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ORIGINAL

Numerical investigation of bearing capacity and lateral response of pile group considering soil interaction

Investigación numérica de la capacidad de carga y la respuesta lateral de un grupo de pilotes considerando la interacción con el suelo

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ABSTRACT

Introduction: piles play a crucial role in major structures like power plants, petrochemical complexes, offshore platforms, and bridges. Ensuring their safe and cost-effective design under lateral dynamic loads is essential. Due to the complexity of soil-pile interaction and the influence of multiple factors, further research is required.
Objective: the main objective of this research is to investigate the parameters affecting the interaction of soil and reinforced concrete pile groups.
Method: the parameters discussed and investigated in this research include the use of UHPC concrete with different strengths instead of conventional concrete in piles, pile length, pile diameter, pile length-to-diameter ratio, and pile spacing.
Results: the results of this research show that if the diameter of the pile is 0,6 meters, increasing the length from 9,15 to 11,65 meters and from 9,15 to 14,15 meters will increase the bearing capacity of the pile by 53 % and 77 %, respectively. In cases where the pile length is 9,15 meters, increasing the diameter from 0,6 to 1 meter results in a 58 % increase in bearing capacity. Additionally, reducing the distance between piles from 1,8 meters to 0,8 meters enhances their bearing capacity by 37 %.
Conclusions: the findings indicate that pile dimensions and spacing significantly influence their bearing capacity. Using larger pile diameters, increasing pile length, and optimizing pile spacing can effectively enhance structural performance under dynamic lateral loads.

Keywords: Bearing Capacity; Lateral Response; Pile Group; Soil Interaction, GFRP.

RESUMEN

Introducción: los pilotes desempeñan un papel crucial en estructuras importantes como plantas de energía, complejos petroquímicos, plataformas marinas y puentes. Garantizar un diseño seguro y rentable bajo cargas dinámicas laterales es fundamental. Debido a la complejidad de la interacción suelo-pilote y la influencia de múltiples factores, se requiere una investigación más profunda.
Objetivo: el principal objetivo de esta investigación es analizar los parámetros que afectan la interacción entre el suelo y los grupos de pilotes de hormigón armado.
Método: los parámetros analizados en esta investigación incluyen el uso de hormigón UHPC con diferentes resistencias en lugar de hormigón convencional en pilotes, la longitud del pilote, el diámetro del pilote, la

relación longitud-diámetro del pilote y el espaciamiento entre pilotes.
Resultados: los resultados de esta investigación muestran que, si el diámetro del pilote es de 0,6 metros, aumentar su longitud de 9,15 a 11,65 metros y de 9,15 a 14,15 metros incrementará la capacidad portante del pilote en un 53 % y 77 %, respectivamente. En los casos en que la longitud del pilote sea de 9,15 metros, aumentar el diámetro de 0,6 a 1 metro resulta en un incremento del 58 % en la capacidad portante. Además, reducir la distancia entre pilotes de 1,8 metros a 0,8 metros mejora su capacidad portante en un 37 %.
Conclusiones: los hallazgos indican que las dimensiones y el espaciamiento de los pilotes influyen significativamente en su capacidad portante. El uso de diámetros de pilote más grandes, el aumento de la longitud del pilote y la optimización del espaciamiento entre pilotes pueden mejorar eficazmente el rendimiento estructural bajo cargas dinámicas laterales.

Palabras clave: Capacidad de Carga; Respuesta Lateral; Grupo de Pilotes; Interacción Con el Suelo; GFRP.

INTRODUCTION

Pile foundations are long cylindrical or sectioned pieces of high-resistance material, such as concrete, that provide a solid base for the building that rests upon them.(1,2) If you have a hand in the process of construction or excavation, you know well that a construction pile, by being placed inside the soil as the foundation of structures, performs an important task in transferring the load of the upper floors to more suitable layers of soil at lower depths.(3,4) In reality, the pile is the same column that is inserted into the soil and transmits the burdens to the structure at the soil's depth, where they are then transferred to the more resistant soil.(5) Considering this importance, in this article, we are going to know the types of piles, especially the concrete type, and provide you with comprehensive information in this field.(6,7)

A pile is essentially a long cylindrical form or parts made of other high-strength materials, such as concrete, that are pushed into the ground or rammed into the ground to support a building.(8) In fact, it can be argued that piled foundations act as a foundation for a wall or column, so that their support is on the piles below. It should be noted that the piles may be implemented singly or in groups under the foundations, and in general, piles implemented with piles have the ability to bear more loads than normal foundations (surface foundations).(9,10)

In general, piling operation is a process that is carried out during the lack of bearing capacity of the soil and in order to strengthen the building and prevent settlement.(11,12) In the piling operation, the applied force is transferred to the lower levels of the soil, which has higher density and strength.(13,14,15) In fact, this method is one of the ways to stabilize the pit. In this regard, it is necessary to know that there are various reasons that the soil surface layer may not have a high capacity to withstand the incoming forces and transfer it to the lower surface of the soil. Therefore, it is recommended to use common soil improvement methods.(16) In the piling method, the excess force is transferred to the subsoil surface. In such a situation, because the lower surfaces have higher resistance, they show better performance against the existing forces, and the possibility of settlement will decrease in them. In the foundation of soil retaining structures, the role of soil is to bear lateral forces, it can bear horizontal forces in addition to vertical forces.(17,18) With the increase of migration to cities, urban construction is increasing rapidly. In such a case, if the development of cities is done horizontally, there will be no room left for development in a short period. In this case, if cities want to grow and develop, vertical development will be the key to solving the problem.(19)

Tall buildings accommodate more people in less space. Tall buildings consume less surface space and therefore more land for the development of infrastructure such as parking lots, gardens, etc. The facility will be provided. High-rise buildings need deep, resistant foundations that ensure their stability. In urban areas with high density of buildings, digging deep basements for high-rise buildings, especially approximately other heavy buildings, causes problems related to excavation. In this case, there will be a need for special foundations such as piles, walls made with concrete mortar, wall bracing and excavation under the adjacent buildings. If there is an underground water level in the excavation site, water pumping will be required. In addition, the water level will decrease, which will cause the surrounding buildings to settle. All these are just a few of the problems and issues that may occur during the construction of civil projects.(20) Examining these issues is done in a branch of civil engineering called geotechnical engineering. Geotechnical engineering is a subset of civil engineering in the field of issues related to the use and investigation of the behavior of soil and earth materials.(21,22) This branch of engineering consists of two general sections: soil mechanics and foundation engineering.(11) In fact, foundation engineering includes the application of the principles of soil mechanics in the design of the foundation of structures and buildings in contact with the soil.(23)

Literature review

In a research conducted by Pour Jafar et al. in 2016,[22] they investigated the behavior of long and short piles with a retaining head under dynamic load. In this research, short and long piles with variable distances from each other were examined. And experiments were done with small scaled models in the laboratory.[24] The results demonstrated that the lateral bearing capacity of the pile group increases as the distance between the piles increases from one to four times the width of the pile; additionally, the group effect is greater for long piles than for short piles, and the connection between the pile heads was determined to be fixed.[1]

Bakhtiari and colleagues in 2015[22] investigated the behavior of group piles against the lateral force of an earthquake by considering the geometric characteristics of the piles. Due to the nature of the presence of piles in the transfer of large loads, it is common to use piles as a group. A significant challenge in studying the ultimate load capacity of multiple piles subjected to lateral pressure and managing the displacement of the pile head in relation to the intricate interaction between semi-rigid piles and elastoplastic soil is a matter of paramount importance in the field known as geotechnics. This article investigates the behavior of group piles by considering the geometrical characteristics of the piles. The modeling of the article was investigated with Abacus software in three different phases, with changes in the length of the piles and the distances between the piles and comparison. Significant results were obtained between the three-modeled samples. According to the results, raising the pile weight is significantly affected by increasing the length of the piles and the distance between them. In conclusion, this study's findings support the idea that pile geometrical modifications significantly impact load and displacement behavior and quantity.[2]

In a research conducted by Mr. Vakili and colleagues in 2015,[22] the reliability of piles under the dynamic force of an earthquake was investigated. Considering the importance of the reliability of vertical piles under the dynamic force of the earthquake, it has been tried in this research to accurately simulate the soil and the pile by using the powerful Plexis software. The nonlinear behavior of the model materials in this software is under the effect of the dynamic force of the earthquake, and the soil parameters were introduced to the model by the test samples. Finally, after analyzing the axial and lateral displacement diagrams of the pile, it can be used for the accurate design of the piles under the effect of the dynamic force of the earthquake. Designed high reliability in seismic areas.[3]

In another article conducted by Shush Pasha et al. in 2014,[22] they investigated the determination of pile bearing capacity using static and dynamic methods, including modified ENR. In geotechnical engineering, the capacity of piles is an essential design consideration. There are varieties of static and dynamic procedures, as well as direct and indirect methods, to calculate pile-bearing capacity. The soil's condition, the pile's kind, and the availability of relevant data determine which approach is most appropriate. This study looks at the ability of driven piles to support soil loads. In order to do this, data from 208 driven piles spread over four locations covering 1500 square meters was collected. With this data, we were able to compare the outcomes of static relationships for pile carrying capacity in fine-grained soil with those of dynamic relationships. In comparison to static approaches, this study's results demonstrate that the method, INR, modified INR, and new modified INR are quite accurate.[4]

In another research, it was done by Mr. Ghaffari and his colleagues in 2013,[22] they investigated the static, seismic and modal analysis of individual piles and pile groups. Several factors influence the seismic behavior of piles, and in this research, the influence of factors including: pile diameter, diagonal pile inclination angle, ratio of the distance between piles to the diameter of the piles has been investigated. The study of the analyzed results shows that in single pile models vertical with increasing pile diameter and in diagonal single pile models also with increasing pile deviation angle in static and dynamic states, the values of force and effective bending moment of the wall decrease. The pile group with a ratio of 3 is the most suited in both static and dynamic modes, according to investigations conducted with piles of 3, 4, and 5 diameters to the distance between them.[5]

In a research conducted by Mohammad Ali Roshan and his colleagues in 2009,[22] they investigated the efficiency of the pile group in static and seismic composite loading. This paper uses three-dimensional finite difference analysis in Flek software to explore the impact of lateral loading and anchoring on the axial bearing capacity of piles in sandy soil.

The investigation follows three-dimensional modeling of the soil and pile (figures 1 and 2). As a result, it has been found that the performance of lateral load and anchorage not only does not result in the loss of axial load efficiency, but also can significantly improve the axial load efficiency. In addition, the effect of different parameters, such as different combinations of loading, spacing of piles on the efficiency of the group has been investigated.[6]

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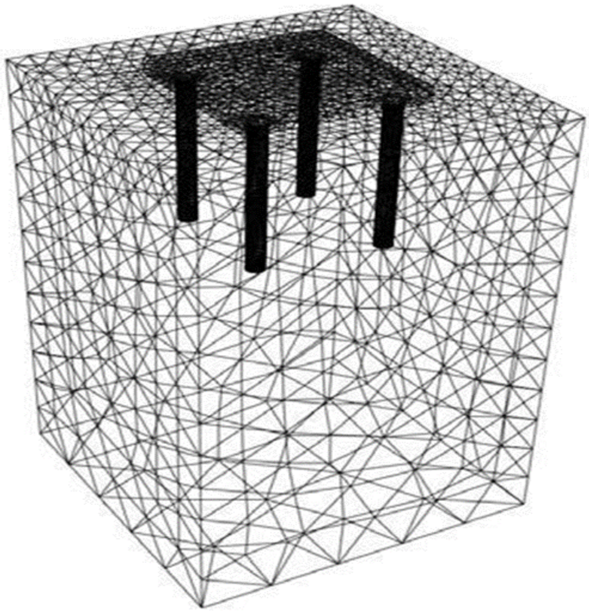

Figure 1. 3D modeling of soil and pile group

In a research conducted by Mr. Alilou and his colleagues in Tabriz University in 2009,[22] they investigated the shear strains of the soil around vertical and inclined piles under lateral loading. It is in sandy soil that the influence of the pile being inclined and under tension or pressure in determining the length of long piles and its effect on the shear strains created around the pile have been investigated and compared. The pile in this article a steel type was used and it was 40 cm long, and in the relevant experiments, 30 cm of the pile was buried in the soil. The angle of inclination of the inclined pile is checked for six situations. Upon conducting the tests and analyzing the results, it was noted that the bearing capacity of inclined piles exceeds that of vertical piles, and the bearing capacity of negatively inclined piles surpasses that of positively inclined piles. The findings indicated that the influence of the pile deviation angle surpasses that of the pile being subjected to pressure or tension. It was also observed that as the pile becomes more inclined, with the application of lateral load, the pile is subjected to more axial force, because of which more shear stress is created. It is buried at a lower depth, and the amount of these shear strains is higher for positively inclined piles than for negatively inclined piles.[7]

In a study carried out by Lee Zhan Ho and colleagues in 2017,[22] utilizing Abaqus software, they examined the lateral load induced by liquefaction on the pile group situated behind the wall soil. The primary objective of examining the behavior of a pile group during lateral earthquakes induced by liquefaction and wet soil is to assess the pressure exerted on individual piles within the group. The test findings are exhibited and analyzed. Notable pile group effect seen by contrasting the consistent bending moments of individual piles within the group. The Abaqus model has been employed to assess the saturated soil pressure on individual piles within a pile group, with both uniform and triangular soil pressures calibrated according to the uniform moment bending of the piles. The saturated soil pressure on the pile adjacent to the wall is about double that of the pile distant from the wall. The saturated soil pressure on a single pile within a pile group is subsequently compared to the results of a vibration test conducted on a pile. A parametric research has been undertaken to examine the influence of column rotation stiffness and pile diameter on the outcome. The conclusive statements derived from the results are provided.[8]

In 2014, Haldar et al.[22] investigated the response of piles under earthquake loading with the help of Flek software. The effects of soil, pile, and earthquake parameters on the bending and buckling failure mechanisms have been investigated. The obtained results show that the pile response is significantly affected by the soil density and the characteristics of the earthquake.[10]

In 2014, Dal Hallman and colleagues[22] conducted a research on the behavior of group and network seismic behavior of micro piles. The experiments that were conducted on a large scale in this project have shown the relative advantage of using a group of small piles as well as their usefulness in the stability of slopes. In this research, a parameter was defined to compare the group of vertical and inclined piles based on the total length of the pile in the group and the measured bending under the applied load, and it was concluded that in lateral loading, the group of inclined piles is seven times more effective than Small piles are vertical. Also, the performance of the micro pile network is strongly influenced by the arrangement and angle of the piles.[9]

In 2013, Cheng et al.[22] investigated the stability of earthen slopes in an article with the aim of finding the most probable sliding surface, which corresponds to finding a surface with the minimum confidence factor. In this research, the modified Bishop's method was used for the analysis of earthen slopes. The obtained results show that it can easily analyze and optimize different soil slopes (homogeneous, heterogeneous, water-leaking slopes, dam slopes, etc.) with high accuracy.[11]

In an article of 2010, Han et al.[22] addressed the effect of micro piles in improving the stability of slopes. For this purpose, by changing the installation angle and the number of micro piles, the effect of the arrangement of micro piles on the seismic performance was investigated have presented an analytical method for the design of micro piles under tension and pressure. In their article, to investigate the load-displacement behavior of such micro piles, an analytical modeling example has been performed in which the soil-pile interaction is considered. This model has calculated the distribution of strains under the micro piles and how the load is transferred, and finally they came to the conclusion that the value of the network coefficient increases with the increase in the number of micro piles used to reinforce and stabilize the slope.[12]

Adahikari et al.[22] investigated the seismic performance of inclined piles in hard soils. In this research, the influence of the deviation angle on the performance of the piles was investigated when applying the Centro earthquake record. These studies have shown that the range of deformation in the group of inclined piles is smaller than that of vertical piles, and the deviation from the vertical direction causes the lateral displacement to be smaller. And haste becomes a candle in the head.[13]

Research carried out in the field of pile group behavior under axial and transverse loading is typically categorized into two groups: Laboratory methods encompass both full-scale and small-scale testing, such as numerical studies and model tests. In the design phases of deep foundations, full-scale experiments are one of the primary components used to verify the performance of the pile system and verify the design parameters that were obtained from local studies. However, they are utilized less frequently because of their exorbitant expenses. Consequently, numerical studies, centrifuge experiments, and model simulations yield a wealth of information regarding the behavior of the pile group. Obviously, these experiments are unable to accurately represent the behavior of the pile due to the fact that they are unable to accurately simulate the actual state of stress in the soil, particularly the stresses that are generated during the pile's construction.[14] In the past, numerous investigations have been conducted to investigate the axial or lateral behavior of piles in relation to the number of piles in a group, the load distribution among group piles, the lateral displacement of the group, and the influence of pile distances. According to Kim and Branger's full-scale experiments, the load-bearing capacity increased by 5,1 to 2 times in the largest distance for two groups with distances of 9,0-2,1.[15]

Wellins et al. in 2005[22] continued the pile tests in sand and obtained the results that the front rows of the group carry more load than the rear rows, which is contrary to the elastic theory which states that the load and anchor in all Pile are distributed in the same row regardless of position.[15,16,17] Rollins found during experiments in granular soil that reducing the distance between piles reduces the lateral resistance. Rista and Tunsand in 1997[22] observed that during lateral loading in sand, the outer piles carry more load than the middle piles.[18]

During centrifuge tests conducted by McVay et al. in 1994 and Brown in 1998,[22] it was found that the load-bearing capacity of a pile group increases as the spacing between piles increases.[19,20] In centrifuge tests performed in dense sand, Kotasso et al. [1994] observed that the front row of piles carries a load comparable to that of a single pile, while the second and third rows carry similar but lower loads.[18,20,25] Similar results were reported by Ias (2004) in tests conducted in sands of varying densities. Additionally, Komodromos (2004), using numerical methods, stated that the efficiency coefficient of a pile group depends on pile spacing, with efficiency increasing as the spacing between piles increases.[22] Kartigian (2005) also indicated that composite loading results in greater displacements within the pile group. Axial loading significantly influences lateral behavior, which varies depending on whether the pile is rigid or flexible and its position within the group. In that study, the efficiency of the pile group under combined axial and lateral loading, as well as anchorage, was examined using a 3D finite difference analysis.[23]

In another research conducted by Chan Heuli et al. in 2017,[22] he presents the results of the seismic table test on a pile of piles behind an earthen retaining wall. The main topic examines the behavior of this type of piles under the secondary expansion caused by settlement and the pressure of the saturated soil that is imposed on one pile from other piles. The results of the tests are presented and discussed. The important effect of group piles is investigated in the instantaneous comparison of the uniform bending of a single pile in piles. In this regard, an object to measure the saturated soil pressure is placed on each pile, where both the constant and uniform soil pressure and its triangular pressure are calculated based on the uniform bending at every moment of the column. The pressure of the saturated soil near the retaining wall is almost twice the amount that is applied to the pile from the wall. Then, the saturated soil pressure on a single pile in the group of piles is compared with that obtained from the vibration test on one pile. In addition, a parametric study has been conducted to investigate the effect of bending strength and pile diameter in the group reaction of piles. Finally, the final statements are presented based on the obtained results.[24,26]

In another study, Shahir et al. in 2016,[22] explored the numerical modeling of pile-soil interaction in liquefied conditions using the nonlinear spring method. This research employed dynamic correlation analysis of the soil-pile-structure interaction to examine pile behavior in a liquefied environment. The p-y dynamic nonlinear spring method was utilized to model pile-soil interaction.[27] Following the validation of the numerical model, a parametric analysis was conducted to assess the impact of various parameters on the dynamic response of the pile and the lateral pressure exerted on it. The investigated parameters included the thickness of the liquefied layer, the input excitation frequency, the pile head restraint, pile stiffness, maximum input acceleration, and the relative density of the liquefied soil. The results indicated that the lateral pressure on the pile remained nearly constant throughout the depth of the liquefied layer, with approximately 7–10 % of the total overburden pressure concentrated at the base of the liquefied layer.

By reviewing previous research on the loading and load-carrying capacity of piles subjected to lateral loads, it is evident that various factors play a significant role. Among these factors, the use of pile groups, pile dimensions, and the spacing between piles are noteworthy. However, the most critical aspect highlighted in the literature is the influence of soil on the bearing capacity of both individual and grouped piles, as well as the impact of soil-pile interaction on lateral and vertical deformations. With this understanding, the next section will explore the effects of soil-pile interaction on pile behavior under different influencing factors.[27,28,29,30]

The purpose of the research

According to past research, the main goal of this research is to investigate the effective parameters on the interaction of soil and reinforced concrete pile group. The parameters discussed in this research include the use of UHPC concrete with different strengths instead of concrete with normal strength in piles, pile length, pile diameter, length to pile diameter ratio, pile distance from each other. GFRP reinforcement, CFRP cover, steel cover, cement-improved soil.

Basic Assumptions

The characteristics of pile and soil group in this research are shown in the figure below.

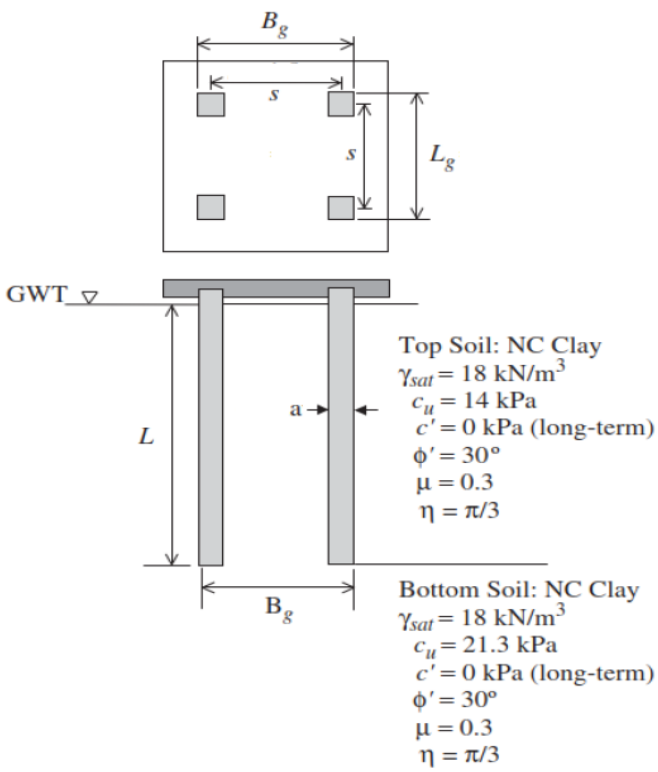

Figure 2. The initial assumption for the pile group

METHOD

This research examines the impact of utilizing UHPC concrete with varying strengths in lieu of normal-strength concrete in relation to piles, including factors such as pile length, pile diameter, length-to-diameter ratio, and spacing between piles, GFRP reinforcement, CFRP cover, steel coating, and cement-enhanced soil. The specifications of the numerical models for each group are shown next.

RESULTS AND DISCUSSION

Effect of using UHPC concrete with different strengths

This group will utilize UHPC concrete with strengths of 140, 160, and 200 MPa. Concrete with strengths of 30 and 50 MPa will be utilized for standard applications. The specifications of the numerical models in this group are presented in table 1.

Table 1. Specifications of numerical models of group 1

Group	Model	Concrete & fc' (MPa)	L (m)	D (m)	L/D	S (m)
1	NC30 (Reff.)	Normal Concrete & 30	9,15	0,6	15,3	1,8
	NC50	Normal Concrete & 50	9,15	0,6	15,3	1,8
	UHPC140	UHPC & 140	9,15	0,6	15,3	1,8
	UHPC160	UHPC & 160	9,15	0,6	15,3	1,8
	UHPC200	UHPC & 200	9,15	0,6	15,3	1,8

After the numerical modeling of the pile force-displacement diagram for the first group, it is shown in the figure 3.

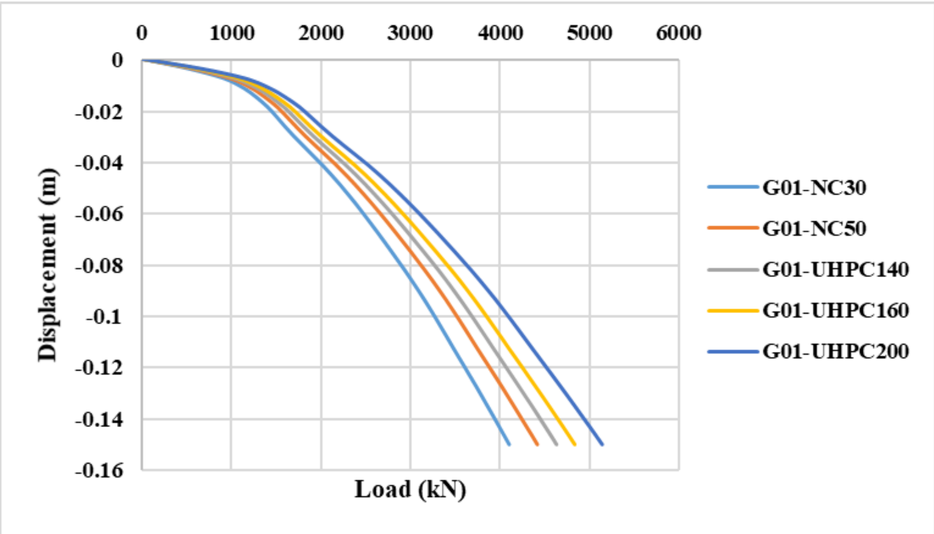

Figure 3. Load-displacement diagram for numerical models of the first group

A higher pile capacity is a direct result of the rise in concrete strength, as seen in figure 3. Figure 4 shows a comparison of the maximum pile capacity values for the first set of numerical models.

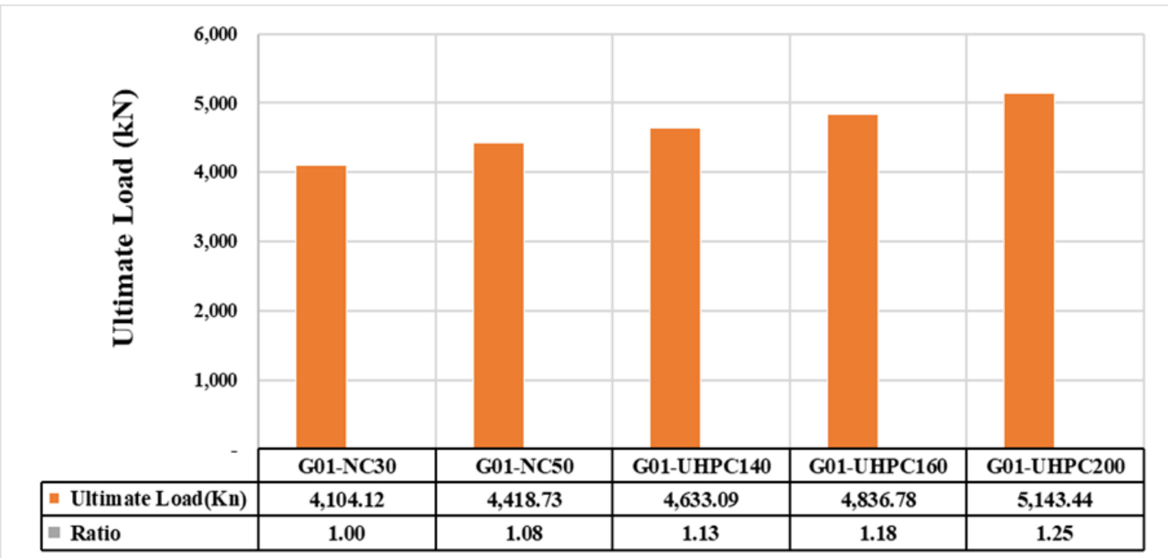

Figure 4. Diagram of the maximum pile capacity in the first group

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Increasing the concrete strength from 30 to 50 MPa has resulted in an 8 % increase in the maximum pile capacity, as is shown. There has been a 25 % increase in the maximum pile capacity due to the increase in concrete strength from 30 to 200 MPa. This suggests that raising the concrete strength of the pile has a positive effect on raising the pile's maximum capacity.

Effect of length, diameter, and ratio of length to the diameter of the reinforced concrete pile

In this group, three different lengths and three different diameters will be used for reinforced concrete piles. In addition, the ratio of length to diameter of reinforced concrete piles is also evaluated. The specifications of the numerical models of this group are shown in the table 2.

Table 2. Specifications of numerical models of group 2

Group	Model	Concrete & fc' (MPa)	L (m)	D (m)	L/D	S (m)
	L9.15D0.6 (Reff.)	Normal Concrete & 30	9,15	0,6	15,25	1,8
	L9.15D0.8	Normal Concrete & 30	9,15	0,8	11,4375	1,8
	L9.15D1	Normal Concrete & 30	9,15	1	9,15	1,8
	L11.65D0.6	Normal Concrete & 30	11,65	0,6	19,41667	1,8
2	L11.65D0.8	Normal Concrete & 30	11,65	0,8	14,5625	1,8
	L11.65D1	Normal Concrete & 30	11,65	1	11,65	1,8
	L14.15D0.6	Normal Concrete & 30	14,15	0,6	23,58333	1,8
	L14.15D0.8	Normal Concrete & 30	14,15	0,8	17,6875	1,8
	L14.15D1	Normal Concrete & 30	14,15	1	14,15	1,8

After performing numerical modeling in the second group, the load-displacement diagram for the second group has been discussed. In the figure 5, the load-displacement diagram for the models of the second group is compared.

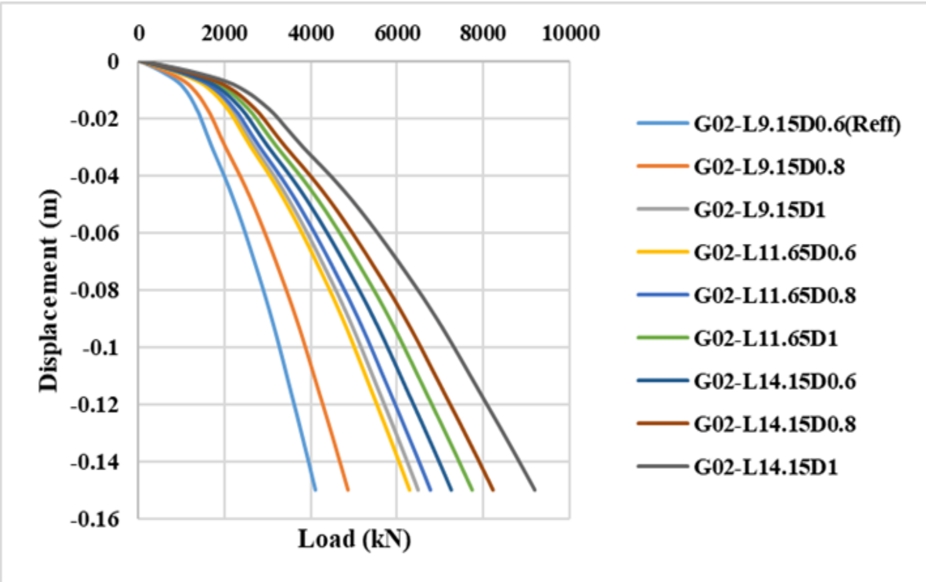

Figure 5. Load-displacement diagram of numerical models of the second group

As can be seen, with the increase in the length of the pile, the capacity of the pile also increases, and with the increase in the diameter of the pile, the laterality of the pile increases. Figure 6 shows the diagram of maximum resistance for numerical examples of the second group.

According to figure 6, in piles with a length of 9,15 meters, with the increase of the pile diameter from 0,6 to 1 meter, the capacity of the pile increases by 58 %. Also, by increasing the length of the pile from 9,15 to 14,15 meters and in the case where the diameter of the pile is 0,6, the capacity of the pile increases by 77 %. In addition, according to figure 6, the pile whose length is 14,15 meters and whose diameter is one meter, has the most capacity and is 2,24 times the reference numerical model.

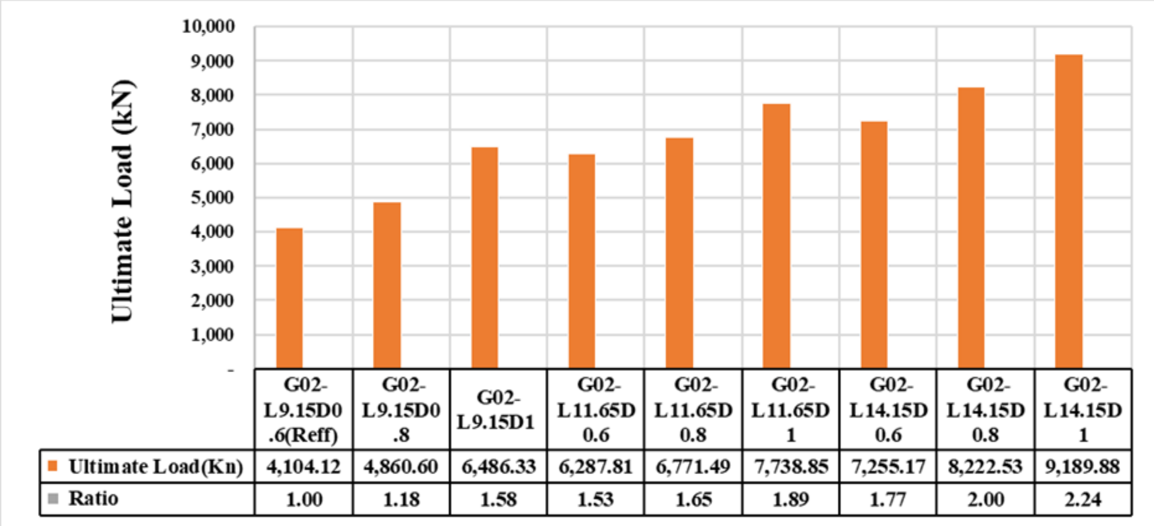

Figure 6. Diagram of the maximum bearing capacity of piles for the second group

The effect of the distance between the piles

In this group, three different distances for pile are considered and evaluated. The specifications of the numerical models of this group are shown in the table 3.

Table 3. Specifications of numerical models of group 3

Group	Model	Concrete & fc' (MPa)	L (m)	D (m)	L/D	S (m)
3	S1.8 (Reff)	Normal Concrete & 30	9,15	0,6	15,25	1,8
	S0.8	Normal Concrete & 30	9,15	0,6	15,25	0,8
	S2.8	Normal Concrete & 30	9,15	0,6	15,25	2,8

Figure 7 shows the load-displacement diagram for the numerical models of the third group.

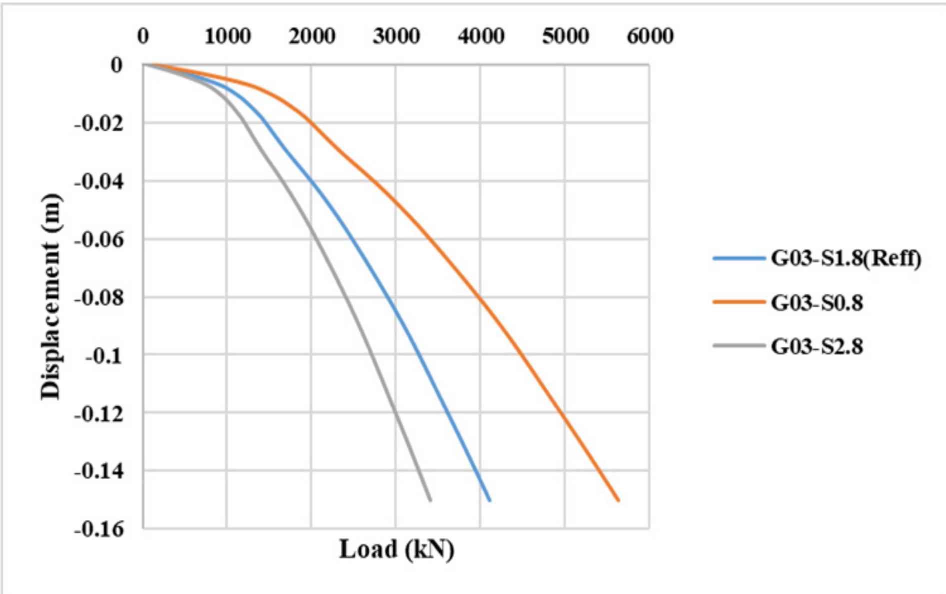

Figure 7. Load-displacement diagram for numerical models of the third group

Based on figure 7, the numerical model with a pile spacing of approximately 0,8 meters exhibits the most favorable load-displacement behavior, while the model with a pile spacing of 2,8 meters demonstrates the poorest performance compared to the reference numerical sample. Figure 8 shows the maximum force for each model in the third group is compared.

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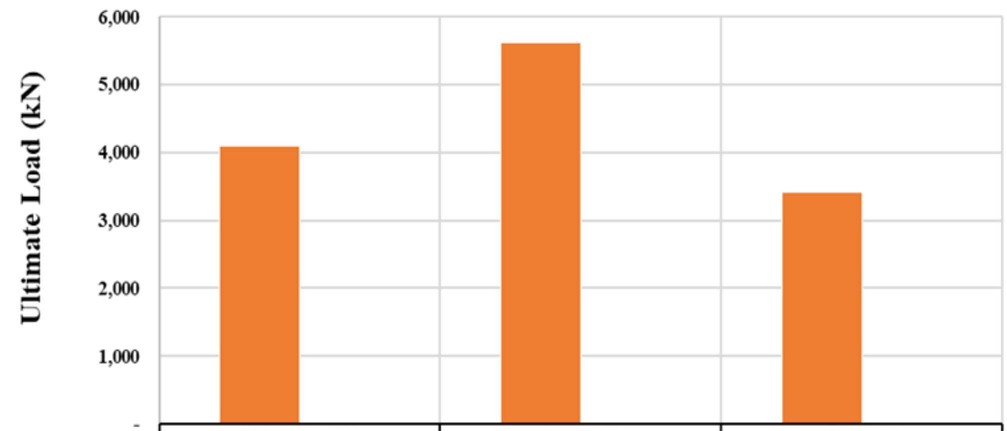

	G03-S1.8(Reff)	G03-S0.8	G03-S2.8
Ultimate Load(Kn)	4,104.12	5,622.64	3,406.42
Ratio	1.00	1.37	0.83

Figure 8. Maximum force in numerical models of the third group.

As shown in figure 8, increasing the pile distance from 1,8 to 2,8 has caused a 17 % decrease in pile capacity, while decreasing the pile distance has caused a 37 % increase in pile capacity.

CONCLUSIONS

After the validation process, numerical models of the piles were analyzed, and the results of this research can be summarized as follows:

1. Increasing the concrete strength from 30 to 50 MPa increases the pile's bearing capacity by 8 %.
2. Increasing the concrete strength from 30 to 140, from 30 to 160, and from 30 to 200 MPa increases the pile's bearing capacity by 13 %, 18 %, and 25 %, respectively.
3. Increasing the pile length enhances its bearing capacity. For example, for a pile diameter of 0,6 meters, increasing the length from 9,15 to 11,65 meters and from 9,15 to 14,15 meters increases the pile's bearing capacity by 53 % and 77 %, respectively.
4. Increasing the pile diameter improves its bearing capacity. For instance, when the pile length is 9,15 meters, increasing the diameter from 0,6 to 1 meter results in a 58 % increase in bearing capacity.
5. Reducing the distance between piles from 1,8 meters to 0,8 meters increases the bearing capacity by 37 %.
6. Increasing the distance between piles from 1,8 meters to 2.8 meters decreases the bearing capacity by 17 %.

LIST OF SYMBOLS

fc' – Compressive strength
UHPC – Ultra high performance concrete
CFRP – Carbon fiber reinforcement concrete
GFRP – Glass fiber reinforcement concrete
L – Pile Length
D – Pile Diameter
S – Pile Spacing

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