Numerical Analysis of the Pile-Grout System in Soft Clay under Vertical and Lateral Load

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Abstract. In this paper, a numerical investigation of the effects of grout parameters on the load response of concrete pile-grout systems in soft clay is presented. The study examines the influence of grout diameter and depth on the load bearing capacity of the pile under vertical and lateral loads. The research findings indicate that grouting can enhance the load bearing capacity of a single pile system by up to 27% under vertical loads and up to 51% under lateral loads, depending on the diameter and depth of the grout used. This is due to the grout's ability to fill voids in the soil and improve the soil-pile interface, resulting in better soil-pile interaction. Additionally, the study demonstrates that increasing the diameter and depth of grout leads to a larger treated soil area and subsequently an increase in load bearing capacity. Furthermore, the research indicates a linear relationship between the amount of grout material utilized and the increase in the load bearing capacity of the pile. The study concludes that grouting is an effective method for improving the pile performance systems, particularly in soft soil conditions. The results of the research are consistent with prior studies on the use of grout material to enhance the load-carrying capacity of pile systems.

Keywords: Concrete pile-grout system; vertical load; lateral load; numerical investigation; soft clay.

1. INTRODUCTION

The use of concrete piles in soft clay is a common method for foundation design in many construction projects. However, the performance of these piles can be negatively affected by lateral and vertical loads, which can cause excessive deformation and ultimately lead to failure. To mitigate these issues, researchers have investigated various grout parameters that can improve the load of pile-grout system. The use of pile-grout systems to support vertical loads in soil has been investigated in several studies. Elsalfiti [1] conducted a study on the shaft resistance of micro-piles that embedded in coarse soils and found that the use of grout significantly increased the skin friction of the pile, leading to improved load-bearing capacity. Similarly, Yu [2] examined the use of grouted piles in soft clay and found the grout significantly improved the performance of consolidation of the composite pile foundation, thereby enhancing its load-bearing capacity. The formulation of solutions for previous concrete pile ground improvement, as well as their behavior under vertical loads, was examined in [3]. They found the pervious concrete pile system was capable of withstanding significant vertical loads and had the potential to serve as a viable alternative to traditional pile-grout systems.

Ren [4] analyzed of the performance of enlarged cross-section, vertically loaded jet grout piles and found that the use of jet grouting significantly increased the load bearing capacity of system that contain the pile-grout. Borthakur [5] conducted experimental investigations on the load-bearing capacity of micropiles in type of soft clay soil and found that the grout significantly improved the load-bearing capacity of the pile. Geißler [6] investigated compaction grouting for offshore pile foundations and found that the use of grouting significantly increased the load bearing capacity of the system of pile-grout. Zhou [7] performed experiments on enhancing the bearing capacity of pile foundations in the soil of loess area by post-grouting and found that the utilizing of post-grout considerably increased the pile load-bearing capacity. The use of jet grouting greatly increased the stability of the pile-grout system, according to numerical research [8] on the performance of jet grout piles for braced excavations in soft clay. According to numerical modeling carried out [9] for grout injection into hybrid-bored prestressed concrete cased piles, the use of grouting considerably increased the pile's ability to support loads. Wan Z. [10] examined the axial bearing mechanism of post-grouted piles in calcareous sand and discovered that post-grouting considerably increased the pile-grout system's ability to support loads.

The behavior of the pile-grout system subjected to horizontal load has been carried out by numerous studies, and their findings and contributions have been presented in various studies. Rollins KM. [11] conducted a full-scale experimental study on the lateral load behavior of pile groups in clayey soil. It was observed that the lateral load behavior of pile groups was dependent on several factors, including the spacing between piles and the soil properties. Their study also revealed that the load transfer between piles influenced the horizontal response of the group of pile. Karthigeyan S. [12] investigated the effect of axial load on the horizontal pile response in sand. Their numerical analysis showed the ultimate horizontal resistance of a pile decreased with increasing vertical load, and the soil stiffness around the pile reduced as lateral displacement increased. They suggested that the existence of vertical load should be considered when analyzing the lateral behavior of piles. Lin [13] conducted numerical simulations to investigate the surrounding soil and the interaction among laterally loaded of piles. Their study revealed that the soil-pile interaction was affected by the pile geometry, the soil properties, and the loading conditions. They also found that the soil deformation pattern around the pile was complex and could not be easily predicted.

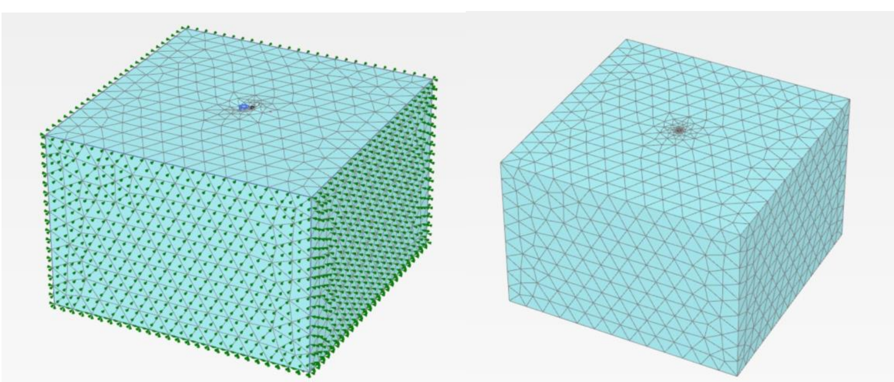
Luo [14] examined the response of a single pile to lateral force. Subsequently examined the impact of the pile length, diameter, and soil characteristics on the lateral resistance of the pile using numerical simulations. The results showed that as the pile diameter and soil stiffness increased, the lateral resistance of the pile increased correspondingly. Dong [15] examined the boundary impact of a single pile under horizontal stress in model experiments. The following numerical research showed that the boundary effect had an important effect on the behavior of the pile under lateral loads and that the pile's lateral resistance decreased as one moved farther away from the boundary. The displacement field of layered soils surrounding a laterally loaded pile was experimentally studied by [16] using transparent soil. The study showed that the geometry of the pile, the loading circumstances, and the qualities of the soil also had an impact on the displacement field surrounding the pile. It also noticed that the soil's lateral deformation was more pronounced near to the pile and less pronounced farther away. The behavior of pre-bored grouted planted piles with larger grout bases was the subject of field research by [17]. According to their research, the pile's lateral load resistance and lateral displacement were both enhanced by the expanded grout base. It suggested that the increased grout base on the pre-bored, grouted planted piles was beneficial in reducing the lateral deformation of the soil.

The use of grouting gel and silica fume to increase the unconfined compressive strength of soft clay has been studied by [24]. The results may reveal details on changes in stiffness or any additional relevant clay-related metrics following the application of these substances, as well as an increase in the unconfined compressive strength. It was determined that the use of grouting gel and silica fume could increase the unconfined compressive strength of soft clays. The purpose of this work is to examine the impact of grout parameters on the load response of concrete pile-grout systems subjected to lateral and vertical loads in soft clay. The study utilizes numerical simulations to analyze the behavior of pile-grout systems and evaluates the impact of grout parameters, such as grout diameter and depth, load response of the system in vertical and lateral. The research aims to provide insight into how the design of grout parameters can be optimized to enhance the performance and load response systems of pile-grout in soft clay conditions.

2. NUMERICAL SIMULATION

To examine the influences of grout parameters on the load response of the pile-grout system under horizontal and vertical loads, numerical simulations that were conducted using the PLAXIS 3D software. PLAXIS is widely used finite element software for geotechnical engineering applications, capable of modeling complex soil-structure interaction problems. In this study, the soil mass was modeled by utilizing the Mohr-Coulomb constitutive model with soft clay properties, while the pile and grout properties were simulated as linear elastic materials [18 and 19]. The numerical model consisted of an individual pile-grout system buried in soft clay, subjected to pure lateral and pure vertical loads. The grout parameters, including grout modulus and thickness, were varied in the numerical simulations to examine their impact on the pile-grout system's load response.

The study performs a numerical analysis of piling groups buried in soft clay soil, using parameters collected from [20], which evaluated conventional and enclosed stone columns beneath an embankment. Table 1 displays the characteristics of the soil. The pile is 12 m in length and 0.6 m in diameter. The piles are simulated as volume elements with a $3x10^7$ kPa elastic modulus and a 24 kN/m^3 unit weight. As illustrated in Figure 1, the boundary conditions are simulated based on basic needs, with boundaries that are fixed in all directions and free from above. Based on references [21 and 22], cement material was employed as jet grouting in order to evaluate the effect of the grout material on the behavior of the pile group. The grouting material is modeled as elastic-perfect plastic, using the Mohr-Coulomb model, with properties shown in Table 2.



(a) (b)

Figure 1: (a) Fixed boundary condition in all direction, (b) mesh generation.

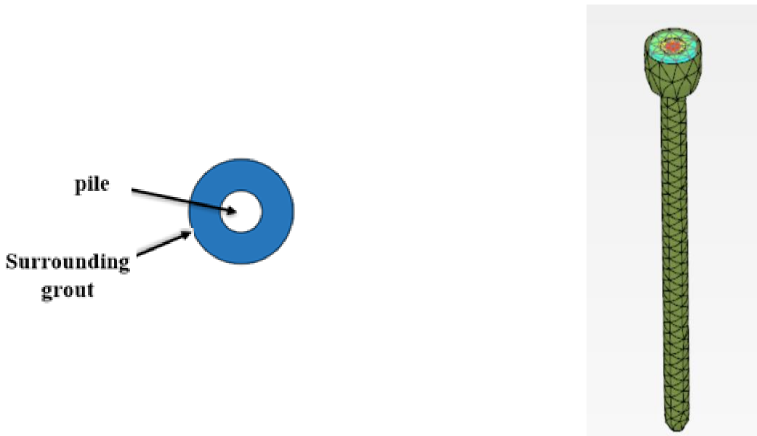
Table 1: The parameters of soft soil [20].

γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	E_{50}^{ref} (kP)	E_{oed}^{ref} (kPa)	E_{ur} (ka)	Cohesion (kPa)	Material model
13.23	18.84	600.1	1424	1802	10.5	model of soil Hardening

Table 2: Parameters of grout material [21].

N	E (MPa)	c' (kPa)	φ' (°)	γsat (kN/m^3)
0.25	150000	900	35	19

As seen in Figure 2, the piles were surrounded with grout material, which was modeled surrounding the pile using three grout radii of (0.5, 0.7, and 0.9 m). The study utilized three grout depths of (0.5, 1, and 2 m). The flow chart of the program consists of 12 tests, as shown in Figure 3.



(a) (b)

Figure 2: (a) A diagram shows a collection of piles surrounded grouting (b) modeling of the grout-pile.

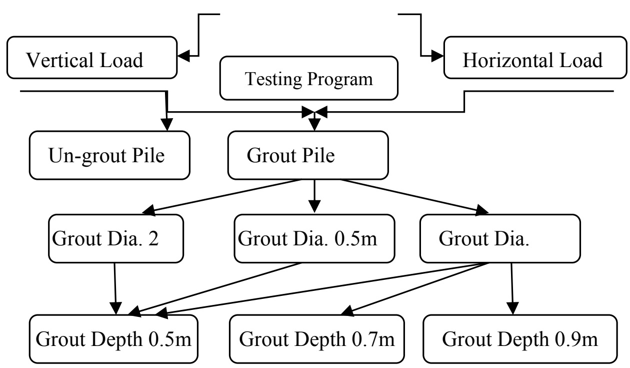
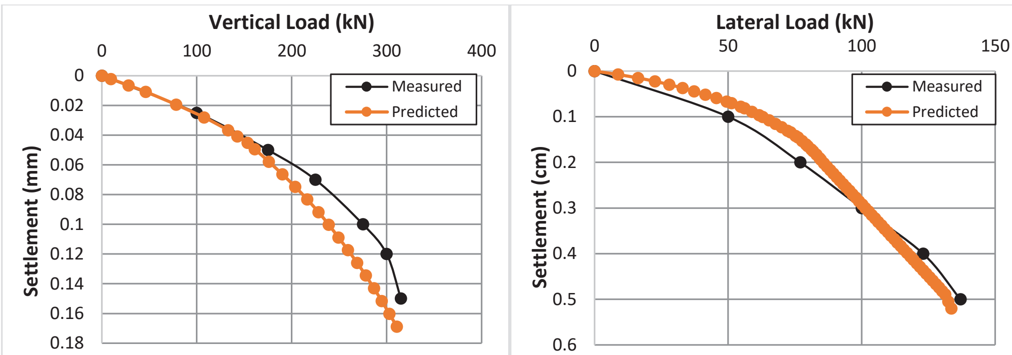


Figure 3: Flow Chart of the current testing program.

3. RESULT AND DISCUSSION

3.1 Model Verification

This verification was completed by comparing the PLAXIS software's output with predicting the pile response from a test data. A case study was explored using the PLAXIS software to achieve the aforementioned goal. Identical geometry, loading, and boundary conditions were employed in the example research to compare the results of a survey conducted by [23] with those produced using PLAXIS 3D. The case study in question relates to laboratory model testing on closed-ended piles made of aluminum with dimensions of 19 mm on the outside and 1.5 mm on the wall thickness that was jacked 500 mm into a soft clay bed that had been prepared (cu = 28 kPa). A single pile was subjected to a laboratory test, in which dead weights were used to provide lateral and vertical stresses to the pile head at the ground level. The combination of vertical and lateral loads was delivered in two stages: the first stage applied a 160 N vertical load, and the second stage introduced a 130 N lateral load progressively while maintaining a 160 N vertical load. The Young's modulus (Es) of the soil used for the current study was 7500 kPa. In Figure 4, the test results are compared with the predicted pile performance under pure vertical loads and a combination of vertical and lateral loads. In both cases, the PLAXIS estimate and test results agreed well.

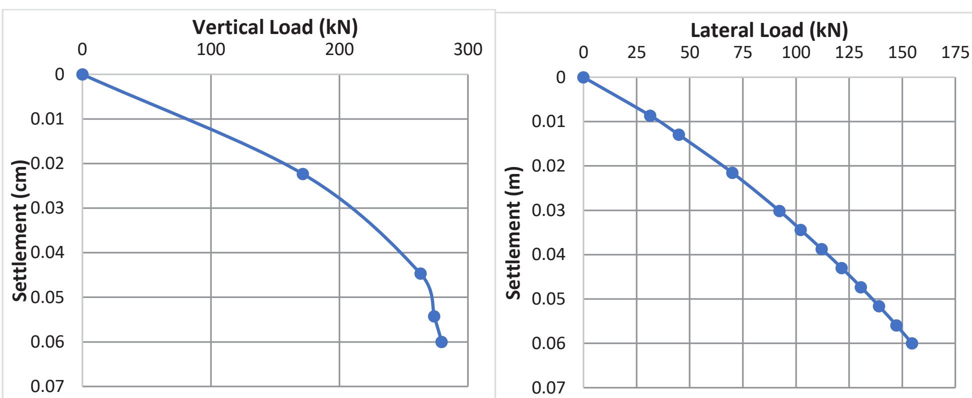


(a) (b)

Figure 4: Comparison between the PLAXIS results and (a) test data of vertical load [23], (b) test data of combination of vertical and lateral loaded [23].

3.2 Single Pile without Grout under Vertical and Lateral Load

Figure 5 illustrates the maximum settlement of the pile under pure axial and pure lateral load in natural soil. It is obvious that the settlement reaches 6 cm at point of failure and the max load reach to (279 and 154) kN under vertical and lateral load respectively.



(a) (b)

Figure 5: Load settlement of single pile without grout (a) Vertical load, (b) Lateral load.

3.3 Single Pile with Grout under Vertical Load

The impact of grout material on performance of single-pile under vertical loads is the topic of this section. There were several grouting patterns investigated around the single pile. Different grout depths (0.5, 1, and 1.5) m and grout diameters (0.5, 0.7, and 0.9) m were studied.

3.3.1 Effect of grout diameter on single pile

Figure 6 shows the result of different grout diameter of (0.5, 0.7, and 0.9) m with fixed depth of 1m. It can be seen when using grout material, the ultimate load carrying capacity increased by 14.6% with respect to un-grouted pile. In addition, with increasing of grout diameter from 0.5m to 0.7m the ultimate load carrying capacity increased by12.5% and from 0.5m to 0.9 the increasing was 27%. When a grout material is used to surround a pile in soft clay, the axial load-carrying capacity tends to increase. This is because the grout enhances the connection between the pile and surrounding soil, resulting in an increase in the piles overall stiffness and strength. To understand the behavior factor to estimate the grouting-induced increase in the axial capacity for carrying loads. The enhancement percent can be calculated as:

$$EP\,\% = \frac{Gp-UGP}{UGP} \times 100\% \tag{1}$$

Where Ep is the enhancement percent, UGP is Un-grouted pile, and GP is the grouted pile

This factor would provide a percentage value that indicates the improvement in the pile's load-carrying capacity due to grouting. The enhancement percent of grouted single-pile ultimate vertical load with various diameters is reveal in Figure 5. It can be noticed at a depth of 1 m; the enhancement percentage ranges between (12.5, 14.5, and 27) % when the grout radius is (0.5, 0.7, and 0.9) m, respectively as shown in Figure 7.

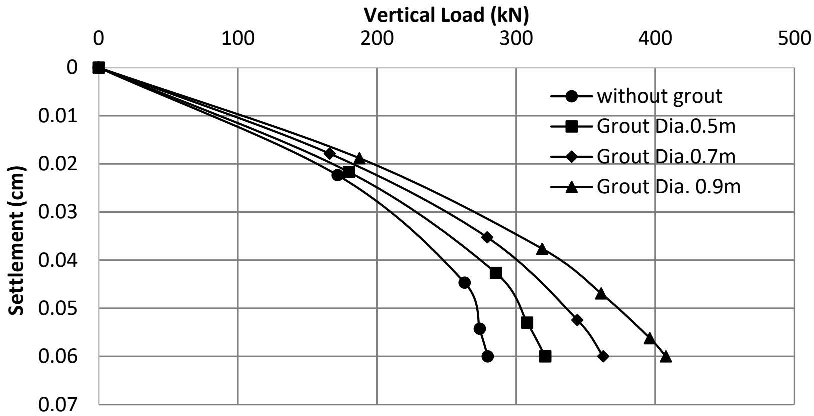


Figure 6: Relation between loads and settlement for a single pile with varying diameters under vertical load and a fixed depth of 1 m.

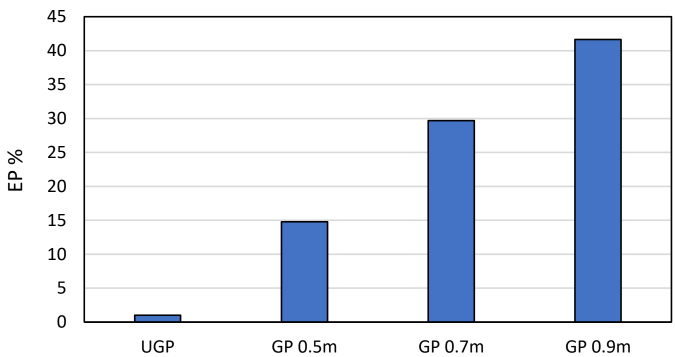


Figure 7: Enhancement percentage of the single pile with different grout diameters under vertical load and a fixed depth of 1 m.

3.3.2 Effect of Grout Depth on Single Pile

The result of different grouting depth of (0.5, 1, and 2) m with fixed diameter of 0.5 m are shown in Figure 8. It can be seen when using grout material, the ultimate load carrying capacity increased by 14.6% with respect to un-grouted pile. In addition, with increasing of grout diameter from 0.5m to 2m the ultimate load carrying capacity slightly increased by 5%. The Enhancement percent of grouted single pile ultimate vertical load with different diameter is shown in Figures 8 and 9. It observed at depth 1 m; the Enhancement percent ranges between 12.5, 3.7, and 1.7% when the grout radius is fixed of 0.5m. The findings of the study suggest that the improvement in load response due to the use of grout material in the pile system appears to have a linear relationship. In other words, as the amount of grout material used is increased, the load-bearing capacity of the pile system also increases proportionally. As a result, Injecting grout into the soil surrounding a pile enhances the interaction the soil-pile system, leading to an increase in the pile's load-bearing capacity. The grout substance occupies the empty spaces in the soil and strengthens the soil-pile interface. The greater the depth of grouting, the more soil is reinforced, and the interface is strengthened to a greater extent.

Consequently, when subjected to axial load in soft clay, the pile system's load-carrying capacity is enhanced. The result agrees with [9 and 10]. The Figure shows the settlement of pile under lateral conditions.

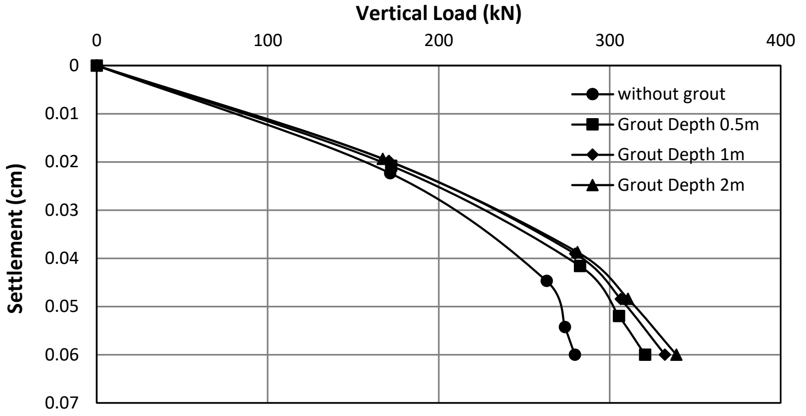


Figure 8: Relation between loads and settlement for a single pile with varying depths of grout under vertical load and a fixed diameter of 0.5 m.

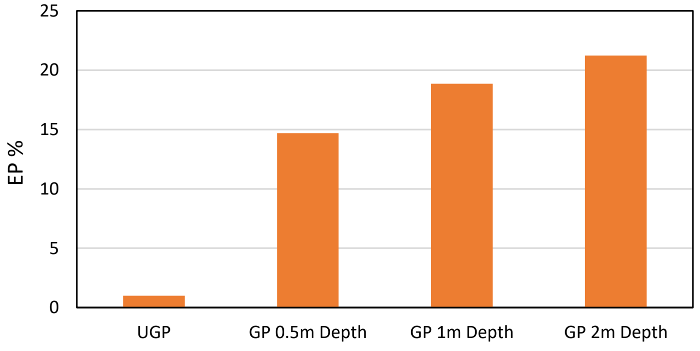


Figure 9: Enhancement percentage of the single pile with different depths of grout under vertical load and a fixed diameter of 0.5 m.

3.4 Single Pile with Grout under Lateral Load

The effects of grout material on single-pile performance under vertical loads in this section are studied. Different grout depths of (0.5, 1, and 2) m and grout diameters (0.5, 0.7, and 0.9) m were analyzed.

3.4.1 Effect of Grout Diameter on Single Pile

The findings of this investigation demonstrate that the diameter of grout is a critical factor affecting the single pile horizontal capacity. As depicted in the Figure 10, there is a noticeable increase in the enhancement percentage of the lateral capacity of piles, with an observed 34% increase as the diameter of grout increases from 0.5 to 0.9. It can be noticed at a depth of 1 m; the enhancement percent varies from (16, 31, and 51) percentage when radius of grout is (0.5, 0.7, and 0.9) m, respectively as shown in Figure 11. The reason for the increase in lateral capacity is due to the grout's potential to fill the voids in the soil and reinforce the soil-pile interface. With an increasing in the diameter of grout resulting to an increase in the volume of grout material injected into the soil, resulting in a larger treated soil area. This eventually leads to an improved soil-pile interaction and an increase in the pile's lateral capacity.

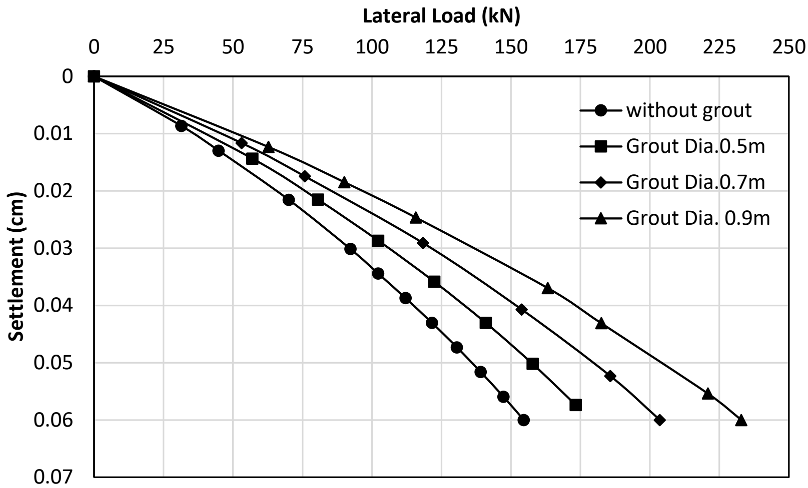


Figure 10: Relation between loads and settlement for a single pile with varying grout diameters under lateral load and a fixed depth of 1 m.

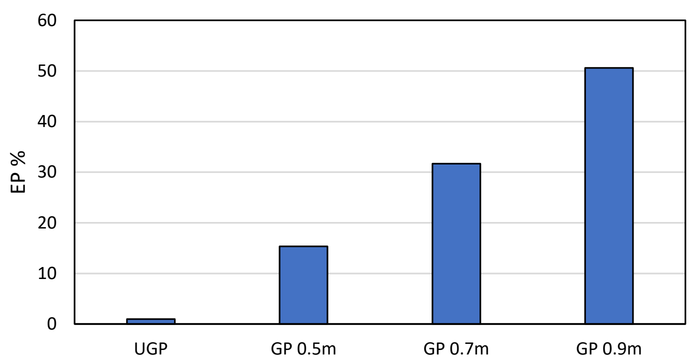


Figure 11: Enhancement Percentage of the single pile with different grout diameters under lateral load and a fixed depth of 1 m.

3.4.2 Effect of Grout Depth on Single Pile

Figure 12 depicts the outcomes of using grout material at different depths of (0.5, 1, and 2) m with a constant diameter of 0.5 m. According to the findings, the pile system's lateral load-carrying capability increased by 12% when compared to an un-grouted pile. Moreover, the ultimate load-bearing capacity of the pile system increased by 3% and 6% when the grout diameter increased from 0.5 m to 1 m and from 0.5 m to 2 m, respectively. The observation of this increase in the load-carrying capacity can be attributable to the grout material's capacity for filling soil voids and strengthen the soil-pile interface, enhancing the piling system's efficiency in the process. The increasing in the grout diameter results in a higher volume of grout material injected into the soil, treating a larger area of soil, leading to a better soil-pile interaction and a subsequent the load-carrying capacity increased.

The enhancement percentage of the ultimate vertical load of the grouted single pile with different diameters is reveal in Figure 13. It indicates that at a fixed grout depth of 0.5 meters, the enhancement percentage ranges between 12.5%, 16%, and 20% at a depth of 1 meter. These results suggest that grouting is an effective method for enhancing the performance of pile systems, particularly in soft soil conditions. The findings highlight the potential of grouting as a viable technique for increasing the load-carrying capacity of pile systems. Figure 14 reveals image from the numerical analysis shows the settlement of pile under different conditions.

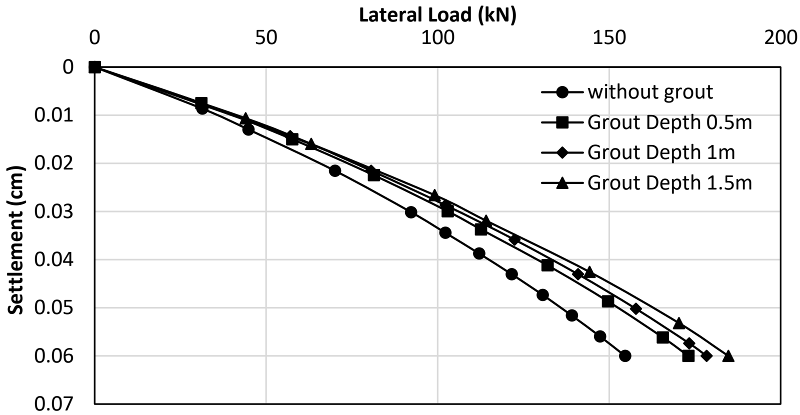


Figure 12: Relation between loads and settlement for a single pile with varying depths of grout under lateral load and a fixed diameter of 0.5 m.

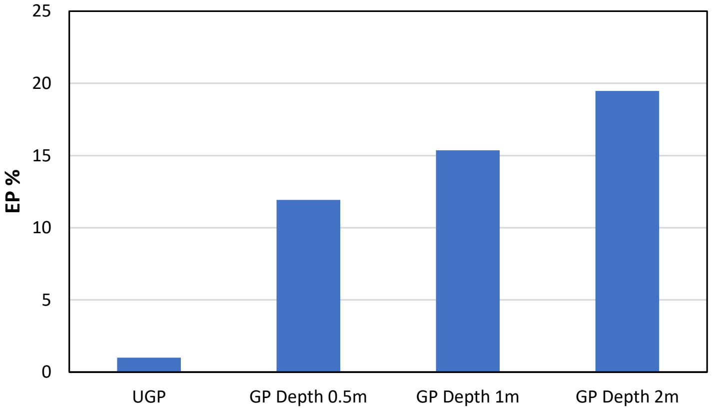
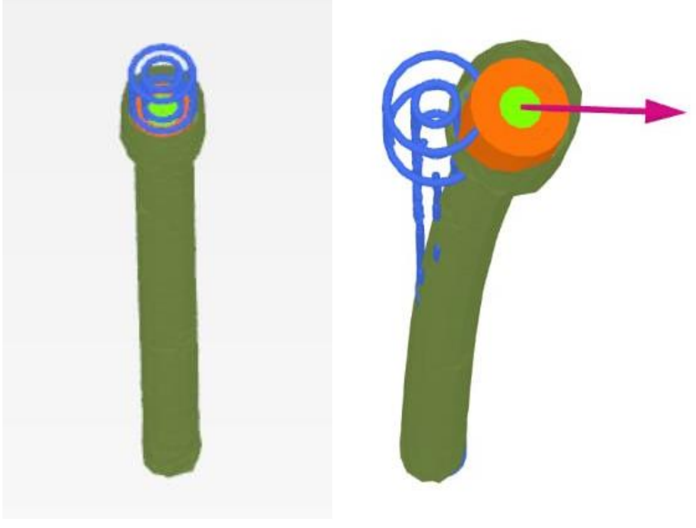


Figure 13: Enhancement percentage of the single pile with different depths of grout under lateral load and a fixed diameter of 0.5 m.



(a) (b)

Figure 14: The displacement of pile under different conditions (a) vertical load, (b) lateral load.

4. CONCLUSIONS

- Depending on the diameter and depth of the grout employed, grouting can increase the ultimate load-carrying capacity of a single pile under vertical stress by up to 27% and under lateral load by up to 51%.
- The improved soil-pile interaction is attributable to the grout's ability to fill cavities in the soil and reinforce the soil-pile interface, resulting in better soil-pile contact.
- Increasing the diameter and depth of grout results in a greater treated soil area and as a result, a higher load-carrying capacity.
- The improvement in load response owing to the use of grout material in the pile system appears to have a linear connection, which meaning that as the amount of grout material used grows, so does the capacity of load-carrying of the pile system.
- Grouting is an efficient way for improving the pile system performance, particularly in soft soil conditions.

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