et al. [7] investigated the centrifuge modeling behavior of a single-helix anchor in sand subjected to cyclic loading. They determined that two anchor models (one instrumented) were embedded at a 7.4D helix embedment depth and loaded 3000 cycles for cyclic testing. It was demonstrated that the pre-stressing load (minimum cyclic load) had some effect on the accumulation of cyclic displacements. There was no evidence of stability in the following cycles, regardless of the load amplitude [7]. The cyclic loading was determined using the mean cycle load (Q_{mean}) and the cyclic load amplitude (Q_{cyclic}), as given in Eqs. 1 and 2 [7].

$$\text{Qmean} = \frac{(\text{Qmax} + \text{Qmin})}{2} \quad (1)$$

$$\text{Qcyclic} = \frac{(\text{Qmax} + \text{Qmin})}{2} \quad (2)$$

Q_{max} is the maximum cyclic load; Q_{min} is the minimum cyclic load.[7]

Abdelghany and El Naggar [8] investigated and numerically analyzed various innovative instrumented composite helical screw piles under axial and lateral monotonic and cyclic loadings. After compressing each instrumented pile, they used a minimum of fifteen cycles of axial stress. Following the completion of the cyclic loading, a final compression test was conducted to verify the pile's capacity and performance characteristics during and after cyclic loading [8]. As a result, the axial pile load tests were conducted using the ASTM D-1143 standard test technique for piles under static axial compression stress and axial cyclic load. Rapid testing has gained wide acceptance in the geotechnical community and has been successfully applied to the evaluation of helical piles (Livneh 2006). As specified in ASTM D 1143, test loads should be applied in increments of 10% to 15% of the intended design load during a two-and-a-half-minute time. Smaller increments, longer time intervals, or a combination of the two are feasible. Loads were applied in 10-percent increments for 2.5 minutes [8]. They used grouted reinforced helical screw piles (RG-HSPs).

Chiavon et al. [9] studied cyclic loading on a single-helix anchor in the sand: a physical model. They introduced that two cyclic axial loading processes may affect the behavior of helical anchors: a) the cyclic deterioration of shaft friction and plate bearing resistance; and b) the buildup of permanent displacement as the number of load cycles increases. Furthermore, they reported in the prototype scale that the maximum downward force imparted to the model anchor head during installation ranged between 63 and 70 kN (in compression).

Based on what was mentioned above from the previous studies, they did not focus on the effect of the number of helices and the change of spacing between helices on the behavior of the helical pile embedded in medium soil under the influence of cyclic load. Therefore, the current study aims to study these effects.

This paper aims to study the performance of helical piles under cycle load using 3D plaxis software (plaxis 2020). Some parameters are selected for investigation in this study, including the amplitude of displacement in the direction of z with and without a helix, the impact of the spacing between helices, the distance between helices, and the configuration of the helices.

2. Program Verification (Plaxis 3d 2020)

The accuracy of the model predictions is verified by comparing the numerical and experimental results. A comparison was conducted between practical work [10] and numerical model simulations. In the experimental work, the fully saturated state was chosen. The experimental work was carried out on a steel helical pile of 600 mm in length embedded in cohesionless soil to a depth of 400 mm, helix diameter D_h 50 mm, and dry sand with 50% relative density. The load-settlement (Uz) for the numerical model and experimental work is shown in Figure (1). According to this Figure, there is a convergence between the numerical model and experimental work regarding the form and results of values. The maximum settlement (Uz) and total load in the numerical model are -8 mm and 0.61 kN, respectively. In comparison, the maximum settlement (Uz) and maximum load in the experimental work are -8 mm and 0.72 kN, respectively. By comparing the results, it was discovered that the settlement values are very comparable, indicating that the software produces outstanding results that accurately simulate the experimental work.

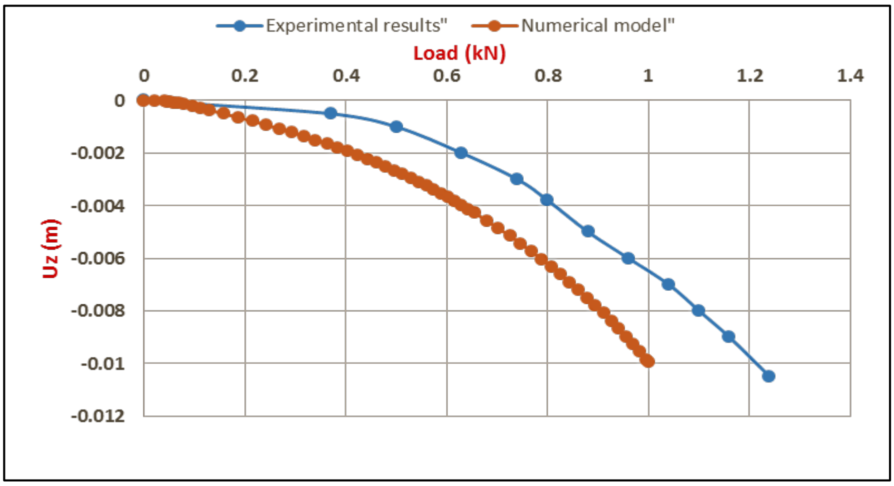


Figure 1: Load-Settlement (Uz) of the helical pile embedded in medium sand soil under compression static load according to hardening soil model for numerical model and experimental work

3. Numerical Modeling

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 m and a thickness of 9.5 mm.
- Helix diameter: 0.762 m, thickness: 25 mm
- Medium sand of soil with dimensions 20×20 m^2, 35 m depth, and R.D = 50%
- The cyclic load applied on the helical pile is according to (Abdelghany and El Naggar) [8].

Plaxis 3D is a specialized three-dimensional finite element software used to study the deformation, stability, and flow in various geotechnical applications. The software has a user-friendly graphical user interface that allows users to quickly create a geometry model and finite element mesh.

Table 1 contains a list of soil properties. Shafts and helices are represented in the same way as plate materials are. To illustrate the materials, two constitutive models were utilized. The "elastic" assumption was used. The sand was modeled using a hardening soil model. Laboratory results were utilized to establish the parameters for the numerical model. A vertical cyclic load is applied to the helical pile as a dynamic surface load, according to (Abdelghany and El Naggar) [8]. After that, the same soil was used, but using the Mohr-Coulomb model, with the use of Young's Modulus (E) 30290 kN/m^2, oedometer loading stiffness (E_{oed}) 4780kN/m^2, and Poisson's ratio (v) 0.3 .The numerical model is shown in Figure (2). It contains the numerical model mesh, the soil dimension, and the helical pile. Figure 3 illustrates the helical pile with different configurations, including pile without a helix, pile with 1 helix, 2 helices, and 3 helices.

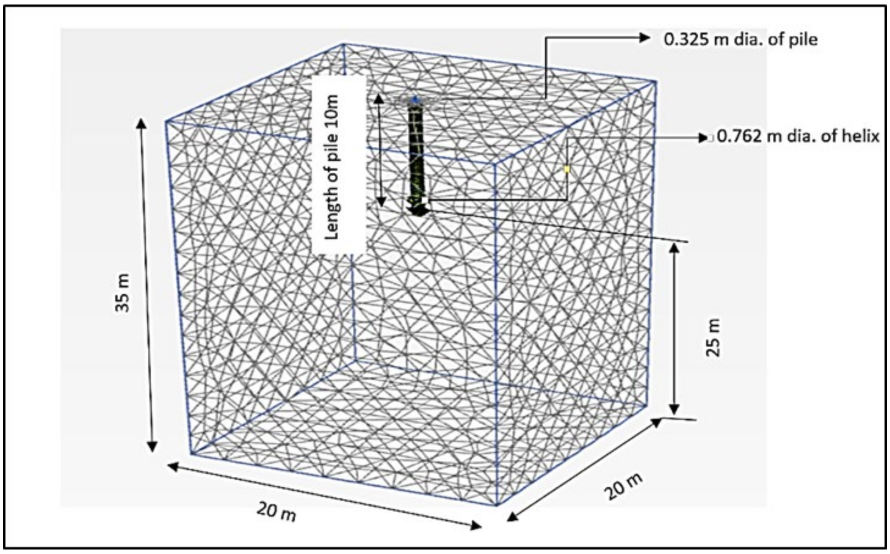
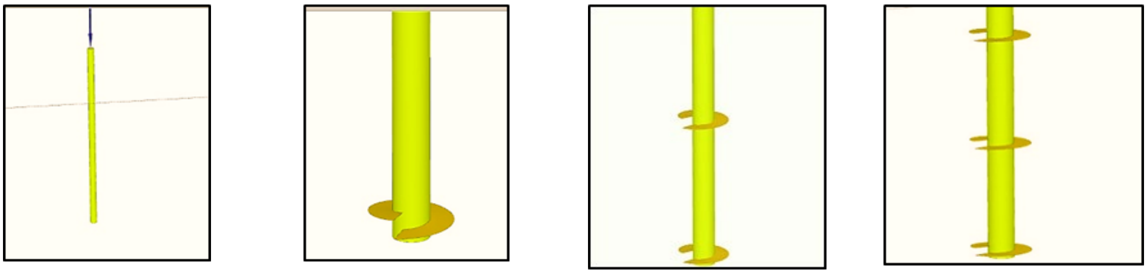


Figure 2: Numerical model soil mesh with dimension soil and helical pile

Table 1: Soil parameters

Properties	Medium sand
Model	Hardening soil
Unit weight $\gamma(\frac{kn}{m^3})$	19.77
$E50^{ref.}$	12120
$Eoed^{ref.}$	21340
$Eur^{ref.}$	36350
The angle of friction ϕ	30
Dilatancy angle ψ	0
R_{inter}	0.7



(a) (b) (c) (e)

Figure 3: Helical pile models in different configurations((a): without helix, (b) :1 helix, (c) :2 helices S=3.5D_h, (d) :3 helices S=3.5 D_h

4. Results and Discussion

4.1 Effect of Number of Helices Using Hardening Soil Model

Figure 4 shows the dynamic time- displacement (with z-direction) for different cases (without helix, 1 helix, 2 helices, and 3 helices). According to Figure (4), the amplitude of displacement in the case of 1 helix decreased by 86.6 %. The settlement amplitude in the case of 2 helices decreased by 81.6 %, while the amplitude of settlement in the case of 3 helices decreased by 77.74 %. All these mentioned cases were compared to the case of the pile without helix. The reason for this is that the higher the number of helices, the higher the bearing capacity of the soil. This resistance caused a decrease in the effect of the cyclic loading through the reduction of the amplitude of cyclic loading. Thus, the values of settlement in the soil decrease. The same reason was previously mentioned in the case of the hardening soil model.

El Sharnouby and El Naggar [11] discovered that early in the loading process, one helix and two helix piles behaved almost identically (i.e., one helix provided almost all of the resistance). But, at higher loading levels, the two-helix pile responded stiffer, indicating that at relatively low load levels, one helix was almost solely resisting the applied load and that at higher loads, the load resistance share was re-distributed.

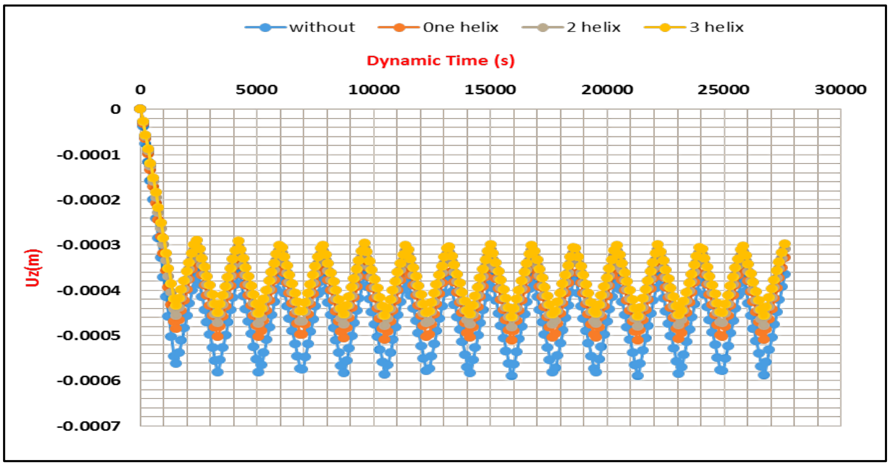


Figure 4: Dynamic Time -Settlement of helical pile embedded in medium sand under cyclic load according to the hardening soil model with 1 helix, 2 helices, and 3 helices

4.2 Effect of a Number of Helices Using Mohr-Coulomb

Figure 5 shows the dynamic time- settlement (with z-direction) for many conditions (without helix, 1 helix, 2 helices, and 3 helices) under cyclic load. According to Figure (5), the percentage of the amplitude of settlement in the case of 1 helix decreased by 92.7 %. The percentage of the amplitude of settlement in the case of 2 helices decreased by 91.9 %, while in the case of 3, helices reached 90.4 %. All of the preceding cases were compared to the case of the without helix. The explanation is that the higher the number of helices, the higher the soil's bearing capacity. This resistance reduced the cyclic loading's effect by reducing the amplitude of cyclic loading. Thus, the values of settlement in the soil decrease.

El Sharnouby and El Naggar [11] demonstrated that multi-helix lead sections are preferable instead of single-helix lead sections for cyclic loading applications.

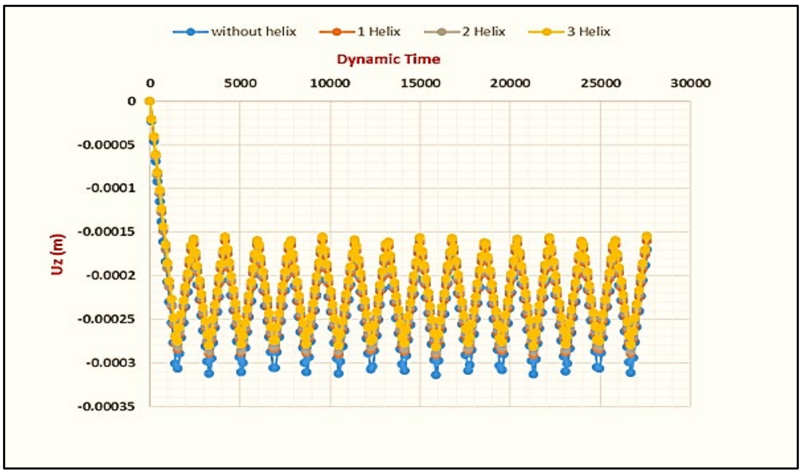


Figure 5: Dynamic Time -Settlement of helical pile embedded in medium sand soil under cyclic load according to the Mohr-Coulomb soil model with 1 helix, 2 helices, and 3 helices

4.3 Effect of Helical Spacing Using Hardening Soil Model

Figure 6 illustrates a comparison of helix spacing using three helices with a spacing of 0.5 D_h, 1D_h, 1.5D_h, 2D_h, 2.5D_h, 3D_h, and 3.5D_h. According to this Figure, the amplitude of settlement with a spacing of 1 D_h decreased by 98 %. The amplitude of settlement with a spacing of 1.5 D_h decreased by 97 %. The amplitude of settlement with a spacing of 2 D_h keeps reducing by 96.8 %, while the ratio returns with a spacing of 3.5 D_h by 97 %. All these mentioned cases were compared to the case of the pile with a spacing of 0.5 D_h. The reason behind this is that the more significant the spacing between the helices, the higher the bearing capacity of the soil. This resistance reduced the impact of cyclic loading by reducing the amplitude of settlement of soil but with less effect than the case of several helices. Alwalan and Naggar [12] reported that the spacing ratio does not influence an HSDT (High Strain Dynamic Test) in a statistically meaningful manner**.**

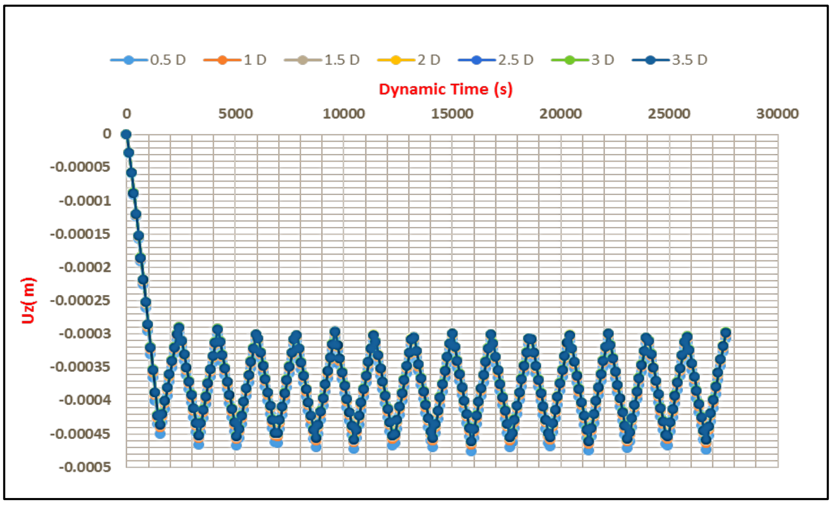


Figure 6: Dynamic Time – Settlement of helical pile embedded in medium sand soil under cyclic load according to the hardening soil model with 3 helices for different spacing between helices

4.4 Effect of Helical Spacing Using Mohr-Coulomb Model

Figure 7 illustrates a comparison of helix spacings under cyclic loading for three helices with spacings of 0.5 D_h, 1D_h, 1.5D_h, 2D_h, 2.5D_h, 3D_h, and 3.5D_h. According to this Figure, the percentage of the amplitude of settlement with a 1 D_h spacing is 100%. With a spacing of 2 D_h, the percentage of the amplitude of settlement reduces by 98.8 %, while it reaches 99 % with a spacing of 3.5 D_h. All of the cases mentioned above were compared to the pile with a spacing of 0.5 D_h. According to the data, different spacing between the helices has little influence on the helical pile's behavior, in contrast to the effect of several helices. As a result, the influence of the number of helices is more than the effect of the spacing between the helices in helical piles embedded in medium sandy soil.

Kim et al. [3] presented that the end bearing capacity is governed by helix spacing and is computed using the individual bearing technique and cylindrical shear method. The piles illustrate the bearing performance of the individual bearing technique when the helix spacing is at least 2.0–3.0D_h of the helix plate diameter D_h. However, where they illustrate the bearing performance of the cylindrical shear technique when they are at most 2.0–3.0D_h of the helix plate diameter D_h.

According to Plaxis 3D- Material Models [13], if stress points meet the Mohr-Coulomb failure criteria when subjected to dynamic or cyclic loading, the Mohr-Coulomb model may create plastic strains, resulting in damping in dynamic calculations. The stress cycles inside the Mohr-Coulomb failure contour, however, will only create elastic strains with no (hysteretic) damping, accumulation of strains, pore pressure, or liquefaction. Therefore, rayleigh damping may be defined to simulate the soil's damping properties under cyclic loads.

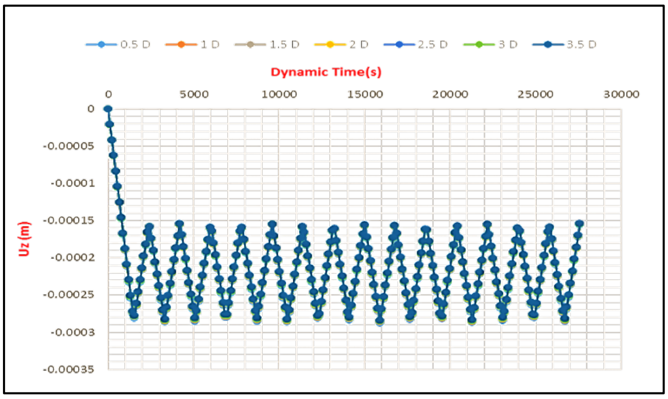


Figure 7: Dynamic Time - Settlement of helical pile embedded in medium sand soil under cyclic load according to the Mohr-Coulomb soil model with 3 helices for different spacing between helices

Figure 8 illustrates the geometry of settlement deformation in the z-direction of the helical pile (3 helices at spacing 3.5D_h) embedded in medium sand soil and subjected to cyclic load. According to this figure, the shape of the deformation is concentrated around the helical pile, particularly around the helices, because the helices and shaft pile cause minor deformation in the soil in contact with them when subjected to cyclic load, and this deformation does not result in soil failure.

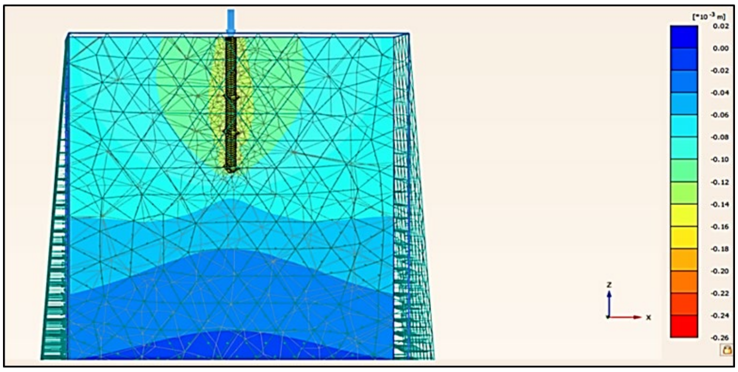


Figure 8: The geometry of settlement deformation in the z-direction of the helical pile embedded in a medium sand under cyclic load soil according to the Mohr-Coulomb soil model with 3 helices for spacing between helices 3.5D_h

5. Conclusions

As a result of this research, the following conclusions can be drawn:

1) The more helices in a pile, the lower the displacement amplitude (in the direction of z) compared to a pile without helices, according to the hardening soil model. As a result, the amplitude of settlement in the case of 2 helices decreased by 81.6 %, while the amplitude of settlement in the case of 3 helices decreased by 77.74 %. According to the Mohr-Coulomb sol model, the more helices in a pile, the lower the amplitude of settlement (in the direction of z) compared

to a pile without helices. As a result, the displacement amplitude in the case of 2 helices decreased by 91.9 %, while the amplitude of settlement in the case of 3 helices decreased by 90.4 %.

2) In the case of 3 helices, according to the hardening soil model, the higher spacing between the helices, the lower value of the displacement amplitude (in the direction of z). As a result, the amplitude of settlement with a spacing of 1 D_h decreased by 98 %. The amplitude of settlement with a spacing of 1.5 D_h decreased by 97 %. The amplitude of settlement with a spacing of 2 D keeps reducing by 96.8 %. In the case of 3 helices, according to the Mohr-Coulomb soil model, the higher spacing between the helices, the lower value of the amplitude of settlement (in the direction of z). As a result, the amplitude of settlement with a spacing of 2 D_h decreased by 98.8 %.
3) The effect of the number of helices in the hardening soil model is more than that of the number of helices in the Mohr-Coulomb.
4) As a final result, increasing the number of helices in a pile has a more significant effect in reducing the amplitude of settlement than increasing the spacing between the helices.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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