



Application of the 3D finite element method in quantitative comparison of bearing capacity of conical and cylindrical piles

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Abstract: Piles are structural members made of wood, concrete, steel, or other materials that are used to transfer surface loads to lower levels in the soil. This transfer is done by distributing the load along the length of the pile body or by directly transferring the load to the lower layer through the pile tip, the first case being called a friction pile and the second being called a support pile. Usually, all piles transfer the load as a combination of body friction and tip resistance, except in cases where, for example, the pile penetrates very soft soil to reach a hard bed. By having data on the bearing capacity and settlement of the pile group as well as the individual piles used in each group, the following results can be obtained: in sandy soils, as the angle of internal friction of the soil increases, the bearing capacity of single tapered piles increases to a certain extent with increasing cone angle. For single cone piles placed in sand, with increasing the angle of internal friction of sandy soil, the frictional load of the piles has always increased and the bearing load has decreased, while at the optimal angle for the total load of cone piles, the percentage of increase in the body friction load is greater than the percentage of decrease in the bearing load. For single piles placed in sand, the optimal angle of taper is in the range. For the group of piles placed in sand, with increasing the angle of internal friction of the soil, the group with the highest taper angle performs the maximum load. The efficiency of a group of tapered piles placed in sand always decreases with increasing the angle of taper. The rate of decrease in the efficiency of a group of tapered piles in sand decreases with increasing the angle of internal friction of the sand. The settlement rate of the conical and cylindrical pile group in the sand is less than the rate considered by Vesic, which is evidence of the more conservative results of this study regarding the bearing capacity of the piles.

Keywords: Finite Element Method, Bearing Capacity, Conical and Cylindrical Piles.

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Introduction

A pile foundation is much more expensive than a strip foundation and almost more expensive than a wide foundation. In any case of foundation design, studies on the characteristics of the soil of the site are very important (Norouzian M. M. & Talebian, M. H., 2023). Based on these studies, it must be carefully decided whether piles are needed and if so, whether a larger number or a longer pile length is needed (Abbaszadeh, M. et al., 2015). The bearing capacity of a pile means the maximum load applied to the pile, under which the pile will settle to an acceptable extent. Considering the bearing capacity to a greater extent than the actual value may have caused severe damage to the structures or their total deterioration. On the other hand, considering it to a lesser

extent than the actual value causes the pile dimensions to be excessively large and makes it uneconomical (Wang et al., 2024; Sohrabi, 2024; b).

Bearing capacity depends not only on the mechanical properties of the soil and environmental conditions but also on its shape, dimensions, material, and execution method (Saba Sultan Qurraie & Nima Gheitarani, 2025). Obtaining a general relationship for calculating the bearing capacity of piles, even by considering a limited number of factors, leads to very complex differential equations that are not generally possible to solve and are only possible in some limited cases (Li, Lin, et al, 2017). However today, useful analytical methods such as the finite element method have led to an increase in the tendency towards numerical analysis methods. Of course, it should be noted that the results obtained

from finite element modeling or similar methods must be verified with laboratory results to be usable (Dizaji, A. A., et al., 2023).

Piles are usually used for the following purposes: Transferring the load of large structures into the underlying layers. (Vertical and lateral loads) Resistance to upward tensile force or overturning, e.g. for uniform foundations below the waterline or to hold bridge piers against overturning due to lateral loads such as wind. Compaction of soft, non-cohesive layers by a combination of displacements by the pile volume and vibratory pile movement (Yi et al., 2021). These types of piles may be later pulled out. Settlement control is when a strip or expanded foundation is laid on soil with a highly compatible layer beneath it (Aghazadeh Dizaji, 2017).

Stiffening of the soil beneath the foundation to control the system's vibration amplitude and natural frequency. As an additional safety factor for bridge piers or abutments. In offshore structures, loads above the waterline to the underlying soil. Sometimes used to control ground movements (e.g., landslides). Piles may fail under vertical and lateral loads. Buckling failure may also occur in long members (Wang et al., 2024).

Theoretical

A cast-in-place pile is formed by drilling a hole in the ground and filling it with concrete. This hole may be drilled in the form of a box or by driving a casing or wall pipe into the ground (Norouzian, M. M., & Sarabi, M. S., 2023). The wall pipe may be driven into the ground by a steel shaft; the steel shaft releases the wall pipe as it rises. Figure (1) shows some of the commonly used cast-in-place piles. It should be noted that these piles are generally of three types: (1) shell or wall, (2) shellless, and (3) columnar.

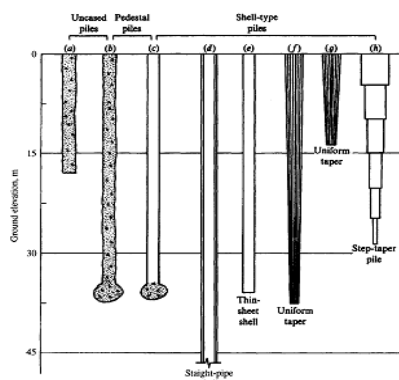


Figure (1), Geometry of Some In-situ Piles

In Figure (1), items (a) and (b) are shellless piles. Items (b) and (c) are columnar base piles that are up to 35 meters long. Piles (c) to (h) are shell types, among which (f) and (g) are conical piles, and (h) is a stepped conical pile. Variable cross-section piles have larger cross-sections at the head of the pile than at the tip.

One type of variable cross-section pile is a pile with a variable circular cross-section that is cone-shaped in appearance and is known as a conical pile (Figure 1 - items f and g). Conical piles have a fundamental advantage over cylindrical piles, which is that in the case of downward friction, the axial force of the pile decreases from the head to the tip (Norouzian, M. M., & Gheitarani, N., 2023). Then, in terms of cross-section, the smaller the cross-sections needed to transfer the structural load to the soil, the lower we go in the pile, which we see in conical piles. This

saves on the volume of materials and the correct distribution of materials in the pile (Dizaji, A. A. 2024; a; b).

Also, for piles under lateral load, when a lateral load is applied to the head of the pile, the amount of horizontal force in the structural body of the pile is reduced from the head of the pile to the tip of the pile due to the transfer of load to the soil (Basack et al., 2022; Mehdi Norouzian, M., & Gheitarani, N. 2024). This is consistent with the shape and volume of the materials and the size of the conical pile sections, which have a decreasing trend along the length of the pile, and in general, it can be said that conical piles have a more suitable distribution of materials for transferring various types of loads than cylindrical piles (Niloufar Akbarzadeh et al., 2016). For a foundation to be defined as a pile, the ratio of depth to average width or radius must be at least 6 (Mir et al., 2024).

According to this definition, the maximum angle that can be considered for a conical pile is 46.9° degrees. Most of the relationships that have been published for piles so far are related to cylindrical or prismatic piles, while for conical piles, no specific theoretical relationship has been presented that can determine their behavior in soil. However, in the last three decades, there has been an increase in interest in studying the behavior of conical piles (Aydin et al., 2020).

How to place piles in the ground. Piles are placed in the ground by several methods: Driving the pile into the ground by applying constant blows to the top of the pile using a pile hammer (Dizaji, A. A. et al., 2023). This method creates significant local noise and vibrations that may not be permitted by local codes or environmental agencies and may also cause damage to surrounding structures. Driving the pile into the ground using a vibrator attached to the pile head (Aghazadeh Dizaji, A. 2017). This method is usually quiet. This method is less applicable for driving in soils with poor cohesion (Mahmoud Zahiri et al., 2023).

Jacking the pile. This technique is more applicable for short, hard piles. Drilling a hole and placing the pile in it or, more commonly, filling the hole with concrete (Aydin, A. C. et al., 2020).

Pile Group with Vertical Loading. When several piles are grouped, it is reasonable to expect that the pressures generated in the soil due to lateral friction or bearing resistance will overlap, as shown in the figure below (MM Norouzian; N Gheitarani., 2025- a, b), (Figure 2)

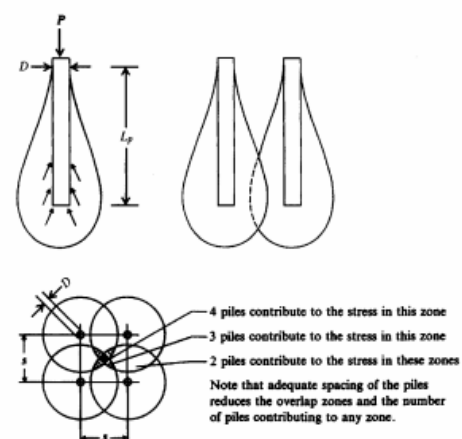


Figure 2. Stresses around a friction pile and the interference of stress ranges in a group.

The intensity of the additional pressure will depend on the pile load and their spacing, and if it becomes large enough, the soil will break in the shear, or we will have additional settlements (Fu et al., 2023). The intensity of the stress in the overlapping stress zones will decrease with increasing pile spacing (S). However, large spacings are often impractical. Usually, the head of the pile group is made integrally to support the columns of the structure and also to distribute the load on several piles over the heads of all the piles, this factor can cause the distance between the piles to be limited (Figure 3).

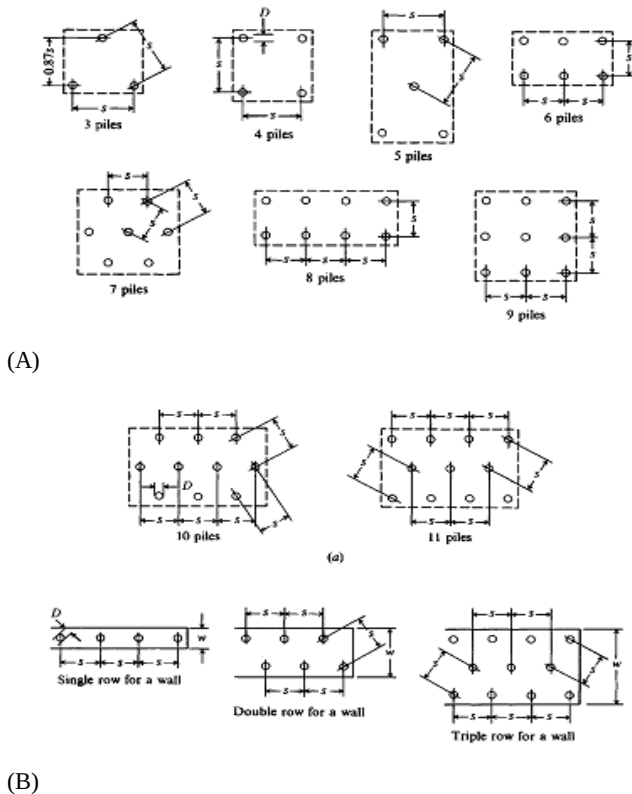


Figure (3), Conventional pile group patterns-(a) for single concrete slabs (b) for concrete walls

Given the lack of numerical studies and modeling by software for tapered piles and especially for tapered pile groups compared to laboratory experiments in this field, this research aims to model tapered and cylindrical pile groups using the three-dimensional software "PLAXIS" and finally compare and examine the results of the modeling using load-settlement diagrams (Saba Sultan Qurraie, 2024). Therefore, we change the characteristics of the pile group, namely the taper angle, the angle of internal friction of sandy soil, the coefficient of lateral soil pressure, and the angle of soil expansion in the group, and compare the models. It should be noted that for tapered piles, we increase the taper angle from zero to 1.6° in several steps. During the modeling stages, the length of all piles is constant, and the distance between piles is also optimally selected and remains constant in the pile group. The modeling is performed for a group of 4 piles (Dizaji, A. A., 2024-a, b).

After obtaining the force-settlement diagrams for each pile group, the total bearing capacity of each group is measured using several different and conventional techniques, and the pile group is analyzed again under the same force. Then, we take the results of the secondary analysis and perform a numerical integration on the

surface of the pile bottoms using a series of data related to the vertical effective stress and transfer them to the commercial software "Surfer 2009". To have the amount of bearing and frictional bearing capacity of the piles. In this way, we will have better comparisons for each pile group. In the next chapter of the thesis, we will review the research and studies conducted and the methods for calculating the bearing capacity of conical and cylindrical piles (Alwalan, M. F., and M. H. El Naggar, 2020).

Methodology

Considering the subject of the research, single pile models have been calculated and selected in a practically applicable way. Also, a suitable comparison can be made between a cylindrical pile with a certain volume and conical piles of the same volume but with different taper angles. For this purpose, it is first necessary to point out that the selection of conical models with a cylindrical reference model is possible in two ways. The first method is to keep the end cross-section of the pile constant and increase the upper cross-section of the pile. In this method, the volume of the piles increases with increasing cone angle.

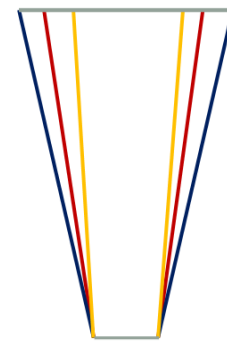


Figure (4), How to make tapered piles by keeping the cross-section constant

The second method is to consider a cylindrical reference pile and change the top and bottom cross-sections of the pile, in such a way that the bottom cross-section becomes gradually smaller and the top cross-section of the pile becomes larger so that piles of the same volume can be made with different taper angles (Figure 5).

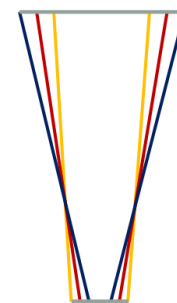


Figure (5), How to make conical piles by changing the cross-section

In this study, considering that the aim is to compare the load-bearing capacity of cylindrical and tapered piles of the same volume, the research is carried out by focusing on the second method. However, a series of models were also built using the first method and are being investigated. In the second method, the

models built for single piles with a length of 10 meters and using a cylindrical reference model with a diameter of 60 centimeters were built (MM Norouzian; N Gheitarani., 2023). To build conical models of the same volume as the cylindrical reference model, the following relations can be used (Figure 5), The complete scheme of the meshed model is presented in Figures (6) and (7):

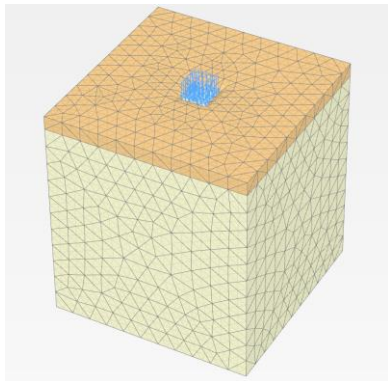


Figure (6). Soil mesh used in the cluster

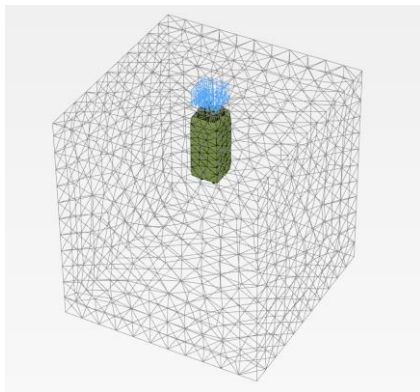


Figure (7), soil meshing used in the cluster and the location of the pile group model in it

In this study, the meshing of the models was done in such a way that at important points, such as the soil environment between the piles and the common surface between the piles and the soil, the elements were reduced to the smallest possible size, and medium-sized elements were used for the soil cluster itself (Norouzian, M. M. 2024). In the next stage of modeling, the stages of placing the piles in the soil and loading them should be defined (Mahmoud Zahiri et al., 2024). In this study, since in-situ piles are considered, three stages are considered, the first stage being the initial soil conditions, and the second and third stages are the placement of the piles in the soil and loading on the group cap or the head of a single pile, respectively. To load the pile group cap, we used an estimated load approximately twice the group bearing capacity so that the load-settlement diagrams obtained are as progressive as possible (Ma et al., 2024).

In this way, we can have accurate results of the bearing capacity using the tangent drawing method. Therefore, the goal for loading the pile group is to use a widespread load of 300 on the group cap in sandy soil and 1500 for clay soil. For single piles, we used a point load on the pile caps in line with the central axis of the pile, which is 1000 kN. The method of surface loading on the pile group

cap is as follows which is uniformly placed on the surface of the pile group cap (Zhang et al., 2025).

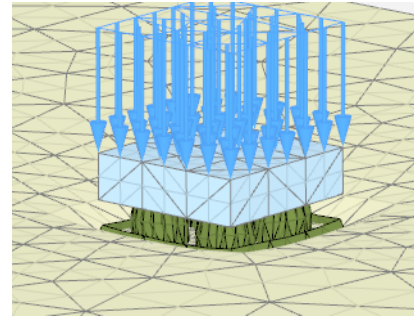


Figure (8), how to load the cap of the group of piles

Findings

For each modeling of a single pile or a group of cylindrical and conical piles, a force-settlement diagram (P-y) can be drawn, where the vertical axis is the amount of force applied to the head of each pile or the head of the pile group and the horizontal axis is the displacement or settlement of that pile or group of piles. In this study, three different soil conditions are considered for each group of piles placed in sand, and each modeling series includes five groups of piles, the geometry of which differs in terms of the cone angle.

The diagrams are drawn to find an optimal angle for conical piles in sand and clay which can be seen in Figure (8). Also, the diagrams related to the efficiency of the pile group are drawn in terms of the cone angle, and the load-settlement diagrams of the pile groups under the same specific conditions are drawn next to each other and compared.

To calculate the bearing capacity, there are several ways to calculate piles through force-settlement diagrams, which, of course, do not provide similar results. However, according to the experience and work of previous scientists, in this study, two methods, Davisson and the US Army, which we will explain below, have been used, which provide similar results. However, the results are still estimates, and since the subject of this study was a comparison, the conditions for the contact of individual piles and groups of piles were considered the same, and using the two methods described for all modeling, the bearing capacity was calculated and compared.

"US Army Corps of Engineers" Curve Tangent Method. In this method, holding the force-settlement diagram at the end of the diagram where the diagram gradually becomes horizontal, we draw a tangent to the diagram. In addition, in the initial part of the diagram, which shows the elastic behavior of the piles, we draw a tangent to the diagram so that the tangents drawn on both diagrams intersect each other somewhere outside the diagram and near the point where the diagram changes direction (Norouzian, M. M. et al., 2024). The point of intersection of these two tangent lines is connected to the vertical axis, and the desired number is considered the bearing capacity of a single pile or a group of piles. The figure below shows how to use this method well (Qurraie, Saba Sultan et al., 2023).

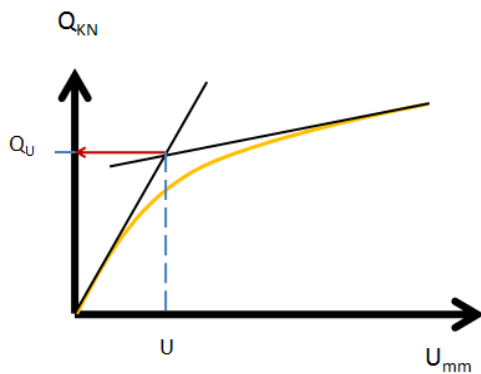


Figure (9), How to Calculate Bearing Capacity Using Tangential Method

As can be seen from the above graphs, a cylindrical pile with a larger stress range and a lower stress value at the center of its end face can be expected to have a higher bearing capacity. As can be seen in the figures, with the increase in the internal friction angle of the sandy soil, the stress distribution at the lateral edges of the pile end face did not decrease, and the bearing resistance increased with the increase in the soil friction angle. In this case, the issue will be clearer by showing the effective stress state at the end of the pile as a stress contour.

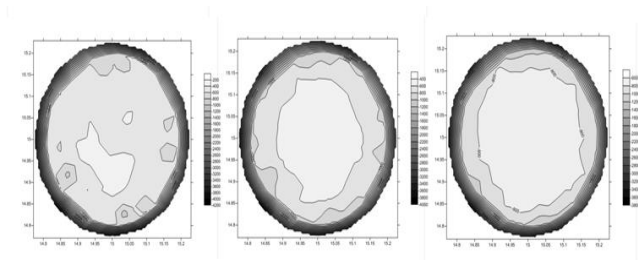


Figure (10), Topography of stress distribution on the end surface of conical and cylindrical piles of the same volume

As is clear from the figures above, with the increase in the angle of internal friction of the sand, there is a region in the center of the end face of the pile that is expanding. This region, which is marked with a lighter color than the other regions, shows that the stress distribution on the end surface of the pile grows almost uniformly, and with the increase in the angle of internal friction of the soil, the bearing load of the conical pile increases. While the bearing load increases with the increase in the angle of internal friction of the soil, the friction load of the conical pile will increase several times (Mir et al., 2024). This alone can be a confirmation of the efficiency of conical piles up to a certain cone angle. The table below shows the bearing load values for a conical pile (with a taper angle of 0.8 degrees) placed in sandy soil with different internal friction angles (Li et al., 2017).

Comparison of settlement factor in a group of cylindrical and conical piles in sand. The settlement factor in a group of piles is defined as the efficiency of the group of piles in such a way that instead of the ratio of the bearing capacity of the group of piles to the individual pile to calculate the efficiency of the group of piles, we use the ratio of the settlement of the group of piles to the individual pile to calculate the settlement factor. To calculate the settlement factor, a diagram was presented by Vesic in 1967, which is the settlement factor in terms of the relative width of the group of piles, that is, the ratio where B is the width of the head of the

group of piles and d is the diameter of the group of piles. The diagram presented by Vesic can be seen below (Li et al., 2023).

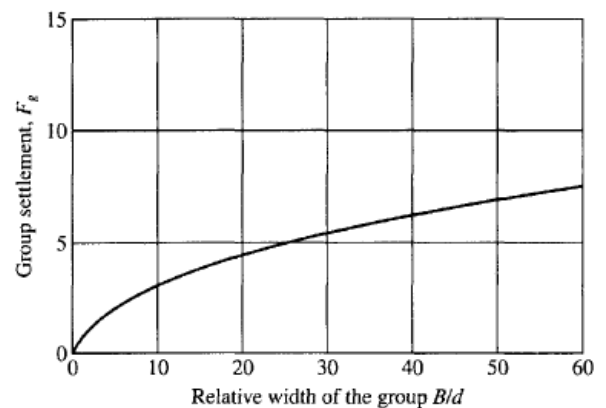


Figure (11), Settlement factor diagram provided by (Vesic)

The settlement factor diagram in this study for different taper angles of the tapered pile group is plotted below:

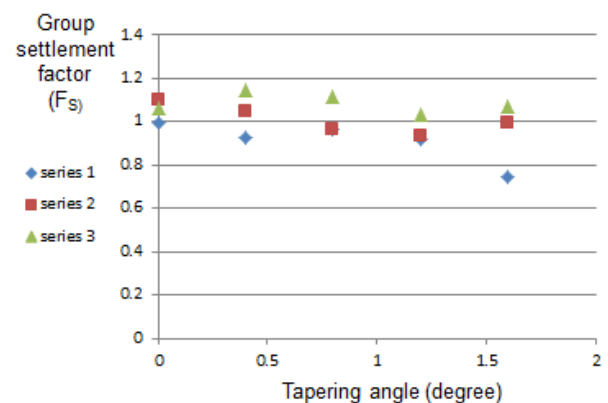


Figure (12), Settlement Factor Graph by Cone Angle

From the graph provided by Vesic for the settlement factor of the pile group, the predicted range for the pile group in this study can be obtained by having the ratio where B is the width of the pile group cap and d is the pile diameter.

Discussion

In modeling pile groups, it is better to consider common planes between the side wall of the pile group block and the surrounding soil during the construction of the pile group model so that at the end of the analysis, the stress state on those planes can also be observed. This issue has been well observed in this study, and the stress state on the planes around the pile group for two cylindrical and conical piles of the same volume with a taper angle of 1.6 in the sand is shown below. Figure (13) shows the shear stress distribution on the side wall of the cylindrical pile group block.

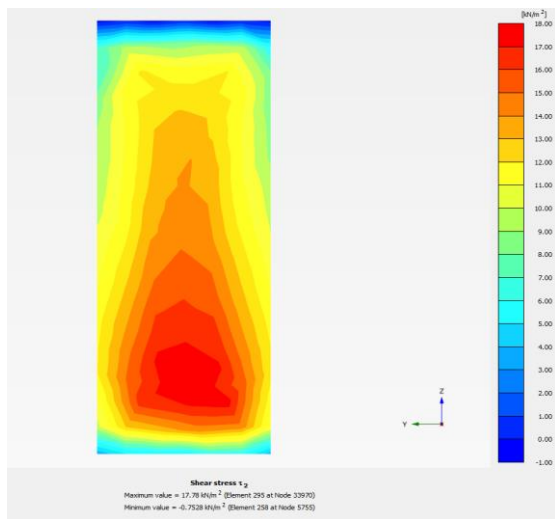


Figure (13) Shear stress distribution on the side wall of the cylindrical pile group block

Figure (13) shows the shear stress distribution on the side wall of the conical pile group block with a taper angle of 1.6 degrees.

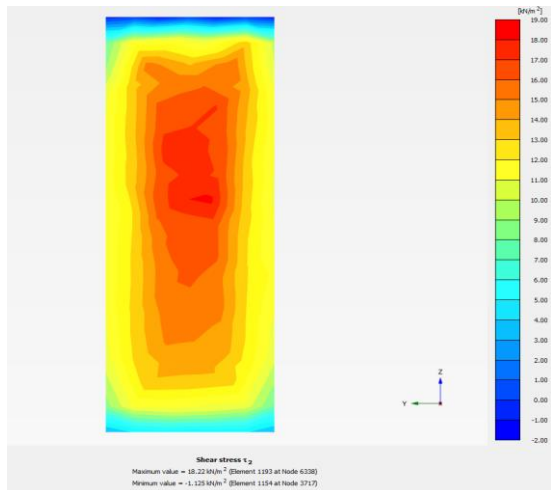


Figure (14), Shear stress distribution on the side wall of the cone pile group block.

As is clear from the figures above, for cylindrical piles, the shear stress is higher at the bottom of the plates, while for conical piles, the stress is higher at the top of the plate. The reason for this is that conical piles are thicker at the top and thinner at the bottom than cylindrical piles of the same volume.

Due to this, the bearing capacity of cylindrical piles, which have a larger end surface than conical piles and, as a result, have a higher bearing capacity, and the stresses at the bottom of the wall plates of the pile group block are also higher. For this reason, the bottom of these plates is seen in a darker red color.

Conclusion

To observe the effective stress condition perpendicular to the defined common planes of the end of the pile group block and the soil, without considering the end surface of the piles, common planes with the soil must be defined for the end of the pile group block during modeling. These planes can be seen in the figures below. These planes are drawn for a group of cylindrical and conical piles with a taper angle of 1/6 placed in sand with an

internal friction angle of 43. Figure (15) shows the distribution of the vertical effective stress on the end surface of the block of the cylindrical pile group without considering the end surface of the piles.

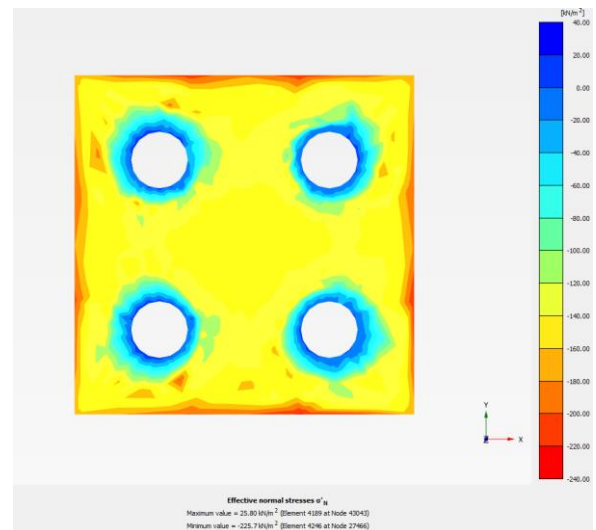


Figure (15), Vertical stress distribution on the end surface of the cylindrical pile group block

Figure (16) shows the effective vertical stress distribution on the end surface of the conical pile group block with a taper angle of 1.6 degrees, without considering the end surface of the piles.

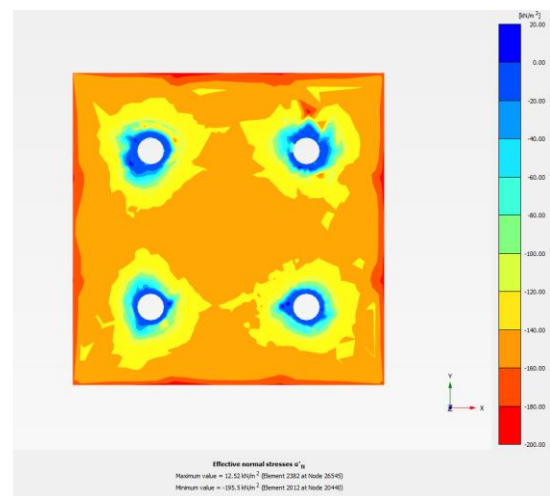


Figure (16), Vertical stress distribution on the end surface of the cone pile group block

According to the above figures, it can be seen that cylindrical piles, which have a greater end load due to their larger end surface, experience less stress on the end plates of the pile group block. However, for cone piles, this relatively effective vertical stress plate experiences more, which can be understood from its boldness.

Plastic and elastic points. To determine the elastic or plastic points in the soil cluster, we must obtain these points from the program output after analyzing them. In this study, both elastic points and plastic points are drawn as three-dimensional shapes. These two cases can be seen in the figures below. Figure (17) shows the elastic points within the soil cluster.

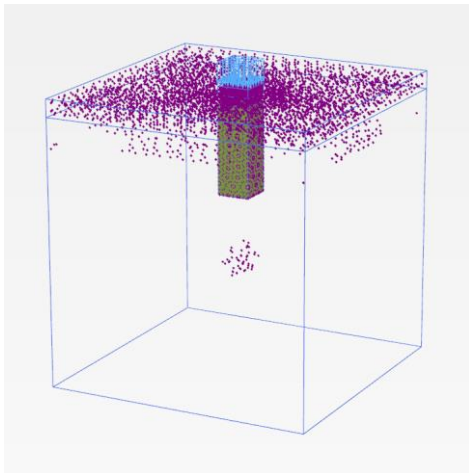


Figure (17), elastic points within the soil cluster

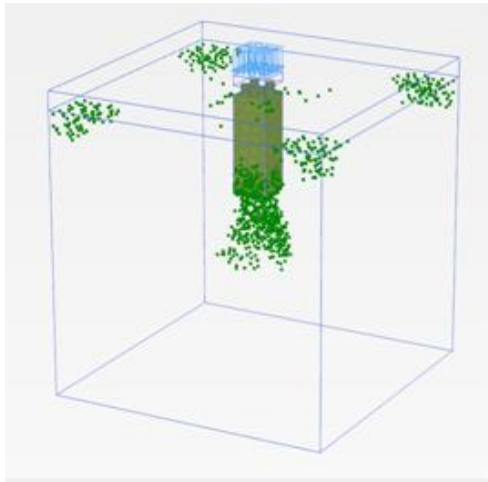


Figure (18), Plastic points inside the soil cluster

According to the above figures of elasticized points on the surface of the soft and loose soil used under the pile caps, it can be seen that at these points, due to the greater freedom of movement of the soil particles, no confined pressure is applied to these points and as a result, these points do not reach a plastic behavior state. In the other figure that shows us the plasticized points, it can be seen that under the block of the pile group, many plasticized points are applied to the soil due to the high vertical stress.

It can also be seen that there are plasticized points in the four corners of the cluster defined for the input soil of the sandy soil surface. The reason for this is that the lack of freedom of movement of soil particles in these corners of the cluster is due to the limited degrees of freedom in the direction of the surface plane on the soil. The boundary conditions of the soil cluster, which close the movement of soil particles from around and provide freedom of movement for them only in the vertical direction, cause.

At these points, confined stress conditions are created for soil particles, and as a result, these points are in tension and become plastic due to the high tensile stress introduced to them. Laboratory experiments to investigate the behavior of conical piles in a group under vertical static load. Numerical modeling of conical pile groups with lateral and tensile loading. Laboratory experiments to investigate conical pile groups under dynamic loading. 3D

modeling of conical pile groups using the finite element method with a focus on the number and spacing of piles.

Investigation of the effect of soil under the cap of the pile group to provide a relationship in predicting the efficiency of the group. Behavioral analysis of conical and cylindrical pile groups in cohesive soils with changes in the length-to-diameter ratio. Detailed investigation of the scale effect in the ultimate analysis of bearing capacity and settlement of conical piles. Presenting a relationship for the efficiency of a group of conical piles in static and dynamic states using existing theoretical methods.

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