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Parametric Numerical Study on the Impact of Intenal Friction Angle and Pile Diameter on Soil Deformation in Nasiriyah

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Abstract

Clarifying the behavior of the soil near the bored pile foundation tips through estimating the boundary of the influence has a great benefit theoretically and practically in the accurate design of pile foundations. This research presents an advanced geotechnical analysis of the piles in Nasiriyah soil applied to the foundation of the Al-Iskan Interchange project. The study employed finite element analysis, utilizing the Plaxis3d Foundation software to systematically investigate the impact of variations in internal friction angles and pile diameters on soil deformations. Through a parametric study, the research sheds light on the intricate relationship between these key parameters and the behavior of the soil. The findings reveal compelling insights: deformations exhibit a discernible pattern in response to internal friction angle and pile diameter alterations. Specifically, deformations demonstrate a diminishing trend with an increasing internal friction angle, while a contrasting escalation is observed with larger pile diameters. This nuanced understanding highlights the importance of selecting the depth to which the pile is driven. The depth refers to the soil with optimal values for internal friction angles and pile diameters in engineering projects, with direct implications for enhancing stability and minimizing deformation.

Keywords: *Geotechnical Analysis, Finite Element Analysis, Plaxis3dFoundation Software, Internal Friction Angle, Pile Diameter.*

1. Introduction

Foundations are the essential and vital elements that constitute the base or support of a particular structure [1]. Foundations are used to bear and distribute loads evenly, aiding in the stability and balance of the system or structure [2]. They are considered fundamental to maintaining the continuity and organization of various systems, whether they are engineering, social, or even mental [3]. They form the bedrock, both literally and metaphorically, upon which the edifice of any construction rests. In this intricate case between the terrestrial and the man-made, understanding the principles and significance of foundations becomes paramount [4]. Within the scope of our advanced study on the impact of foundations on the Al-Hawraa Project, it becomes evident that piles play a crucial role in this context [5]. These engineering elements are key components responsible for transferring and directing the loads generated by the bridge towards the underlying soil. Our analysis specifically addresses the role of piles in this context, highlighting their significant effect on vertical and horizontal deformations in the surrounding soil [6] [7]. Through our prominent study, we observe how piles interact with variations in the internal friction angle and pile diameter. It becomes apparent that the technology of load redirection and distribution employed by piles significantly contributes to reducing pressure on the soil, thereby improving the stability of the building [8] [9]. In this context, piles are not only a means of load transfer but also a primary tool for enhancing the stability of the surrounding soil [10] [11]. In recent years, the Finite Element Analysis (FEA) was an analytical engineering method used to study complex structural interactions and estimate stresses and deformations in intricate structures. FEA divides the structure into smaller units called elements, where the behavior of each element is analyzed individually, and the results are then combined to form a comprehensive representation of the entire structure. Plaxis3dFoundation is a finite element software specifically crafted for geotechnical engineering analysis [12]. It provides sophisticated capabilities for modeling intricate soil-structure interaction challenges, encompassing scenarios like pile rafts and footings. Additionally, Plaxis3dFoundation offers specialized geotechnical functionalities, including the modeling of soil behavior, consideration of pile-soil-raft interaction, and the simulation of foundation load responses [13]. This study addresses a problem in soil-structure interaction, focusing specifically on the Al-Hawraa Project. The challenge revolves around understanding the impact of variations in internal friction angle and pile diameter on deformations and stresses in the surrounding soil.

Lina Xu (el.) [14] conducted a study on the impact of increasing the diameter of the foundation at a specific depth. The study revealed that soil areas were less affected by external loads distributed over the region, especially in areas where an increase in the

foundation diameter occurred. The study showed that increasing the foundation diameter at a specific depth contributes to reducing the effect of distributed external loads on the surrounding areas. This work bears some resemblance to the study conducted in this paper, where the impact of diameter and internal friction angle is investigated. The study explores how these factors influence the depths and areas of soil that are affected and distorted due to external loads.

Milad and Vahid [15] conducted a comprehensive study on the influence of soil parameters, including excavation depth, soil column weight, and pile diameter. Through meticulous investigation and finite element analysis using the Plaxis2d software, the results revealed that both excavation depth and soil unit weight exhibit varying degrees of effectiveness compared to other parameters. Notably, pile diameter emerged as a critical factor, showcasing that alterations in its dimensions lead to significant changes in the areas of soil affected by external loads.

The aim of this study is to illustrate how foundation design can be enhanced to ensure the stability of the Al-Hawraa Project amidst these variations. The impact of piles will be analyzed using finite element analysis techniques, with a focus on improving the understanding of soil-structure interactions. The purpose of this study can be summarized in the following points:1. Examine the impact of variations in the internal friction angle on deformations in the soil surrounding the Al-Hawraa Project 2. Analyze how pile diameter influences the stresses resulting from applied loads. 3. Investigate the interaction of piles with the surrounding soil and estimate its effects on the overall stability of the structure. 4. Improve the understanding of fundamental interactions between piles and soil to enhance foundation design. 5. Provide practical recommendations for enhancing the stability of the Al-Hawraa Project based on the results obtained from the analysis.

2. The Study Area

This study focuses on the soil in Nasiriya applied to Al-Iskan Interchange Project, the southern region of Iraq (Figure 1). Nestled within the historical landscape of Mesopotamia, Nasiriyah holds a significant position both geographically and culturally. Nasiriyah is situated by providing coordinates. The Tigris River flows nearby, influencing the city's landscape and contributing to its historical importance. The city's topography is characterized by describing any notable geographical features [14]. The study relied on the analysis of data obtained from Al-Iskan Interchange Project, as illustrated in Figure 2. The figure depicts the approved project location, which served as the primary source of information for this research.

Fig. 1: Geographical Documentation of Nasiriyah City's Location on the Map of Iraq.

Fig. 2: Geographic Analysis of Al-Iskan Interchange Project

3. Developing the Theoretical Framework

In this context, the theoretical framework explores the relationship between changing the internal friction angle of the soil and the development of vertical and horizontal deformations in the soil in the presence of foundations with piles, along with the impact of altering the pile diameter on these deformations. Assumptions about the deformation shape around the end of a pile in sandy soil are based on engineering models and mechanical failure analysis. These

models rely on various hypotheses and equations to estimate soil behaviour under different loads. Some of the assumptions and models that can be used include:

3.1. Terzaghi Model:

This engineering model was developed by Terzaghi for evaluating the failure of the soil and for studying its behaviour in terms of loading. Terzaghi's Theory is based on the ideas of stress distribution in the layers of the soil under loading. In the Theory, it is argued that in soil failure, the stress derived from the load exceeds the stiffener strength of the soil. This failure can be prophesized through evaluating stresses and pressures in the soil layers taking into consideration information about the type of soil and loads likely to be applied to the soil layers. The Terzaghi Model employs specific failure criteria in order to plot results for soil failure such as the Mohr-Coulomb failure criterion [15]. With reference to this criterion, the shear strength of the soil is measured with respect to the consolidated stresses. Other theories might have different failure criteria or assumptions on the manner the soil fails [3]. For Terzaghi, deformations around the pile end are cone shaped [16], which drives into the soil from the pile as depicted in figure 3b.

3.2. Eslami and Fellenius Model

The Eslami & Fellenius Model is a model that is used in the area of soil engineering to determine and forecast failure of soils. This model uses simple mechanics of principles and stress-strain theory to analyze response of soil under loading as well as failure mode of soil. The originality of this model resides in the fact that it does not only assess structural loads but also calculated stresses and strains, thus estimating that a particular type of failure, vertical collapse, lateral slide or surface bend will occur in a specific soil. Other theories may give a general idea of the mode of failure of a soil without necessitating the expected failure modes. Eslami and Fellenius offered some recommendations in regard to the deformation shape which is present in the soil around the pile end as suggested in [5] and[17] and[18] present an oval deformation shape as depicted in Fig. 3(a).

3.3. Janbu's Model

Janbu's Theory is a geotechnical theory defined for the assessment of the stability and mechanical response of soil under loading conditions. This model was originally established by the Norwegian engineer Rolf Johan Janbu while he was working on the researches of geotechnical stability ad soil mechanics. Using Janbu's Theory, it is assumed that the soil mass acts like a continuous medium that can be modeled mechanically in the simplest form. It includes triangles for the soil by certain assumptions that were made (Figure 3c) [18].

3.4. Vesic's Model

Vesic's model is a geological model applied to determine the state and stress/deformation properties of the soil mass under load. It seeks to analyze the behavior of the soil and how it will deform depending on the loads to be imposed on it. Vesic's model has been derived with elastic and static principles with similar response of the soil to that of an elastic engineering material. This Theory employs mathematics, in particular differential equations to define deformations and stress in the soil under applied loads. Vesic shows that in response to loads, the deformation of the soil can be modeled by a cavity beneath the end of the pile as presented in fig 3d [19].

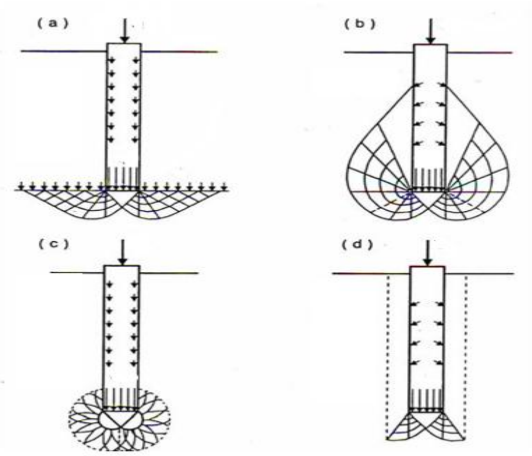


Fig. 3: Suggested soil deformation profile around the end of the pile a) Eslami & Fellenius model b) Terzaghi model c) Janbu's Model d) Vesic's Model

These moodles rely on assumptions, laboratory experiments, and field observations to apply them to soil behaviour. Typically, the deformation length is assumed to be greater at the upper end of the pile than at its lower end. This is attributed to the presence of frictional resistance force in addition to the end-bearing resistance. Consequently, this combination results in a larger deformation in the upper region of the pile's end. Advanced computer analysis and mathematical models are preferred for more accurate deformation estimations.

4. Methodology

This engineering study employs four distinct friction angles to analyze and comprehend their influence on the soil. Simultaneously, four varying diameters of piles are utilized to estimate and analyze the resulting deformations in the soil. Subsequently, the data is analysed using PlaxisFoundation3d V20, the finite element analysis software. The Mohr-Coulomb (MC) constitutive model has been chosen to characterize the soil's behaviour. The Modified (MC) model is a commonly used linear elastic model, offering a direct and clear approach to simulating soil behaviour. Another useful approximation for soil behaviour is a perfectly plastic model, particularly effective as an initial estimation. In a Plaxis3d program, conducting a mesh convergence study is essential for selecting the appropriate mesh size. The available built-in mesh options include Very Coarse, Coarse, Medium, Fine, and Very Fine, with each mesh consisting of elements. To assess the impact of mesh type on boundary condition bearing capacity values in stress concentration regions, the effect of each mesh type was investigated independently.

Three layers represent the site's soil profile, and the pile was tested at a depth of 25 meters. Table 1 provides a detailed presentation of each soil layer's geotechnical characteristics. A 1.5-meter-diameter bored pile that was 18 meters embedded below the earth surface was used in this investigation. Table 2 provides specifics on the pile's composition and mechanical characteristics.

Table 1: The parameters of the soil profile.

Depth (m)	0-4	4-8	8-11	11-13	13-50
Soil description	stiff clay	Sand	stiff clay	Medium stiff clay	Very stiff clay
Modulus of elasticity, Es (kN/m2)	55000	67200	65000	30000	100000
Poisson's ratio, ν	0.3	0.25	0.25	0.3	0.3
Cohesion, c (kN/m2)	-	1	-	-	-
Un drain shear strength (kN/m2)	110	-	130	60	200
Dry unit weight, γd (kN/m3)	16	20	18.5	18	18
Total unit weight, γt (kN/m3)	19.8	20	20	19.8	19

Table 2: Details of the concrete pile.

Identification	Value
Material model	Linear elastic
Modulus of elasticity, Ep (kN/m2)	25×106
Poisson's ratio	0.15
Type of material	Non-porous-concrete
Material density (kN/m3)	25

Various potential applications can be harnessed through the use of Plaxis3d software for calculating the ultimate bearing capacity of different soils and analyzing their impact on soil layers. In this study, soil bearing capacity was calculated using numerical analysis. The study revealed that Very Fine and Fine meshes provided more accurate results and were closer to the actual field values. Therefore, the choice of mesh size should balance accuracy and computational efficiency based on the specific needs of the analysis and available resources. This results in generating a numerical model (Figure 4) at node number 10935, centred within dimensions of 20×20 meters. The outcome of this analysis provides a refined and lucid representation of the impact and deformations. Two key components that make for proficient soil analysis are internal friction angle and diameter. Figure 5 illustrates the flow of scientific work in this study, clearly depicting the overall structure and key steps of the research process.

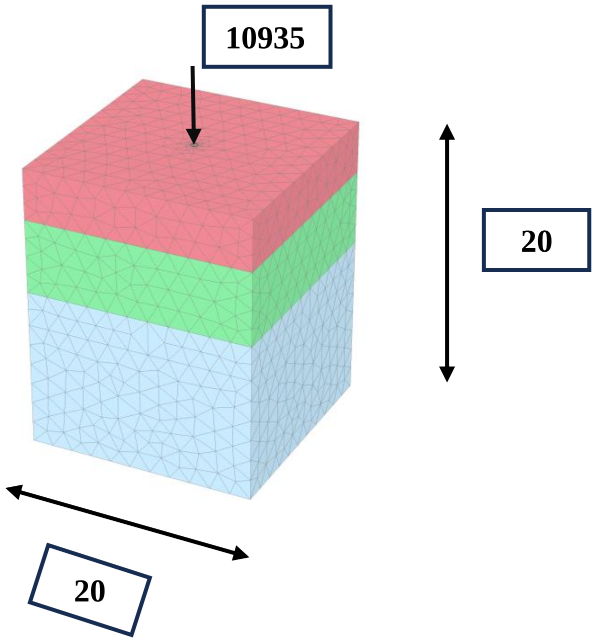


Fig. 4: The Soil General Mesh Model

In this study, the range of angle of soil friction consisting of four values (32, 38, 42, 50) are considered to observe deformations occurring during angle variations. The depths of these deformations, resulting from numerical analysis, are then determined and correlated with other findings in the study.

Similarly, the study adopts variations in the diameters of the foundation piles (0.3, 0.35, 0.4, 0.45) m and subjects them to numerical analysis processes. Subsequently, the changes in the soil layers beneath the pile are monitored. This includes observing alterations in the depths of vertical deformations and horizontal distortions on both sides of the foundation pile.

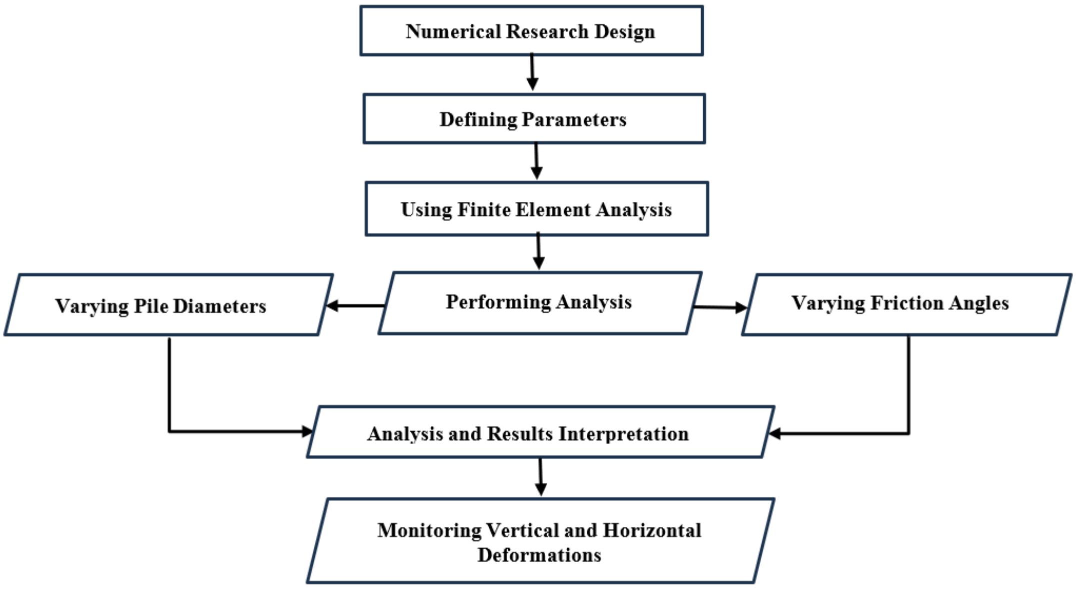


Fig. 5: Numerical Design Overview.

5. Results and Discussion

It is crucial to highlight the extent to which soil-bearing capacity is affected by applied loads and how this impacts soil behaviour, including the degree of deformation resulting from the stresses induced by these loads. The numerical analysis results demonstrated the soil-bearing capacity using the finite element method. The study revealed that Very Fine and Fine meshes provided more accurate results and were closer to the actual field values. However, it's noted that analyzing these finer meshes requires more time due to increased computational complexity (Table 3). Therefore, the choice of mesh size should balance accuracy and computational efficiency based on the specific needs of the analysis and available resources. The results indicated that the bearing capacity obtained from the numerical analysis closely matched the actual field values, as shown in Table 1. This outcome encouraged the utilization of the software's capabilities to analyze the impact of loads on soil layers and determine the depths affected.

Table 3: Comparison of results for various mesh size values.

Size of mesh	The actual Bearing Capacity (ton)	The Bearing Capacity resulting from numerical analysis (ton)	Total number of nodes	Analysis time (minutes)
Very coarse	450	437	2920	5
Coarse	450	440	9464	5
Medium	450	447	12051	10
Fine	450	449	16988	30-45
Very fine	450	450	26880	30-45

5.1. Effect of ϕ on the influence zone

The angle of internal friction (ϕ) refers to the angle between two surfaces inside the material, where the force parallel to these two surfaces is equivalent to the applied vertical force. When dealing with the sand soil, understanding the (ϕ) is important to determine its behaviour during loading. This parameter is used in the design of engineering foundations such as piles, as well as in understanding ground movement and geotechnical design [21].

Table 4 presents the result of four piles in soil, where the soil represents loose, medium, dense, and very dense cases, according to the selected angle of internal friction. It displays the numerical results obtained by finite element solution. The first column denotes the proposed soil type, and the second column specifies the friction angle at which it is chosen. Meanwhile, the third and fourth columns depict the depths of vertical deformations, and the fifth and sixth columns detail the outcomes of horizontal deformations in the soil resulting from applied loads. The numerical results confirmed that altering the friction angle significantly affects the depth of both vertical and horizontal deformations in the soil, as indicated in columns three and four. In the case of loose soil with a friction angle of 38o, the results showed vertical deformation depths at the upper and lower ends of the pile to be 7.9 and 2.0 m, respectively. Similarly, the results of columns five and six reveal horizontal deformations in the soil, 3.0 m in both directions. While the soil behaviour is evident in case four (Very Dense) with a friction angle of 50o, soils with this angle value may be like sand and gravel, where the value of the friction angle exceeds 45o with increasing gradation and cohesion of the material and the quality of the grains. Also, crushed stone, which gives a California bearing capacity of 100%, is considered a material with high density and excellent cohesion, and its internal friction angle may reach 50o, as illustrated in Table 4. The results showed vertical deformation depths at the upper and lower ends of the pile to be 4.3 and 2.0 m, respectively. Then, the results of columns five and six reveal horizontal deformations in the soil, 2 m in both directions.

Furthermore, the depths of vertical and horizontal deformations in the soil, influenced by external loads, are affected and must be considered. The first case, shown in Table 4, with a 38o angle, has the greatest vertical and horizontal influence depth compared to the other cases. Meanwhile, the results indicate that the depths of deformations in the fourth case with a 50o angle exhibit less vertical and horizontal deformation.

Table 4: Vertical and horizontal boundary of deformation for soil with different ϕ

	Soil Type	**Φ (degree)**	**Vertical Deformation**		**Horizontal Deformation**	
			Upper Limit (m)	**Lower Limit (m)**	**Right Limit (m)**	**Left Limit (m)**
1	Loose	32o	7.9	2.0	3.0	3.0
2	Medium	38o	7.8	1.95	3.2	3.2
3	Dense	42o	6.1	1.6	2.5	2.5
4	Very Dense	50o	4.3	1.3	2.0	2.0

Figure 6 (a) observes a reduction in vertical strain with increasing internal friction angle, which can be attributed to enhanced soil particle interlocking and shear resistance. Higher internal friction angles promote stronger particle interactions, thereby limiting the ability of soil to undergo significant vertical compression or settlement. These findings have implications for soil engineering practices, emphasizing the importance of considering internal friction angle in design and analysis to predict soil behaviour and deformation more accurately.

Based on the available information, we can examine the equation. The relationship between vertical deformations (upper and lower limits) in soil and the internal friction angle (Figure 6a) can be expressed mathematically using the following equations:

$$U = 0.1516 \tan(\Phi) \tag{1}$$

$$L = 0.04 \tan(\Phi) \tag{2}$$

Where:

U: upper limits, L: lower limits, Φ: friction angle

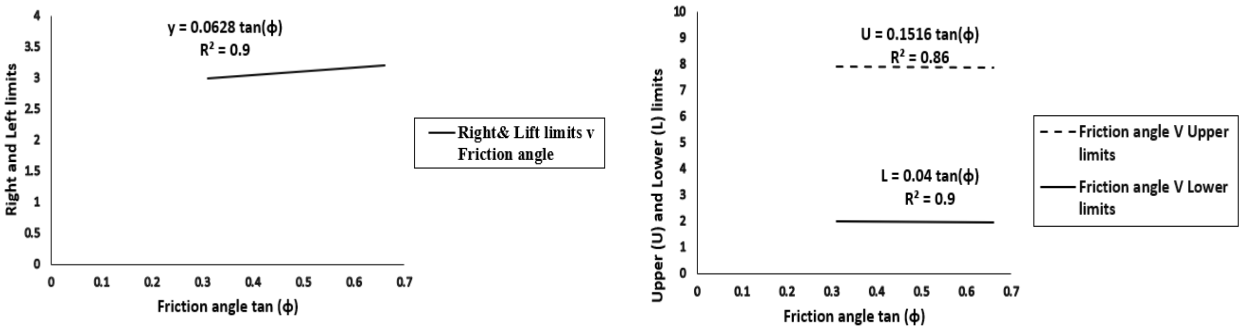
Figure 6b illustrates the relationship between the friction angle (Φ) and horizontal deformations on both sides of a foundation. The findings suggest that the changes in deformations are minor or barely noticeable, leading to the proposal of an equation to understand this relationship better. The results revealed an equation that relates the friction angle (Φ) to the horizontal deformations of the soil:

$$Y = 0.0628 \tan(\Phi) \tag{3}$$

where:

y= right and left limits, ϕ: friction angle

This equation provides insights into how changes in the friction angle impact horizontal deformations.



a

b

Fig. 6: Failure envelope plot with friction angle. a: upper and lower limits V friction angle b: right and left V friction angle

At the same time, the deformations of soil were accurately described by presenting a shown in Figure 7 (a, b, c, d) generated from the numerical analysis. Regarding Figure 7a, the deformation states are explained comprehensively and precisely. The vertical deformation depth at the upper and lower ends of the pile is evident, in addition to horizontal deformations in both directions.

Significant deformations in both vertical and horizontal directions are evident at the ends of the foundation pile. The analysis emphasizes the areas of soil affected by the applied loads, as depicted in Figure 7a. In the figure, red lines indicate the impact on the soil near the end of the foundation pile due to the applied loads. These lines progress from the closest to the farthest away from the pile, demonstrating changes in the depth and extent of deformations in the soil. The progression of lines can be described as follows:

1. The line closest to the pile tip represents the most heavily impacted zone by the applied loads, resulting in deep vertical and horizontal deformations within the soil.
2. The subsequent line represents a slightly less affected area than the first line, showing a reduction in the depth of vertical and horizontal deformations.
3. Further away from the pile, the gradient of lines towards the last line shows a gradual decrease in the impact on the soil. Each line represents an area of decreasing influence on the soil's deformation.
4. The last line, farthest from the end of the pile, represents the least affected area of the soil, with a significant reduction in the extent of vertical and horizontal deformations caused by the applied loads.

This analysis provides valuable insights into how the applied loads affect the soil at different distances from the pile foundation, highlighting variations in deformation depths and impacts across the soil profile.

In Figure 7b, a similar mechanism is observed in depicting the area subjected to stress due to applied loads, employing a comparable approach. The line closest to the pile tip represents the region most susceptible to stresses compared to the farthest and last line, which signifies the least impacted area. This interpretation follows a consistent pattern where the line nearest to the pile tip denotes the most stress-affected zone, gradually diminishing as it moves towards the line farthest from the pile's end. The decreasing order of impact is evident, with the final line indicating the least affected area. Afterwards, we move to the final Figure 7d, illustrating how deformations have decreased and contracted compared to Figure 7a, with an increase in the internal friction angle of the soil. This alteration resulted in reduced vertical deformations compared to the previous cases, while it is observed that the vertical deformation remains unaffected by this change. The diminishing values of the internal friction angle correlate with decreased depths of vertical deformations, showcasing a discernible impact on the overall deformation behaviour.

With this explanation, one can understand how the depth of deformations in the soil gradually decreases with increasing distance from the end of the foundation pile, with the greatest impact in the nearest zone and decreasing gradually in the farther regions. Consequently, the relationship between the internal friction angle and the depth of the influence zone of soil is demonstrated. The consequences analysis emphasized that with an increase in the internal friction angle of the soil, the soil becomes less affected to the applied loads. Consequently, the depth of soil deformation decreases (Figure 7).

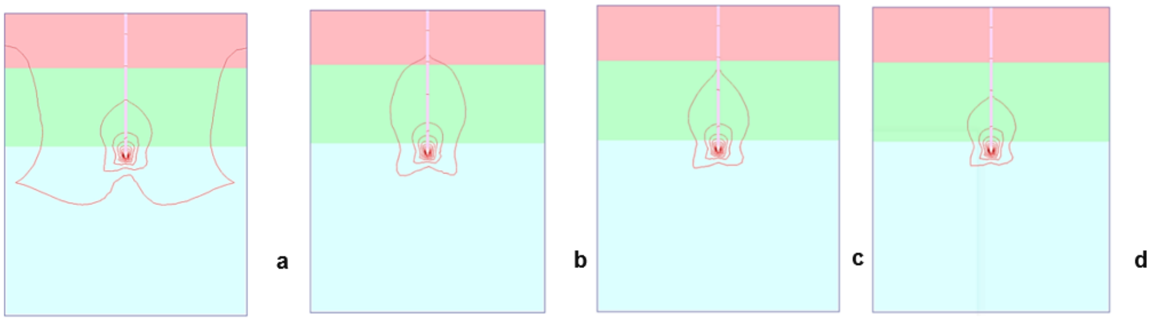


Fig. 7: Depth of soil deformation for a: loose, b: medium, c: dense, and d: very dense

5.2. Pile diameter effect

The impact of the pile diameter on the soil depends on many factors. One of these factors is the distribution of pressure, where an increase in the footing diameter reduces pressure on the soil, thus affecting its ability to bear loads. The footing diameter can also influence the stability of the foundation, contributing to increased stability in the soil. In some cases, an increased footing diameter may lead to a greater transfer of pressure to the lateral walls of the soil, affecting the geologic structure of the soil in the surrounding area.

At the same time, this part discussed researching the influence of various diameters of piles on the deformation leading to the soil. The values of vertical and horizontal deformations in the picked points in the soil are shown in table 5 for different diameter (0.3, 0.35, 0.4, 0.45 m) of a single pile as per numerical analysis. Another important study was performed by researcher Surendra Patel et al. [22] where the effects of internal friction angle of soil and pile length-to-diameter ratio on the soil bearing capacity were investigated. The results showed an increase in the value of the internal friction angle of the soil increases the modulus of elasticity and, hence, the load-bearing capacity of the soil, thus decreasing both the vertical and horizontal movements of the soil. However, the study of the load-displacement behaviour of piles revealed that an increase in the length-diameter ratio is favourable to the load-carrying capacity of the soil and, consequently, the depth of the observed deformation. These conclusions show that the internal friction angle and the geometry of piles are decisive in improving the stability and deformability of the soil under loads.

Table 5 has five columns, which are explained as follows: the first column shows the recommended diameters for this work and is the basis for the investigations done for this study. The third and fourth columns display the degree of vertical displacement in the soil, and the fourth and fifth columns represent the degree of lateral movement in the soil. As presented in Table 5, there is a significant difference when using a diameter of 0.3m, with the vertical deformation above the pile reaching 6.25m and that below the pile reaching 1.55m. The results of deformations at a diameter of 0.35 m were slightly different from the previous findings. Table 5 illustrates that the depths of deformations above and below the pile were 6.35 and 1.56 m, respectively. This indicates an increase in the depth of vertical deformation in the soil, which is in line with the increase in diameter.

Similarly, for both diameters (0.4, 0.45) m, the numerical analysis results yielded depths of vertical deformations above and below the pile. For a diameter of 0.4 m, the values were (6.45, 1.6) m, and for a diameter of 0.45 m, the values were (6.55, 1.6) m. This indicates an increase in the depth of vertical deformation in the soil, corresponding to the increase in the diameter of the pile. In the same manner, Table 5 illustrates the numerical analysis results for vertical deformations on both sides of the pile, corresponding to columns four and five. Presented scientifically and precisely, these values reveal the vertical deformation depths for the specified conditions. The results of the last two columns indicate that horizontal deformations did not show a significant impact. For instance, with a diameter of 0.3 m, the value of horizontal deformation was 2.5 m on both the left and right sides of the pile.

Similarly, both diameters, 0.35 m and 0.4 m, yielded identical results. Finally, for a diameter of 0.45 m, the horizontal deformation value was 2.6 m, showing a slight difference from the previous results that is considered negligible. In the case of horizontal deformations, the deformations occurring on both sides of the pile were symmetrical in all scenarios with different diameters. They remained consistent and unaffected by the variation in the diameter. Finally, the last two columns in Table 5 explain the complete vertical range and horizontal range of the impact boundaries.

Table 5: Presents numerical results for deformation depths using varying diameters

	Diameter of pile (m)	Vertical Deformation		Horizontal Deformation		Effective length in vertical direction (m)	Effective length in horizontal direction (m)
		Upper Limit (m)	Lower Limit (m)	Right Limit (m)	Left Limit (m)		
1	0.30	6.25	1.55	2.5	2.5	7.8	5
2	0.35	6.35	1.56	2.5	2.5	7.91	5
3	0.40	6.45	1.6	2.5	2.5	8.05	5
4	0.45	6.55	1.65	2.6	2.6	8.2	5.2

Figure 8 illustrates and demonstrates the relationship between the diameter of the column and the depth of deformations affecting the soil in both vertical and horizontal directions. Figure 8a shows the vertical deformations above and below the column, where the study results indicate an increase in soil deformation with an increase in column diameter. Consequently, it is possible to infer an equation representing the increase in deformations with increasing diameter, with a constant value for the equation. The equation is as follows:

$$U= 16.739\ D \tag{4}$$

$$L= 4.1626\ D \tag{5}$$

Where:
U: upper limits, L: lower limits, D: diameter of pile

Previous researchers have conducted numerous studies to define the zone of soil affected by applied loads, highlighting the significance of this topic. Due to the significance of load-bearing capacity in soil, extensive scientific effort has been dedicated to estimating the degree and the size of the influenced area. Meyerhof (1956) [23] proposed a hypothesis about the relationship between the effective depth of soil supported by a pile and the pile diameter, with clear reluctance to add. Depending on the type of soil, the area of the effective depth in which piles can be fully utilized is likely to be limited to (1-2) times the diameter of the pile where the soil is sandy; but maybe (3-5) times the diameter of the pile for clayey sub-surface materials. This relationship confirms that the pile diameter is equally essential for assessing the degree of soil deformation and ranking the depth of influence in cohesive and granular soils. Paul and Simons, in their work presented in 2005, put forward a hypothesis on clay soils asserting that distances influenced by loads exhibit greater extent than granular soils. That is why they noted that the affected depth could increase up to (3-4) times the pile diameter due to the softer and more compressible nature of clay soils. This increased depth is due to the relatively low bearing capacity of clay soils as they resist the applied loads, leading to a wider influence zone of the pile. On the other hand, Bowles (1996) [24] proposed that the depth of soil affected by loads for soils with high bearing capacity generally extends to about 1.5 to 3 times the foundation width. This range reflects the depth of significant stress distribution, especially in strong, load-bearing soils.

Figure 8b illustrates the relationship between the diameter (D) and horizontal deformations on both sides of a foundation. The findings suggest that the changes in deformations are minor or barely noticeable, leading to the derivation of an equation to better understand this relationship. The results revealed an equation that relates the diameter (D) to the horizontal deformations of the soil:

$$y = 6.251\ D \tag{6}$$

where:
y= right and left limits, D= diameter of pile

This revised statement provides a clearer and more scientific explanation of the relationship depicted in the figures, highlighting the findings of the study regarding soil deformations concerning column diameter variations.

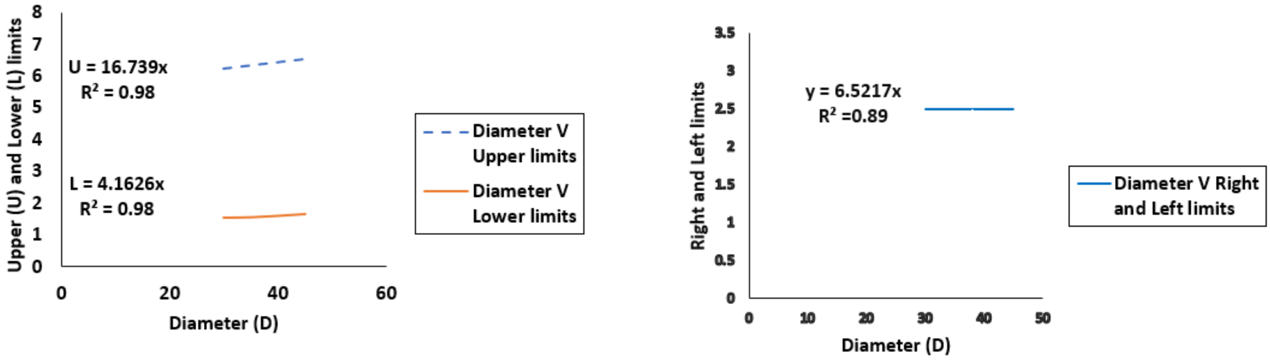


Fig. 8: Failure envelope plot with diameter. a: Upper and lower limits V diameter b: right and left limits V diameter

Figures 9 (a, b, c, d) illustrate the vertical and horizontal deformations of the soil resulting from numerical analysis. These figures provide a clear depiction of the deformation depths, showcasing the outcomes of the numerical analysis in a scientific, precise, and effective manner. Figure 9a illustrates the vertical and horizontal deformations in the soil influenced by external loads, as previously explained. The red lines indicate the gradients of the areas affected by stresses. Figures 9b, 9c, and 9d depict the gradient of soil area influence based on changes in diameter. Through the analysis of the generated figures, it is evident that with an increase in pile diameter, the impact on the soil intensifies, consequently leading to an increase in the vertical depth of surrounding deformation. On the other hand, it is observed that the horizontal deformation on either side of the foundation remains unaffected by this change. This description is provided in a scientific, accurate, and effective manner. Clearly and precisely, Figure 9 demonstrates that vertical deformations increase with the diameter while horizontal deformations remain largely unaffected.

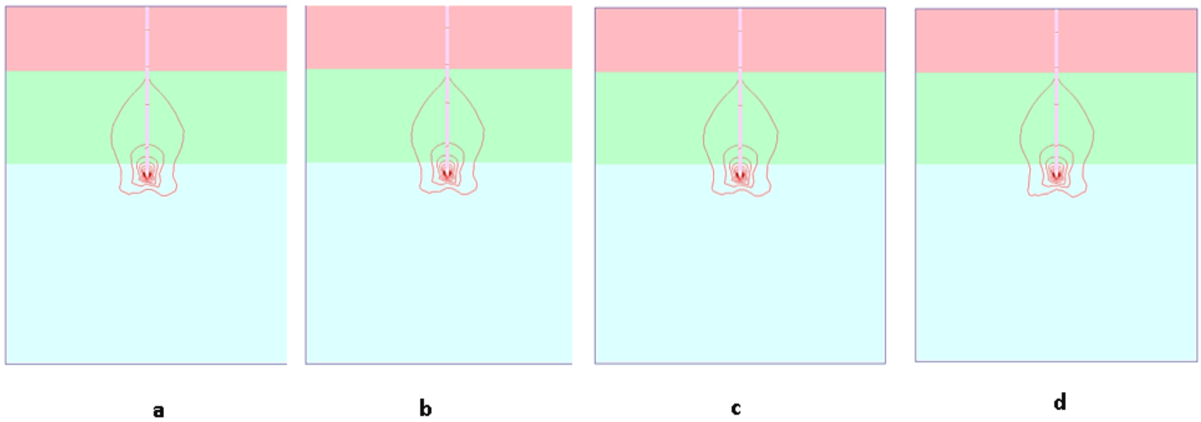


Fig. 9: Depth of soil deformation for piles with different diameters a: D= 0.3, b: D= 0.35, c: D= 0.4, and d: D=0.4.

Based on the comprehensive scientific findings presented, we can determine the nature and extent of influence exerted by both the friction angle and pile diameter on soil behaviour, particularly in shaping and determining the depths of deformations. Increasing the friction angle (φ) has a mitigating effect on soil deformations, reducing their magnitude. Conversely, enlarging the pile diameter augments the depth of deformations observed within the soil subjected to external loads. These observations prompt inquiries into the specific types of influence exerted by these factors, their impacts on soil morphology, and the feasibility of deriving mathematical equations to describe these relationships. Additionally, it raises the question of whether it's possible to identify and integrate various influencing factors—such as length, diameter, and soil properties, into a unified model or equation.

6. Conclusions

In this study, both the diameter and the angle of internal friction were changed to study the changes that occur in soil deformations due to induced stresses. Modern modelling techniques (Plaxis3d) were used, and the results were presented in a detailed and comprehensive manner. The results of this study were as follows:

The friction angle (ϕ) represents soil characteristics that influence its ability to resist deformations caused by external loads. Installing the piles in soil with a high friction angle enhances the foundation stability and reduces deformations. Higher ϕ values improve the soil's capacity to withstand pressures without significant distortions.

The diameter of the pile directly affects the depth of deformations in the surrounding soil.

Increasing the pile diameter expands the area affected by deformations, thereby increasing the depth of deformations due to external pressures.

This conclusion emphasizes the importance of studying influencing factors on soil behaviour and the intricate interactions between them. It highlights the need for ongoing research and development in geotechnical engineering to enhance understanding and improve soil-related engineering practices.

References

[1] S. Subramanian, N., & Sankaran, "Structural Engineering: Concepts, Theory, and Practice," CRC Press, 2013.

[2] A. Smith, J. ،Johnson, "The Importance of Foundations in Structural Engineering," J. Struct. Eng., 2020.

[3] J. K. Thajeel, R. Adel, H. M. Ali, and R. R. Shakir, "Effect of the covariance matrix type on the CPT based soil stratification utilizing the Gaussian mixture model," J. Mech. Behav. Mater., vol. 31, no. 1, pp. 492–500, 2022, doi: 10.1515/jmbm-2022-0049.

[4] H. Yáñez-Godoy, A. Mokeddem, and S. M. Elachachi, "Influence of spatial variability of soil friction angle on sheet pile walls' structural behaviour," Georisk, vol. 11, no. 4, pp. 299–314, 2017, doi: 10.1080/17499518.2017.1297465.

[5] R. A. Fahad, "Evaluation of SPT Based Design Methods of Piles in Nasseriyah Soil," 2021.

[6] B. Turkel, J. E. Orozco-Herrera, L. G. Arboleda-Monsalve, B. Hyun Nam, and L. Jones, "Comparative Analysis of Pile Driving Numerical Modeling Approaches," no. October, pp. 484–495, 2021, doi: 10.1061/9780784483404.044.

[7] A. Ata, E. Badrawi, and M. Nabil, "Numerical analysis of unconnected piled raft with cushion," Ain Shams Eng. J., vol. 6, no. 2, pp. 421–428, 2015, doi: 10.1016/j.asej.2014.11.002.

[8] L. T. Hoang, K. X. Dao, X. Xiong, and T. Matsumoto, "Performance analysis of a jacked-in single pile and pile group in saturated clay ground," Soils Found., vol. 62, no. 1, p. 101094, 2022, doi: 10.1016/j.sandf.2021.101094.

[9] X. Z. & B. H. Meiqi Liu, Guirong Li, Kunming Wu, Yuheng Wang, "Model Testing Technique for Piles in Soft Rock Considering the Overlying Layers," Proc. 9th Int. Conf. Civ. Eng., vol. 327, pp. 401–408, 2022.

[10] R. R. S. Adel, "Evaluation of the Bearing Capacity of A Single Pile by Numerical Analysis and Various Methods," 4. Chinese J. Geotech. Eng., no. 1000–4548, pp. 1–17, 2021.

[11] F. F. Chimdesa et al., "Numerical analysis of pile group, piled raft, and footing using finite element software PLAXIS 2D and GEO5," Sci. Rep., vol. 13, no. 1, pp. 1–19, 2023, doi: 10.1038/s41598-023-42783-x.

[12] L. Xu, C. Qi, L. Niu, and X. Ding, "Effect of Expanded Body Diameter on the Soil Surrounding a Pile Based on the Half-Face Pile Model Test of Undisturbed Soil," Buildings, vol. 13, no. 4, 2023, doi: 10.3390/buildings13040951.

[13] M. Nakhaee, "Numerical and Genetic Study on Bending Moment of Bored Pile Wall Numerical and Genetic Study on Bending Moment of Bored Pile Wall Supporting Excavation in Clay," no. August, pp. 0–10, 2017.

[14] R. A. Fahad, R. R. Shakir, and H. M. Ali, "Evaluation on the SPT Based Design Approach for Shallow Foundations," E3S Web Conf., vol. 427, pp. 1–10, 2023, doi: 10.1051/e3sconf/202342701025.

[15] A. KRASIńSKI and M. Wiszniewski, "Static load test on instrumented pile - field data and numerical simulations," Stud. Geotech. Mech., vol. 39, no. 3, pp. 17–25, 2017, doi: 10.1515/sgem-2017-0026.

[16] Karl Terzaghi, "Géotechnique, vol. 13, no. 4, pp. 267–268, 1963, doi: 10.1680/geot.1963.13.4.267.

[17] Amel Benali, Ammar Nechnech, and Ali Bouafia, "Bored pile capacity by direct SPT Methods applied to 40 case histories," Int. Congr. Mater. Struct. Stab., vol. 5, no. November, pp. 118–122, 2013.

[18] B. M. Das, "Principles of Foundation Engineering," McGraw-Hill handbooks, pp. xvii, 595 p., 2002.

[19] A. S. Vesic, "Bearing Capacity of Deep Foundations in Sand," Highw. Res. Rec., vol. 39, pp. 112–153, 1963.

[20] W. H. Al-Soudani and B. S. Albusoda, "An Experimental Study on Bearing Capacity of Steel Open Ended Pipe Pile with Exterior Wings Under Compression Load," Geotech. Geol. Eng., vol. 39, no. 2, pp. 1299–1318, 2021, doi: 10.1007/s10706-020-01559-0.

[21] A. K. S. S. N. Jha, "Numerical Study of Laterally Loaded Piles in Soft Clay Overlying Dense Sand," Civ. Eng. J., vol. 4, no. 7, pp. 730–746, 2021.

[22] S. Patel, A. Pratap, S. Rathor, A. Solanki, and J. K. Sharma, "Response and Behaviour of Granular Pile in Layered Soil," 2024.

[23] Meyerhof, "Bearing capacity and settlement of pile foundations," J. Geotech. Eng., vol. 1023, pp. 195–228, 1976.

[24] J. E. Bowles, Foundation Analysis and Design International Fifth Edition. 1997.