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Evaluation of the behavior of screw pile groups in clay soils under compressive and uplift forces

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Abstract. Screw piles, which is one of the ground improvement methods, are finding more place in practice day by day. For this reason, there is a need for studies to investigate the behavior of screw piles under compressive and uplift loads. In this context, the behavior of screw piles with different number of helixes in groups was investigated with different number of screws and group patterns. To evaluate behavior of screw piles, settlement ratios, group efficiency and helix number efficiency values were calculated by using finite element method. Based on an experimental study from the literature, modelling was performed on PLAXIS 3D, which works with the finite element method, and the results were matched. As a result of this study, it was observed that increasing the number of helixes increased the bearing capacity under both compressive and uplift forces. In addition, it was determined that group efficacy values changed in different patterns and different number of pile groups. Optimum screw pile type for group patterns also differs for different load conditions. The modelling results were visualized and were found to match with the failure surfaces reported in the literature. It was suggested that optimum helix number and group pattern for screw pile applications can be achieved with evaluating settlement and efficiency values together.

Keywords: compressive forces; finite element method; ground improvement; screw piles; uplift forces

1. Introduction

Investigation of soil parameters is of vital importance for new buildings construction or building reinforcement. It has been observed that soil-structure interactions do not show the desired performance in constructions where adequate research is not carried out or the correct soil parameters are not obtained. In addition, when necessary, precautions are not taken in weak soils under dynamic loads, loss of life and property are observed. To solve these problems, soil improvement methods are used worldwide, and the solutions offered by these methods are becoming more diversified day by day (Qian *et al.* 2017, Lu *et al.* 2023, Dong and Zheng 2015, Demir and Sarici 2017, Sarici and Ozcan 2024a). Screw piles are also an increasingly widespread soil improvement solution today (Kim *et al.* 2023). Screw piles were first used by a lighthouse worker in 1863. Although it lost its potential for use in the early times due to the technological developments of the period, it was brought back to the agenda and started to be used again with the discovery of hydraulic torque applications (Perko, 2009). The first literature study on screw piles was done by Trofimenkov and Maruipolshii (1965) by developing a bearing capacity method for single helical piles. Adams and Klymn (1972) were the first to apply this method to multiple helical piles. Mitsch and Clemence (1985) and Mooney *et al.* (1985) later investigated the co-operation of all bearing plates by cylindrical shear method analysis.

Demir and Ok (2015a) carried out studies investigating the uplift capacity of helical piles in layered soils and found that sand density affects the bearing capacity. Demir and Ok (2015b) also conducted experimental investigations and numerical analysis using Plaxis for the uplift capacity of helical anchors in soft clay. As a result of their study, they stated that the ultimate uplift capacity depends on the anchor embedment ratio and anchor spacing ratio; and the agreement between the ultimate uplift capacities obtained from experimental studies and numerical analysis is excellent for anchors up to embedment ratio of six. Zhang *et al.* (2023) investigated the bearing capacity characteristics of screw piles using numerical simulation software. They compared the behavior of screw piles and standard piles in single layer sandy soil. They selected pitch sizes, helix diameters, tilt angles, helix numbers and helix spacing as variables effect bearing capacity in their study. Liu *et al.* (2023), stated that steel screw piles are applicable in permafrost regions, but may cause settlements different from the design due to climate changes. To prevent this problem, they developed a method to freeze the ground where the screw is applied by using liquid coolant and conducted a series of laboratory tests. They also investigated the power required to remove heat from the ground by modelling with finite element method. As a result of numerical and experimental studies, they concluded that this method is applicable for screw piles in permafrost regions. Ma *et al.* (2023) investigated the mechanism and calculation methods of ultimate lateral capacity of screw piles. They studied the effect of variables such as screw pitch, the effective screw thread width, and the dip angle of

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thread surface on the lateral capacity of screw piles. They stated that a smaller dip angle of thread surface and a larger effective screw thread width should be selected to increase the ultimate lateral resistance of the screw pile. Kim *et al.* (2022) carried out ten full scale load tests to investigate lateral resistance behavior of helical piles by using p-y springs method. They stated that the influence zone of the helix plates is a function of their diameters. Park and Lee (2021) investigated circular plate anchors placed in layered clay soil. They stated that breakout factors depend on embedment depth, layer thickness and soil's self-weight. Vignesh and Muthukumar (2023) investigated the behavior of four helix screw piles with different patterns under uplift and lateral forces. They also examined the effect of the distance between the piles under group effect by varying the value of S_g, which is the distance between the centers of the piles. Nowkandeh and Choobbasti (2021) investigated the how pile spacing effect the pile group failures with finite element-based software. According to the findings of their numerical analysis results, for pile spacing/diameter of pile ratio equals 1.05 helical pile groups fail as a block which decreases the group efficiency significantly. They also mentioned that group efficiency differs for shallow and deep pile applications. Recent research showed that machine learning applications also can be adopted screw piles to improve predictions of screw pile performance under loads (Igoe *et al.* 2024).

The common advantages of screw piles are listed in the literature as being suitable for areas with limited access, being removable and reusable, requiring very little drainage, having high uplift and compressive capacities, being used in sloping terrains, producing minimal noise and vibration during application, and being economical (Zhang *et al.* 1998, Schmidt and Nasr 2004, Livneh and Naggar 2008, Sakr 2009, Sakr 2011, Ok 2014, Venkatesan *et al.* 2023, Nowkandeh and Choobbasti 2021, Sarici and Ozcan 2024b). As a result of the literature review, it has been observed that there are not enough studies on the effect of changes in the number of screws on the group efficacy of screw piles and the effect of different number of screws on screw pile behavior in groups with different patterns. Since these parameters significantly affect the performance of screw pile groups and the optimum conditions should be determined, it was thought that further research should be carried out. In this context, an experimental study (Vignesh and Muthukumar 2023) was modelled on 3D FEM based software called as Plaxis 3D. After validation of the model developed, parametric analyzes was conducted to investigate effects of the screw pile group patterns and helix numbers under both compressive and uplift forces. To evaluate changes with different parameters, settlement ratios, helix number efficiency and group efficiency values were calculated. Outputs of numerical analyzes were visualized to investigate failure types and stress distribution for screw pile groups. It was considered that the results obtained from this study will provide guidance for literature studies and field applications.

Table 1 Soil parameters of the model (Vignesh and Muthukumar 2023)

Parameters	Value
Unit volume weight (kN/m^3)	γ=16 γ_{sat}=17
Young's Modulus (E, kN/m^2)	Secant Stiffness, E_{50}^{ref}=24550 Oedometer Stiffness, E_{oed}^{ref}=28000 Unloading/ Reloading Stiffness E_{ur}^{ref}=73650
Poisson Ratio (μ)	0.3
Soil strength (s_u, kN/m^2)	7.5
Friction Angle (φ_u)	0

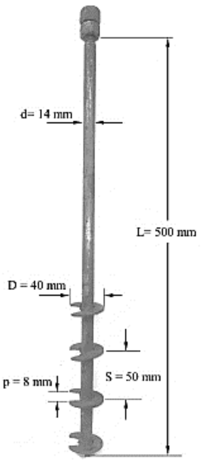


Fig. 1 The pile used in the experimental study by Vignesh and Muthukumar (2023)

2. Material and method

In this study, at the first stage, the model loading test performed by Vignesh and Muthukumar (2023) on helical piles was modelled with Plaxis 3D. In the next stage, the results of the model loading test were compared with the results obtained from Plaxis 3D to prove the accuracy of the model. In the last stage, parametric studies were carried out using screw piles in 3 different patterns formed by selecting 5 different number of helixes.

2.1 Soil used in modelling

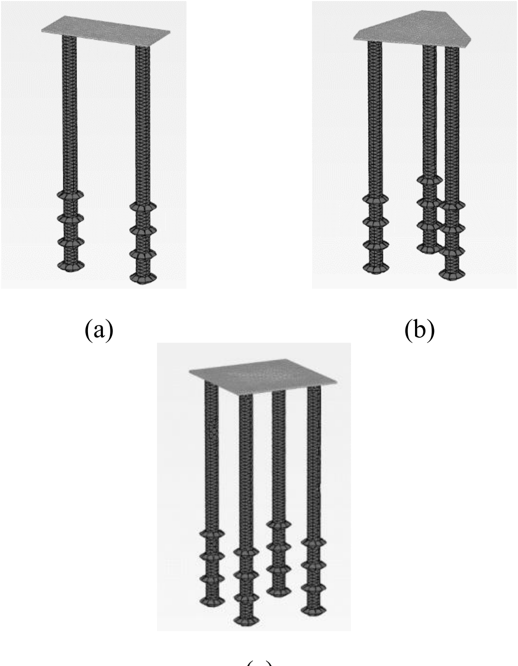
The soil used in the experimental studies conducted by Vignesh and Muthukumar (2023) was selected for the modelling in this study. The parameters related to the soil are shown in Table 1.

2.2 Piles used in modelling

The helical pile given in Fig. 1, which was used in the experimental studies conducted by Vignesh and Muthukumar (2023), was modelled in this research. The number of helixes of this pile was changed and Traditional Pile (TP), 2 Helix Pile (2HP), 4 Helix Pile (4HP), 6 Helix Pile (6HP) and 8 Helix Pile (8HP) were modelled. In

Table 2 Types of piles used in the analysis

Identification	Number of Helix	Length (mm)	Helix Diameter (mm)	Shaft Diameter (mm)	Number of Pile
TP	0	500	40	14	1
2HP	2	500	40	14	1
4HP	4	500	40	14	1
6HP	6	500	40	14	1
8HP	8	500	40	14	1
LTP	0	500	40	14	2
TTP	0	500	40	14	3
STP	0	500	40	14	4
L2HP	2	500	40	14	2
T2HP	2	500	40	14	3
S2HP	2	500	40	14	4
L4HP	4	500	40	14	2
T4HP	4	500	40	14	3
S4HP	4	500	40	14	4
L6HP	6	500	40	14	2
T6HP	6	500	40	14	3
S6HP	6	500	40	14	4
L8HP	8	500	40	14	2
T8HP	8	500	40	14	3
S8HP	8	500	40	14	4


(a) (b)

(c)

Fig. 2 Pile groups (a) 2 pieces linear pattern, (b) 3 pieces triangular pattern and (c) 4 pieces square pattern

addition, Linear 2 pieces (L), Triangular 3 pieces (T) and Square 4 pieces (S) patterns were formed to analyze the piles in groups (Fig. 2). Information about the pile types and patterns used in modeling are shown in Table 2. In addition, the parameters required for the design of the piles are given in Table 3.

Table 3 Design parameters of piles (Vignesh and Muthukumar 2023)

Parameter	Volume of the pile	Pile shaft plate	Helix plate	Interfaces	Pile Cap
Unit weight (kN/m^3)	78.5	0.0785	78.5	γ=17 γ_{sat}=17	78.5
Young's Modulus (E, kN/m^2)	200 x 10^6	200	200 x 10^6	24550	200 x 10^6
Poisson's Ratio (μ)	0.3	0.3	0.3	0.3	0.3
Soil strength (s_u) (kN/m^2)	-	-		7.5	-
Friction Angle (φ_u)	-	-		0	-

The results obtained from the experimental studies were compared with the results of the analyses performed in PLAXIS 3D to check the accuracy of the model. The dimensions of the soil environment created for the experiment were determined as 1 m x 1 m x 1 m x 1 m. The width values were determined to represent 25 times of the helix diameter (D), and the depth was determined to represent 2 times of the pile length (L).

2.3 Mesh generation

In order to represent the pile body during modelling, the pile body was created as a soil by defining the soil parameters created for the pile given in Table 2 into the software. Hardening soil model was chosen for clay soil to reflect experimental behavior of soil more realistically. Then, to ensure that the helixes and the pile body work together, the plate was assigned according to the pile body plate values given in Table 3. The plate defined here has much less stiffness than the plate element used in the helix. Therefore, this plate layer was intended to connect only with the helixes. Again, a positive directional interface was defined on this plate according to the interface parameters given in Table 3. This interface command provides a disconnection while creating a mesh with the element on which it is defined, allowing the element to work separately from the surrounding soil. Unlike helixes, by giving only a positive interface to the shaft plate, it is ensured that the plate interacts with the ground created for the shaft but works separately from the ground surrounding the shaft. In addition, within the defined interface parameters, the operating effect of these parameters $R_{interface}$ was selected 0.65 as suggested by Vignesh and Muthukumar (2023). In this way, it was suggested that the behavior of the soil and pile elements was brought closer to experimental studies.

The helix plates were then formed, and the center of the pile shaft was aligned with the center of the helix plates. The distance between the helixes was chosen as 50 mm. Two directional interfaces, positive and negative, were defined for the helixes. For all pile group patterns, the center-to-center pile spacing S_g was chosen to be 4 times the diameter of the helix. After the pile groups were formed, the piles were connected with the pile cap given in Table 3 and the prescribed displacement was applied to this pile cap. Displacements corresponding to 10 percent of the helix

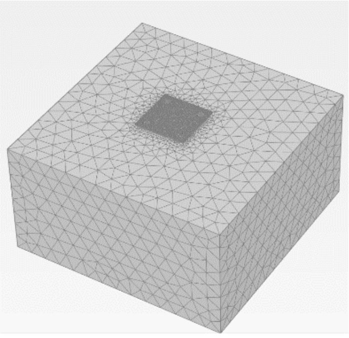


Fig. 3 Mesh image generated in the finite element method

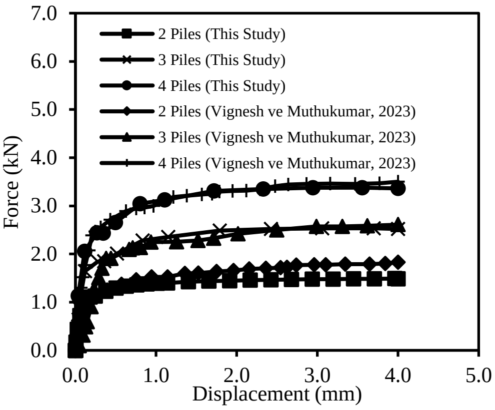


Fig. 4 Comparison of experimental and numerical analysis results

Table 4 Mesh sensitivity analysis results

Mesh	Elements	Nodes	F_z
Mesh 1	23477	39903	1.62
Mesh 2	24591	41774	1.56
Mesh 3	29070	48850	1.46
Mesh 4	41546	67342	1.41
Mesh 5	74246	114568	1.39

diameter were defined to determine the ultimate bearing capacity under uplift and compressive forces. Model boundaries were fixed both x and y directions. The width values were determined to avoid possible boundary effects and to be sure stresses were kept inside soil deposit. Mesh sensitivity analysis also was made to define proper mesh size for the analyses (Table 4). According to mesh sensitivity analysis, “Mesh 2” was chosen. The mesh image of the model created for the analysis is shown in Fig. 3.

3. Results and discussion

The modelled piles were subjected to uplift force in the first stage. The load-displacement behaviors obtained from the experiments were compared with the behaviors obtained from PLAXIS 3D analyses and significant agreement was observed. The related graph is given in Fig. 4. Numerical analyses were then carried out to investigate the behavior of the piles under compressive force. In addition, group efficiencies and settlement ratio (Rs) values were investigated to examine the performance of the piles in groups and are presented in this section.

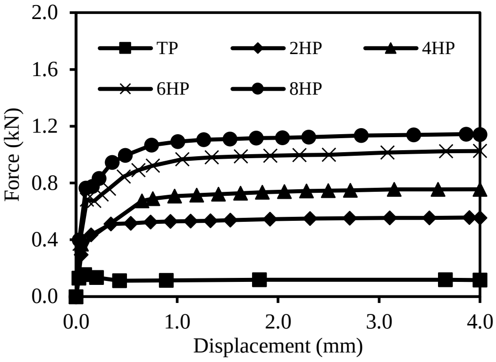


Fig. 5 Behavior of single piles under uplift force

3.1 Behavior of pile groups under forces

After the agreement between the numerical analysis results of the modelled piles under uplift load and the experimental results were obtained, TP, 2HP, 4HP, 6HP and 8HP piles were subjected to numerical analyses to determine the bearing capacity of the piles at different numbers of helixes. The load-settlement graph of these piles under uplift load is given in Fig. 5.

As can be seen in Fig. 5, the change in the number of screws has a significant effect on the carrying capacity. Based on the TP; 2HP, 4HP, 6HP and 8HP have 4.78, 6.51, 8.84 and 9.84 times more carrying capacity, respectively. As the failure surface area increases with the increase in the number of helices, it is thought that the bearing capacity also increases.

TP, 2HP, 4HP, 6HP and 8HP piles were subjected to numerical analyses to observe the bearing capacities of the piles under compressive forces at different number of helixes. The load-settlement graph of these piles under compressive force is given in Fig. 6. Like the uplift case, increasing the helix number increased the bearing capacity under compressive force.

In the next stage, to examine the bearing capacity of the piles as a group in different patterns, patterns were created for each pile type and the numerical analysis results are shown in Fig. 7. It was observed that the bearing capacity increased as the number of piles increased. Because the distance between the piles was chosen to minimize the interaction between the piles and thus failure surface area increased. But, when the piles were in groups, they showed different performances in variable patterns. As can be seen from Fig. 7, the increase in bearing capacity in each pattern is not proportional as in single piles. This shows that optimum patterns should be determined for different numbers of helixes. For example, while 6HP linear and square patterns have bearing capacity values close to 8HP, the difference in bearing capacity increases in triangular pattern. Similarly, while 2HP is close to 4HP in linear pattern, the difference increases in triangular and square patterns.

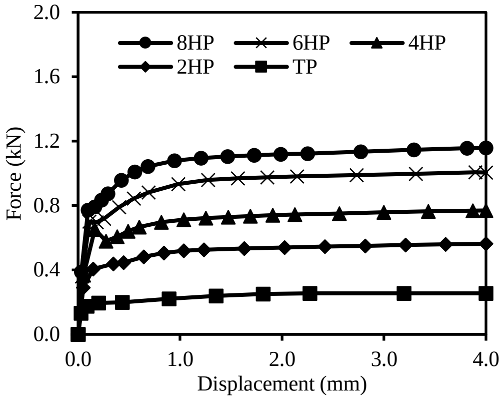
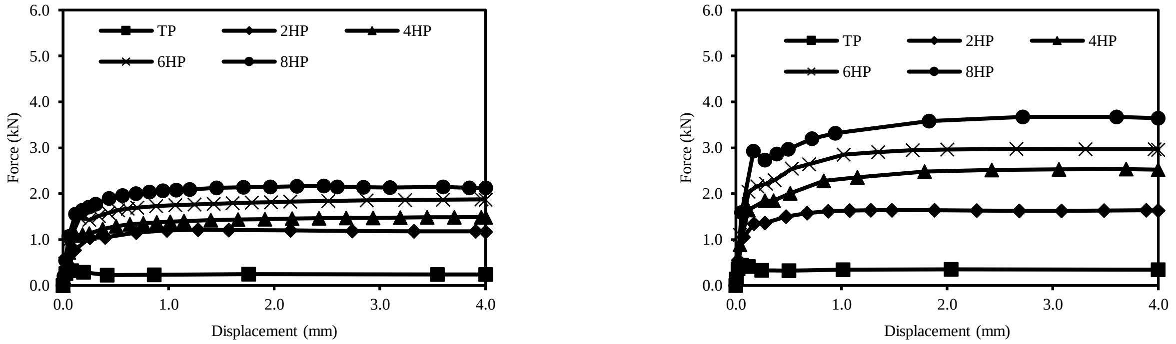
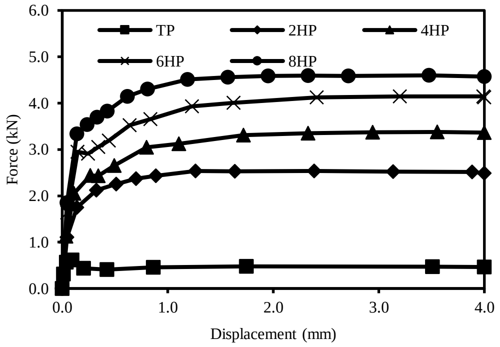


Fig. 6 Behavior of single piles under compressive force



(a) Linear pattern

(b) Triangular pattern



(c) Square pattern

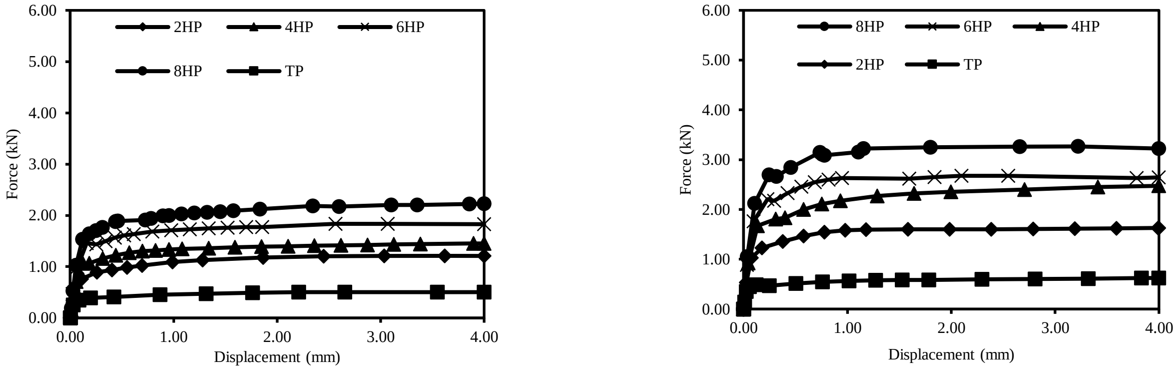
Fig. 7 Load-settlement behaviors of different patterns in pile groups under uplift forces

Numerical analysis results of group screw piles with different patterns under compressive force are presented in Fig. 8. Although increasing the number of piles increased the bearing capacity, the piles performed differently in variable patterns when they were in groups. As can be seen from Fig. 8, the increase in bearing capacity in each pattern is not proportional as in single piles. This shows that the optimum patterns should be determined for different numbers of helixes. For example, while 6HP triangular and square patterns have bearing capacity values close to 8HP, the difference in bearing capacity increases in linear pattern. Similarly, while 2HP is close to 4HP in linear pattern, the bearing capacity difference changes and increases in triangular and square pattern. Under compressive action, the behavior is even more variable as the pile end forces also come into play. In contrast to the uplift force, TP shows a performance closer to the other piles under compressive force.

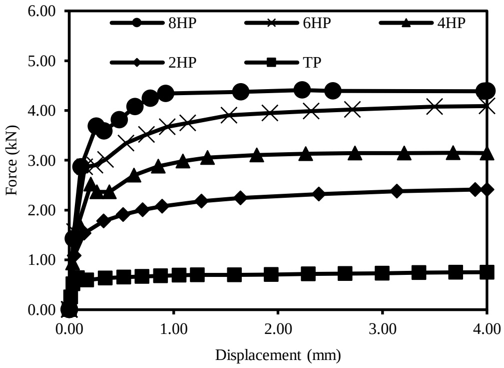
In this context, it is seen that the optimum number and pattern should be evaluated and found separately for each type of pile under compressive forces. So, it is important to have the correct number and placement of piles in the project.

3.2 Settlement ratio (Rs) of pile groups

To examine the efficiency of the piles as a group, the settlement of the single piles under the same load was



(a) Linear pattern (b) Triangular pattern



(c) Square pattern

Fig. 8 Load-settlement behaviors of different patterns in pile groups under compressive forces

compared with the settlement of the pile group using relation (1) proposed by Paulos and Davis (1980).

$$Rs = \frac{\text{Settlement of pile group}}{\text{Settlement of single pile at average group load}} \tag{1}$$

To calculate the Rs value, the bearing capacities of piles with different helix numbers in linear, triangular, and square patterns corresponding to 0.1 D displacement were divided by the number of piles in the group and the average load on a pile was calculated. Then, a prescribed displacement of 8 mm was applied to the piles modelled alone under both uplift and compressive forces and the settlement values corresponding to this load were determined. In these analyses, settlement of single pile at average group load value was taken as 8 mm since the load-settlement curve passes to linear position in cases where the average load is not reached within 8 mm displacement. Since the helix diameters are constant (40 mm), the settlement of pile group is taken as 4 mm. This value was divided by the settlement value obtained for each individual pile and Rs values were determined. Rs values in different patterns are shown in Fig. 9. Also, as can be seen in Fig. 9, the evaluation of Rs values for TP piles does not seem to be reasonable, but acceptable results were found for other pile types.

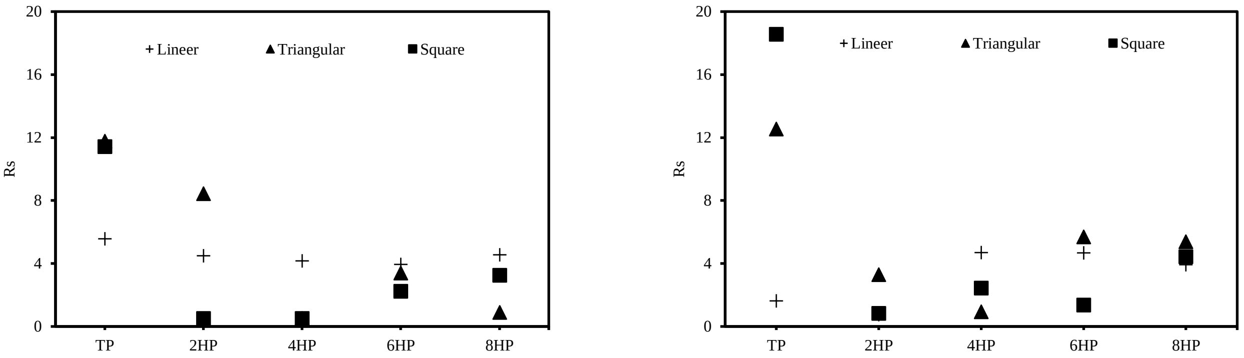
Considering the Rs values, in the linear pattern under tensile force, the number of helices did not affect the settlement ratio value much but 6HP was found to be the most suitable pile. In triangular and square patterns, the optimum piles were 4HP and 2HP, respectively. Under compressive force, the optimum piles in terms of Rs value for linear, square, and triangular patterns are 2HP, 2HP and 4HP, respectively. In the triangular and square pattern, it was observed from the Plaxis 3D outputs that the increase in the number of helixes changes the stress surfaces, so it was observed that 2HP and 4HP were the optimum piles.

3.3 Group efficiency (η_g) of pile groups

To analyze the efficiency of the pile groups, it is necessary to examine the group efficiency value. Whitaker (1957) defined this parameter as follows

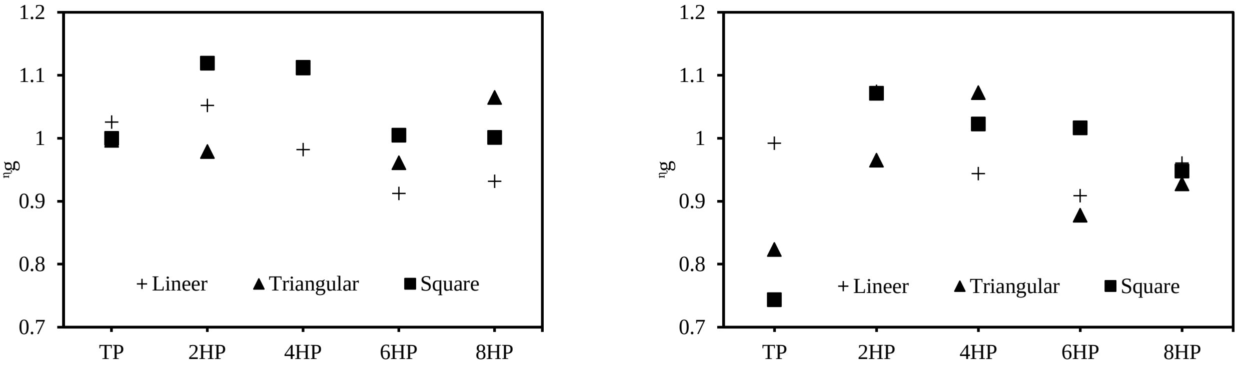
$$\eta_g = \frac{\mathit{Ultimate\ capacity\ of\ group/Number\ of\ pile}}{\text{Ultimate capacity of single pile}} \tag{2}$$

To calculate the η_g value, the load value for the displacement value corresponding to the 0.1D failure condition in the load settlement graph is divided by the number of piles in the group. The load value corresponding to the displacement of the individual piles at the same failure criterion is calculated and these two values are divided. With this parameter, it can be evaluated how efficient the group is. In this study, the bearing capacities of the groups under both compressive and uplift forces were calculated and η_g values were obtained and given in Fig. 10. As a result of η_g values, it was found that piles in different patterns have different efficiencies.



(a) Pullout force (b) Compressive force

Fig. 9 Rs values of pile groups



(a) Pullout force (b) Compressive force

Fig. 10 ɳg values of pile groups

According to ɳg values, it is seen that 2HP, 2HP and 4HP are the optimum piles for linear, square, and triangular patterns, respectively, under compressive force. Under the effect of the tensile force, 2HP, 2HP and 8HP are found optimum piles for linear, square and triangular patterns, respectively. It is thought that this is caused by an extra stress surface formed between the piles. This stress surface limits the contribution to the bearing capacity as the number of helixes increases. In addition, for tensile forces, with the angular extension of stress areas above the top helix, stress areas may overlap and lead to decrease in bearing capacity due to pile interactions. For triangular pattern, all piles have exactly same center to center placement and stress areas flow into the middle of the triangle which may lead to more overlaps. However, for square and linear patterns pile stress areas were not forced to overlap in one specific cross section. This is thought to be the main reason for difference in optimum pile selection for triangular patterns.

3.4 Efficiency of helix number (ɳ)

The effectiveness of increasing the number of helixes compared to a single helix pile needs to be determined. Lutenegger (2011) proposed the following formula to find this value.

$$ɳ = (Q_{MU}/\sum Q_{IU})x100 \quad (3)$$

where;

ɳ : efficiency

Q_{MU} : Bearing Capacity of Multi-Helix Pile

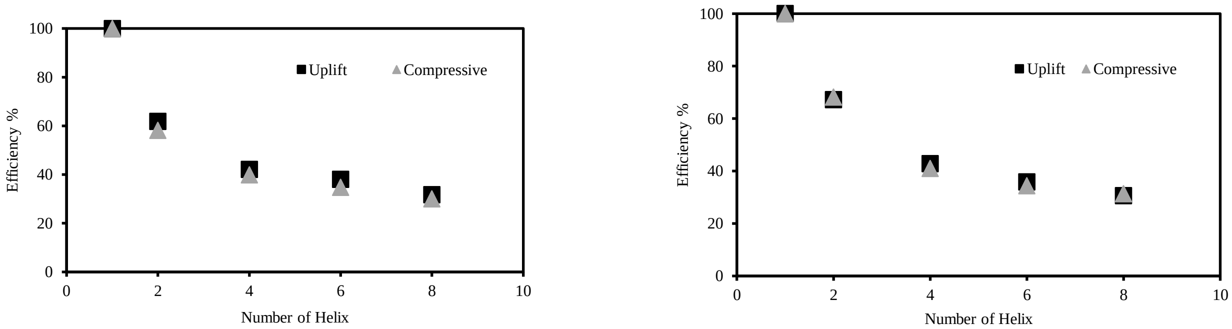
Q_{IU}: Bearing Capacity of Individual Single-Helix Pile

As a result of the numerical analyses, piles with different numbers of helixes were compared with single helix piles both as a group and individually and the results are given in Fig. 11. According to this, increasing the number of helixes decreases the efficiency.

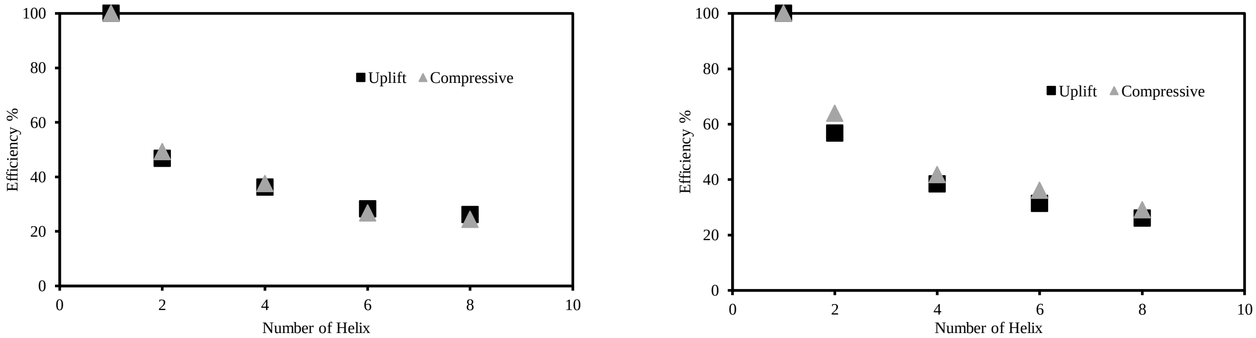
Increasing the number of helixes may be less costly than adding a new pile. Thus, to evaluate the total efficiency in groups and piles, the investigated parameters should be evaluated together.

3.5 Failure surfaces of piles and pile groups

The results of the numerical analysis were visualized to examine the results of this research and to investigate the behavior of the screw piles under load in case of different number of helixes. The failure surfaces of the screw piles were determined by the visualizations and presented in Figs. 12 and 13. When the relevant figures are analyzed, it is seen that the piles fail along a cylindrical shear plane starting from the bottom helix to the top helix under uplift force. When examined for compressive force, it is seen that



(a) Single Pile (b) Linear Pattern Pile Group



(c) Triangular Pattern Pile Group (d) Square Pattern Pile Group

Fig. 11 Efficiency of number of the helix usage

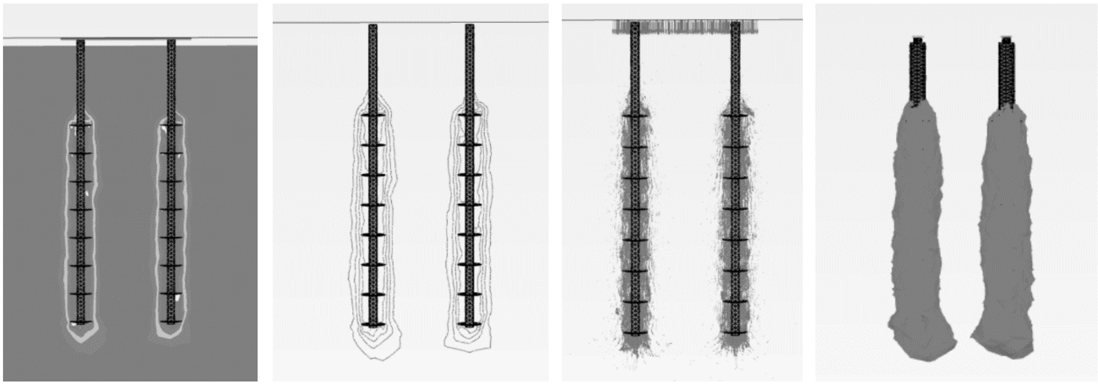


Fig. 12 Failure surfaces of screw piles under compressive force

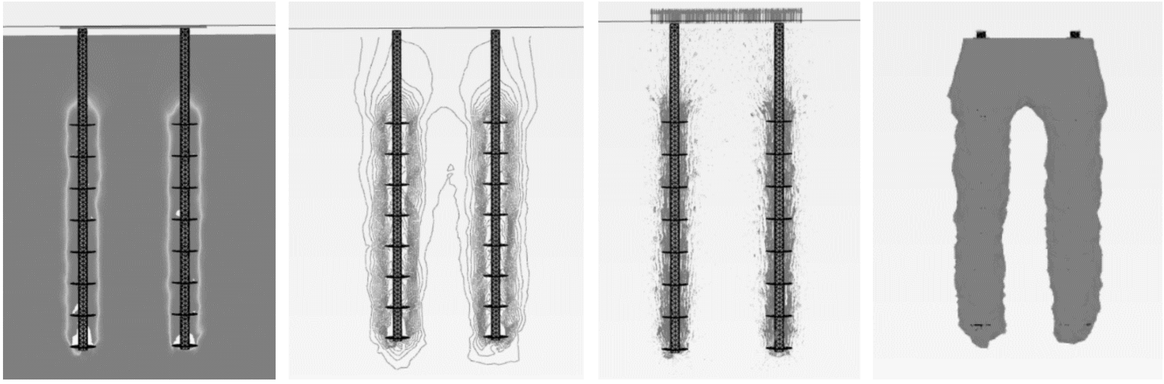


Fig. 13 Failure surfaces of screw piles under uplift force

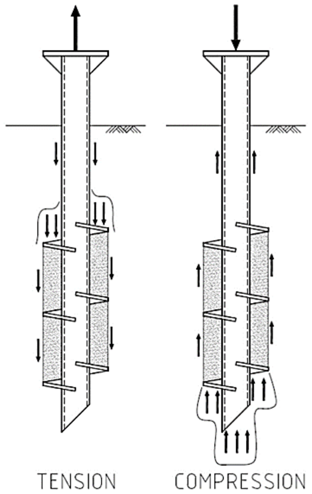


Fig. 14 Failure surfaces of screw piles (Mohajerani *et al.* 2016)

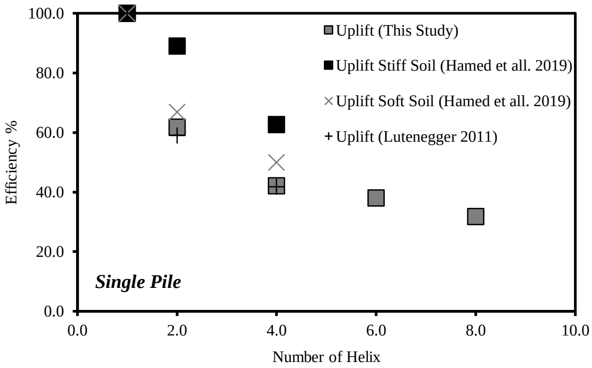


Fig. 15 Comparison of efficiency of helix number values with previous studies

in addition to the similar behavior starting from the top helix to the bottom helix, and pile tip stresses also occur. These observed behaviors are consistent with literature studies given in Fig. 14. This shows that the behavior of the modeling created with Plaxis 3D in this study agrees with the theoretical studies.

The results obtained from the analyses were compared with the results of previous studies in literature and discussed in this section. In this context, the graph of efficiency of helix number (η) values, which is the parameter that examines the effectiveness of the number of helix usage, is combined with the results of the studies made by Hamed *et al.* (2019) and Lutenegger (2011) and presented in Fig. 15. It is also seen that the results obtained from this study are in the behavior and range that matches the literature. It has been confirmed by previous studies that the efficiency of the helix number decreases as the number of helixes increases.

In addition, to make a comparison for Rs values, the results of the study of Lanyi Bennett and Deng (2019) used in Fig. 16. As can be seen in Fig. 16, the results of this study match with the previous studies. It was seen that Rs values decrease with the increase in the ratio of the distance between the piles to the diameter of the helix. So, the Rs value calculated in this study coincides with the behavior in the literature. Fig. 16 clearly shows that as the distance between the piles increases, the settlement behavior improves as the interaction between the piles decreases.

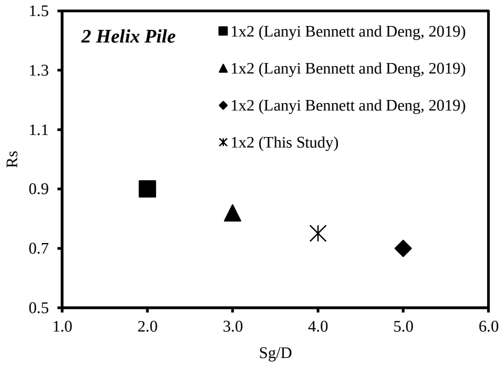


Fig.16 Comparison of Rs values with previous studies

4. Conclusions

In this study, the behavior of screw piles with different number of helixes and group patterns under uplift and compressive forces was investigated. In addition, group efficiency, efficiency of helix number and settlement ratio values were calculated for different patterns. The results obtained within the scope of the study can be listed as follows:

- The increase in the number of helixes caused an increase in the bearing capacity both under uplift and compressive forces. For compressive forces, bearing capacity of 8HP is 1.82, 1.97 and 1.85 times of 2HP for square, triangular, and linear pattern, respectively. Under the effect of uplift forces, these values were calculated as 1.84, 2.24 and 1.84. However, the rate of increase in bearing capacity of group piles is lower than that of single piles. This is because it is thought that there is some interaction between the piles as the number of helixes increases in groups.
- When the pile-soil interaction visualizations of all analyses taken from Plaxis 3D are examined, it is seen that as the number of helixes increases in triangular and square patterns, an extra failure surface is formed in the area between the piles in addition to the cylindrical failure surface formed around the helixes. In the efficiency of helix number values, the increase in the number of helixes decreases the efficiency for screw piles.
- When the settlement ratio and group efficiency values were analyzed, it was seen that the optimum values occurred in piles with different number of helixes. Therefore, only increasing the number of helixes may not always be a satisfactory solution. However, in some cases, it was estimated that an economical solution can be found by increasing the number of helixes instead of using extra piles to achieve the desired bearing capacity.
- Group efficiency, helix number efficiency and

settlement ratio parameters should be examined together, and economic choices should be made in this context. For example, while efficiency decreases in one parameter, the gains obtained in other parameters can compensate for the decreases. For this reason, it is important to select patterns according to the application area, soil, and related project.

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