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STUDY ABOUT THE EFFECTS OF PILE SPACING ON THE PERFORMANCE OF PILE GROUP UNDER COMPOSITE LOADS, ADJACENT STRUCTURE LOADS, AND BENDING MOMENT IN SAND

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SUMMARY

Pile group is a particular type of deep foundations which is designed and installed as the ultimate solution to foundation construction, load transition to the resistant subsurface layers, providing lateral resistance, and overcoming the poor performance of surface soils. Pile design should be done with respect to structural consideration, the load-carrying capacity of the surface and surrounding soil, settlement, and constructional, technical and environmental problems. Piles are mostly and widely utilized in coastal and offshore structures, and sustain vertical and lateral loads. Considering the imposed loads on structure, the effect of these loads on the pile behavior should be analyzed with an appropriate method. In this study, a 4x4 pile group with piles of 100-cm diameter and center-to-center spacing of 2, 3, 4 times the diameter is modeled using the Plaxis 3D foundation program, which uses the finite element method, and the Mohr-Coulomb model, and the behavior of piles subjected to loading, driven in sand, are investigated. Taking the achieved results, the mechanism of the pile group behavior under composite loads, adjacent structure loads, and bending moment are calculated, and displacement in the x-direction, y-direction and along the length, the bending moment and the axial force for each pile within a distance of 2, 3, 4 times the diameter are attained.

Keyword: *lateral load, finite element, pile group, adjacent load, Mohr-coulomb model*

INTRODUCTION

For centuries the deep foundations are being used as transitional elements of transferring structural loads to the resistant subsurface layers. In general, piles are quite slender columns which are utilized either vertically or with a small slope to transfer the compression, tension or lateral loading to the more resistant subsurface layers. The fact that in most cases piles are more economical than other types of foundations can be justified with two reasons: 1-Due to technological advances, nowadays the use of pile foundations is more economical and feasible than it was in the past. 2-The required time for the design and installation of pile foundations is usually shorter than it is with other types, and therefore will expedite the construction of the project, resulting in a more economical project with lower expenses. Moreover, there is usually no solution other than this type of foundation for building sea structures like waterfronts or stone benches. So far different actual and experimental studies on axial and lateral behavior of the pile group in relation to the number of piles in group, load distribution between piles and lateral displacement of the group have been carried out. Vertical and lateral load cause large displacements in group at the same time. Axial loading extremely impacts lateral behavior, while this behavior, depending on the type of pile (rigid or flexible) and its fixity, differs [1].

A centrifuge experiment with the purpose of determining the pile response under lateral load was conducted on single pile and also pile group 2x2, 6x3 with center-to-center spacing of 2d, 4d, 8d, with the small sample 9.5-mm diameter to 16-mm diameter. During this experiment acceleration varied from 30 to 120, and in order to determine the group effect, Poulos theory (1971) was used for analysis. This research was done mostly in order to explore the accuracy of elastic method and determine the necessity of non-linear analysis on the response of pile group [2]. Lateral load resistance depends on the spacing of the piles, and as this spacing decreases, the reciprocal effect of group gradually gains importance [3]. When the distance between piles increases, the bearing capacity of the pile group increases as well [4].

The deviation of a laterally loaded pile group is 2 times the deviation of a single pile at the same load level [5]. The lateral resistance of a long flexible pile decreases when the water level changes from horizontal to sloping [6]. The soil lateral pressure in lateral load state varies with the width and depth of the pile, while this depends on the severity of the load and water level [7]. A test for examining the interaction of pile group and its effects, in order to assess their behavior, considering the pile spacing in group under lateral load, was conducted, in which groups of 3x3, 3x4, 3x5 were spaced at 3.3d, 4.4d, 5.65d respectively, and it was concluded that lateral load resistance depends on the spacing of the piles, while, by having this spacing decreased, the reciprocal effect of group gradually gains importance [8].

Another study was carried out [9] in order to evaluate the behavior of laterally loaded pile groups in sand. Tests were conducted on 3x3and 7x3 pile groups with 3D pile spacing. Moreover, single piles were tested in order to provide comparison [9] used p-multipliers method in analysis of the behavior of the pile group under lateral load and concluded that group response and p-multipliers approach is independent of soil density, but mainly a function of group geometry and row position, as suggested in the table 1 below [9].

Table 1. Testing Of Large Laterally Loaded Pile Group In Sand

Row position	Three rows	Four rows	Five rows	Six rows	Seven rows
Lead row	0.8	0.8	0.8	0.8	0.8
Second row	0.4	0.4	0.4	0.4	0.4
Third row	0.3	0.3	0.3	0.3	0.3
Fourth row	-	-	0.2	0.2	0.2
Fifth row	-	-	0.3	0.2	0.2
Sixth row	-	-	-	0.3	0.2
Seventh row	-	-	-	-	0.3

SOFTWARE INTRODUCTION

Currently, there are many software packages for analyzing the geotechnical environments among which the Plaxis 3D Foundation with many features, e.g. considering soil-structure interaction, calculating large deformations, different behavioral models of soil and structure, and considering uplift pressure, is both quick and precise. The Plaxis 3D Foundation is a 3D finite element program which, using a graphical environment, enables the user to create a 3D actual grid based on a combination of horizontal sections in different vertical layers. Due to three-dimensionality of the grid, we can generally and precisely explore the behavior of soil and structure, and also their interaction without having to utilize assumptions [10,11].

NUMERICAL MODELING OF PILE GROUP UNDER LATERAL LOAD, ADJACENT STRUCTURES LOAD, AND BENDIG MOMENT USING THE PLAXIS 3D FOUNDATION

Modeling is created by using the finite element method and considering the problem as 3D parallel plates. The particular model is assumed to be a 10x10 foundation on the surrounding soil of 50x50x20 meters with three pile groups of 10m in length, 100-cm in diameter, and center-to-center spacing of 2,3,4 times the diameter; in addition, for further precision in results, meshing has been used in finer scales. In the Plaxis 3D Foundation basic elements of a finite element soil mesh are wedge elements of 15 nodes. These elements, created in the 2D mesh generation process, are composed of 6-node triangular elements. The 15-node wedge elements are composed of 6-node triangles in horizontal direction and 8-node quadrilateral elements in vertical direction. The accuracy of the 15-node wedge elements and compatible structural elements are comparable with 6-node triangular elements and compatible structural elements in 2D analysis. The proposed models show the foundation of a building which is situated under the issued loading from the weight of the building, lateral load, adjacent structures load and bending moment. There are four rows of piles, the nearest row to the lateral load is designated as the first row, and the following rows as second, third and fourth respectively. For boundary conditions, the Plaxis 3D Foundation program takes into account a series of general fixities for the boundaries of the soil geometrical model so that, in all directions, the floor and parapets of the modeled soil are fixed and that its top plate is free. Moreover, in the Plaxis 3D Foundation program there are distinct options for applying horizontal and vertical boundary conditions which can be put in use. Figure 1, illustrates an example of the plan related to arrangement of piles and direction of the loads.

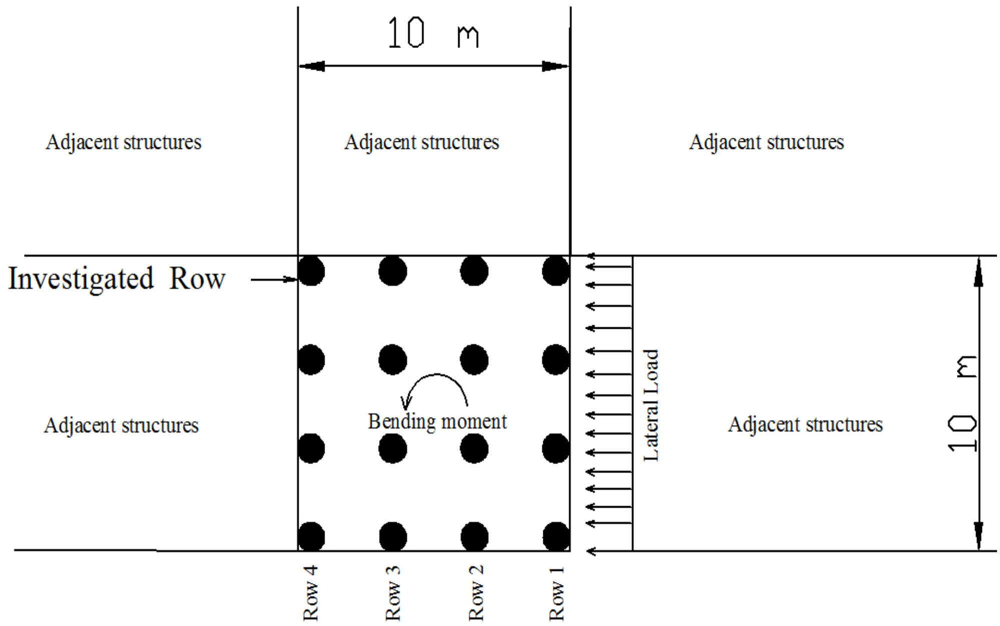


Figure 1. Arrangement of piles and directions of the load plan.

SOIL, PILE AND PILE CAP PROPERTIES

To model the problem, a soil with the properties (given in table 2) and the Mohr-Coulomb model have been used. In this research, the behavior of the piles has been defined as linear elastic and their type of material as non-porous. Piles are modeled as a 4x4 pile group, and in order for piles to simultaneously resist against horizontal and vertical forces, and bending moment, a pile cap is defined over the pile group. The properties of pile and pile cap are given in table 3.

Table 2. Soil properties

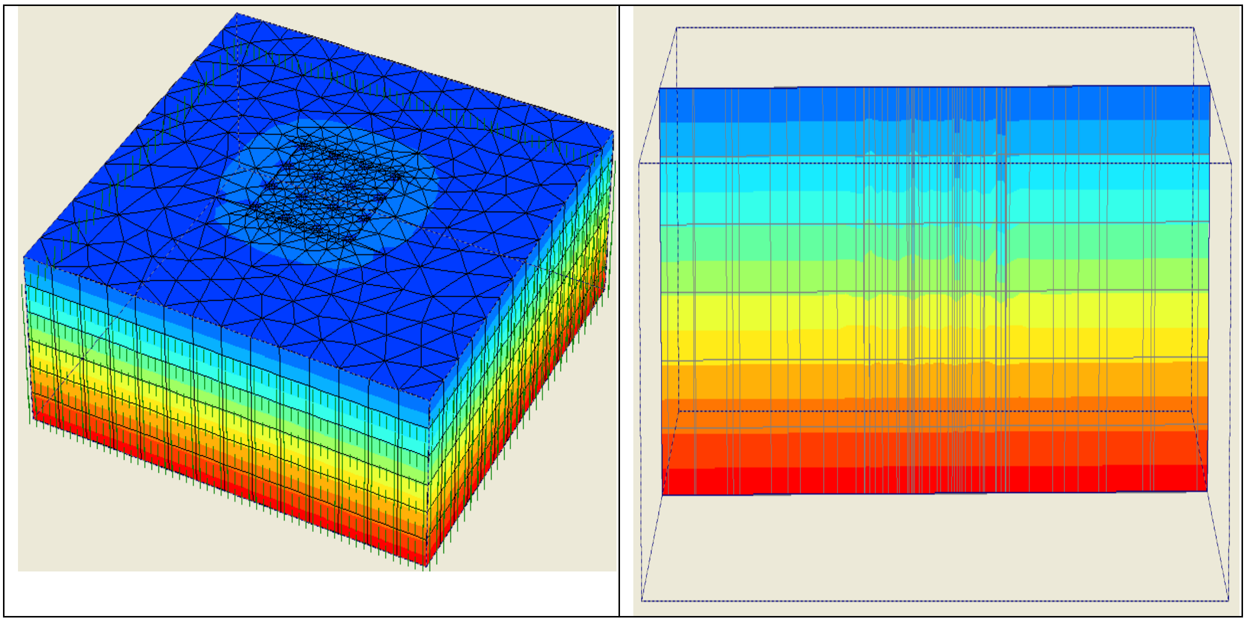
Material	E(kN/m^2)	υ	C(kN/m^2)	φ	γ(kN/m^3)	ψ
Sand	10000	0.35	0.0	28	17	0.0

Table 3. Pile and pile cap properties

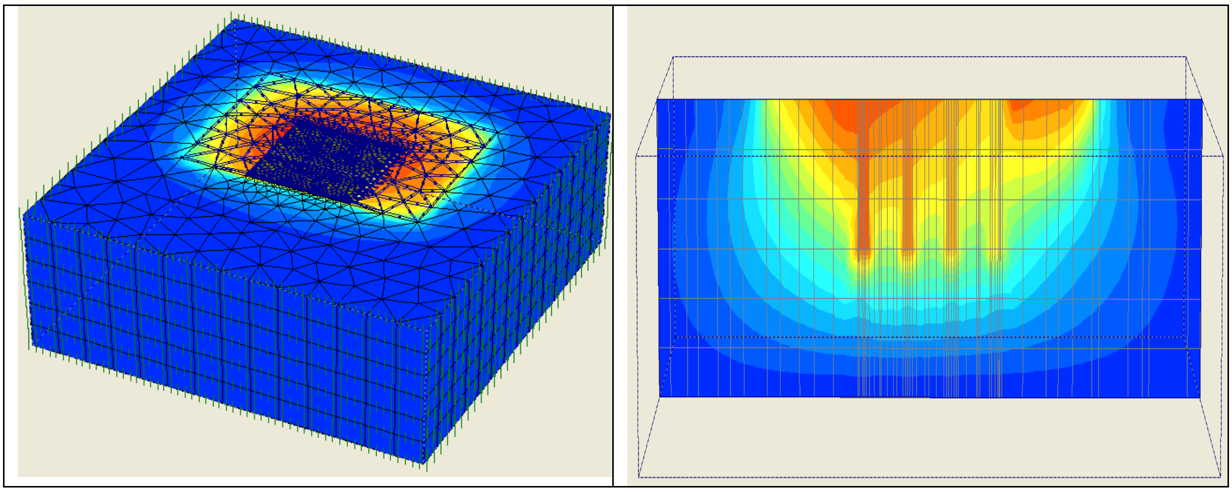
Material \ Parameter	BxL(m)	h (m)	D (m)	E (kN/m^2)	υ	γ(kN/m^3)
Pile	-	10	1	21000000	0.2	25
Cap pile	10 x 10	1	-	21000000	0.2	25

THE ANALYSIS OF RESIDUAL STRESSES IN MODEL

The next step, after having had the soil, pile, pile cap and the lateral load along with the bending moment modeled, is the calculation process. The proposed program in this article has a series of phases in the calculation mode which have to be defined. In the phase 0 – or the initial phase – which contains the natural state of the soil without any operations performed, the stresses of soil weight are generated and then calculated. The initial phase involves assigning the piles and the second the pile caps. In the last calculation phase (loading), all loads are assigned to the structure. The residual stresses in sand, in the initial and loading phase, are shown in Figures 2,3 and Figures 4,5.



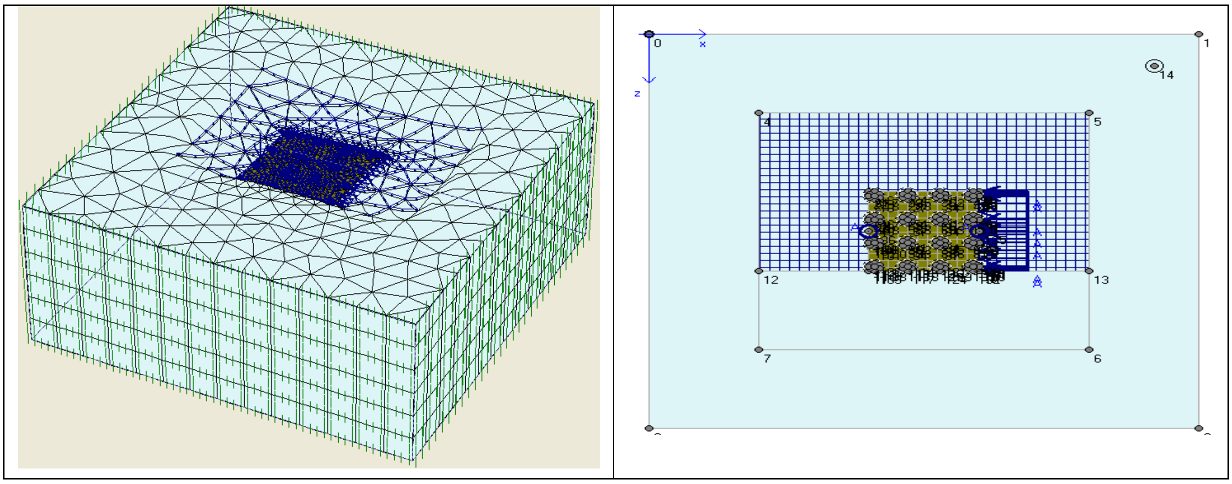
Figures 2 and 3. Three and two dimensional residual stresses of sand in initial phase.



Figures 4 and 5. Three and two dimensional residual stresses of sand in loading phase.

LOADING

The imposed loads from the structure, adjacent structures, and bending moment should be applied. Therefore, after having assigned the material properties of model piles and pile cap in the first and second phase respectively, vertical and horizontal loads are assigned in the last phase (or the Loading phase). The assumed values for the issued loads are as follows: the imposed load from the weight of the structure is 300 kN/m^2, the exerted lateral load is 900 kN/m, the adjacent structures loads is 225 kN/m^2, and the imposed bending moment on the structure is 24000 kN/m. According to the equation $K_0 = 1 - \sin \varphi$, adjacent structures loads cause exertion of force to piles in the horizontal direction. As it was mentioned, the proposed behavior in study and analysis is assumed to be Mohr-Coulomb model. The applied loads to the piles are shown in Figures 6 and 7. After performing the operation for each model, the amounts of displacement along the length of the pile, lateral displacement of the pile, axial force and bending moment along the piles were attained.



Figures 6 and 7. Applied loads to piles

DISPLACEMENT ALONG THE LENGTH OF THE PILE IN VERTICAL DIRECTION

Figure 8 shows the pile group displacement, with piles spaced at 2-3-4 meters apart, in vertical direction and figure 9 shows the pile group displacement, with piles spaced at 2-3-4 meters apart, in pile head. As shown in figure 8, in each pile group, as moving to the depth below the ground surface, the displacement along the length of the pile decreases so that axial strain in pile decreases. Displacement values along the length at the top, the middle, and the bottom of the pile group are specified in table 4. In addition, by comparing piles spaced at 2-3-4 meters apart in figure 10, it is observed that the vertical displacement of the pile head increases 18% with increasing the spacing up to 4 times the diameter, and the displacement of pile head decreases 19% with decreasing the spacing up to 2 times the diameter. In other words, in pile group, the displacement of pile bottom increases with increasing space, and large settlements occur. The reason is that when piles are spaced closely, created stresses in piles affect one another, and soil block acts in its integrity, and system is settled simultaneously, and there is smaller displacement; however, when piles are spaced widely, created stresses in piles do not affect each other, and vertical displacement is increased. Therefore, vertical displacement increases with increasing the pile spacing.

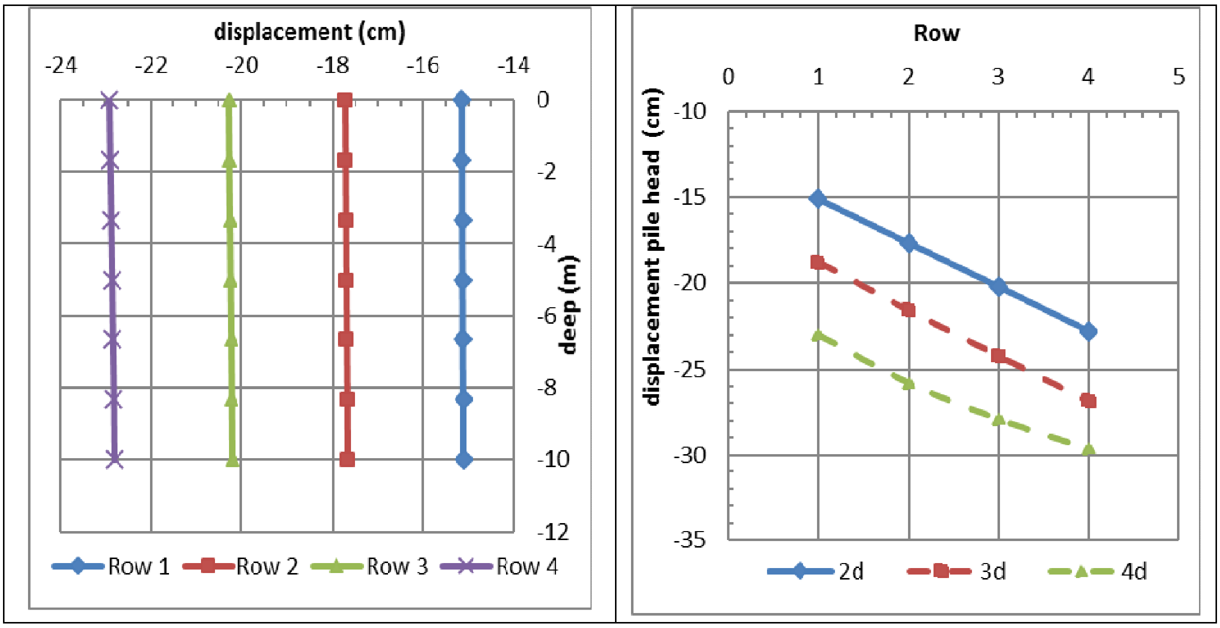


Figure 8 and 9. Displacement of pile in group and Displacement pile head in 2 – 3 – 4 times of diameter

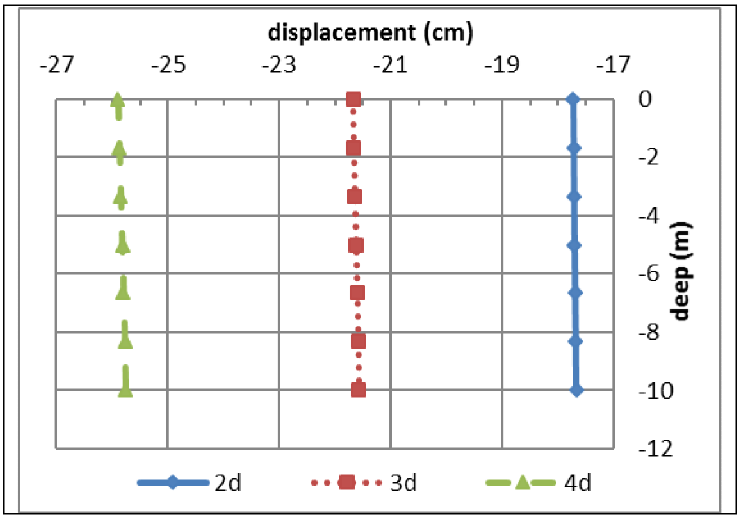


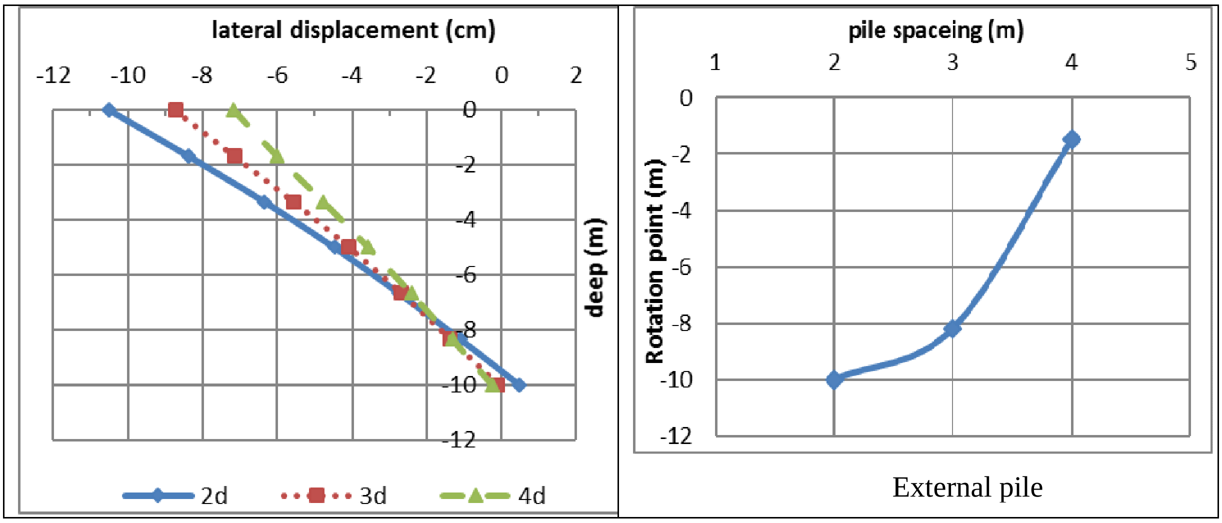
Figure 10. Displacement of pile in group 2-3-4 times of diameter

Table.4 Displacement values in length of pile at top, middle and bottom of pile group

Displacement place / Pile	Top of the pile cm	Middle of the pile cm	Bottom of the pile cm
2D	-17.72	-17.65	-17.60
3D	-21.69	-21.62	-21.55
4D	-25.89	-25.80	-25.73

LATERAL DISPLACEMENT IN HORIZONTAL DIRECTION

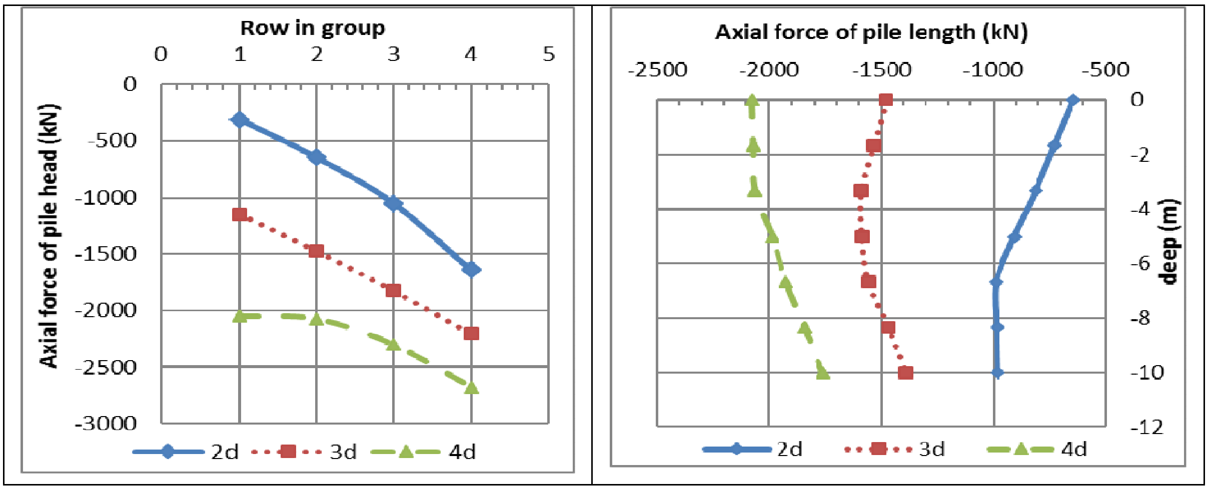
By comparing the curves shown in figure 11, the horizontal displacement can be seen to decrease with increasing center-to-center spacing of piles so that with increasing the distance to 4 times the diameter, the displacement of the pile bottom in the x-direction decreases 18%; and with decreasing the distance to 2 times the diameter, displacement increases 18%. The reason is that when piles are spaced closely, pile block is near the lateral load, and this causes further displacement in the x-direction. Moreover, with increasing the spacing of the piles, the soil block is extended and piles are distanced from lateral load, hence a smaller lateral displacement of piles. Therefore, in figure 12 with increasing the distance, piles resist more force, and displacement in the x-direction decreases; furthermore, with increasing the distance, rotation point in 2 times the diameter approximately equals 10 meters, in 3 times the diameter approximately 8, and in 4 times the diameter near the ground surface. Thus, with increasing the distance, rotation point of piles in the group nears the ground surface.



Figures 11 and 12. Lateral displacement of pile and Rotation point in pile group

SPACING EFFECT ON FORCE OF PILES

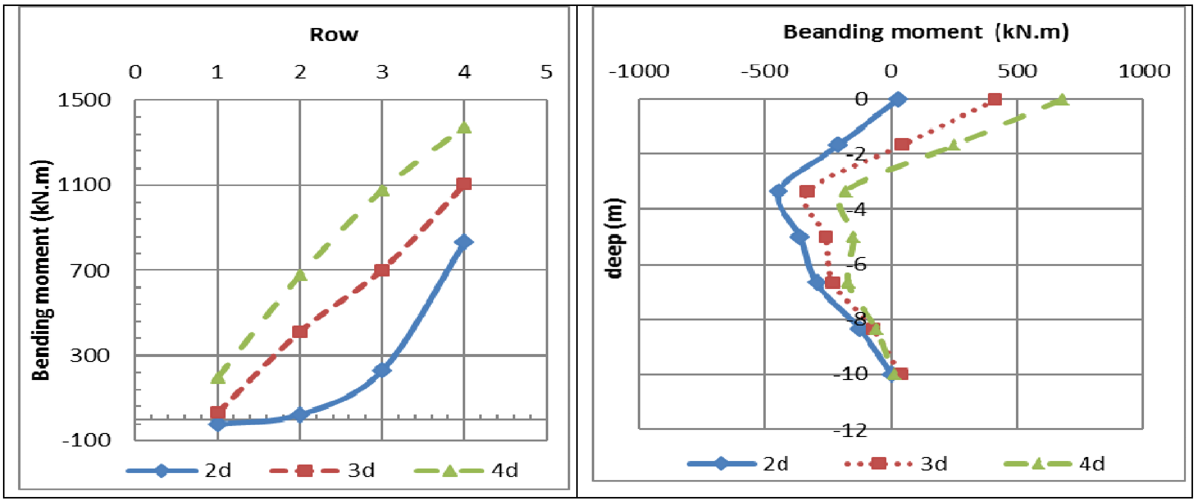
Figure 13 shows axial force curves of the studied row of piles in each group. As shown by the curves, axial force can be seen to increase from first row to fourth row with increasing the spacing of the piles and moving away from lateral loading. In addition, Figure 14 compares axial force curves in piles spaced at 2-3-4 times the diameter center-to-center, showing that in pile spaced at 4 times the diameter, as compared to pile spaced at 3 times the diameter, axial force increases 33%, and with decreasing the distance to 2 times the diameter, the value is decreased to 57%. Therefore, with increasing the center-to-center spacing of piles, axial force increases, and with decreasing the distance, axial force decreases.



Figures 13 and 14. Axial force of pile head and Axial force of pile length

BENDING MOMENT ALONG THE LENGTH OF THE PILE

Figure 15 shows the variations of bending moment curve of the pile head in pile group with distances of 2-3-4 times the diameter apart. As shown by the figure, the bending moment can be seen to increase with increasing the spacing of the piles. Comparing the curves of piles spaced at 2-3-4 times the diameter (figure 16), it is observed that, near the ground surface, with increasing the distance to 4 times the diameter, bending moment increases 58%, and with decreasing the distance to 2 times the diameter as compared to the middle state, which is 3 times the diameter, bending moment decreases 99%, and at a depth of-4 meters, this value moves towards the negative, and this procedure is maintained along the length of the pile.



Figures 15 and 16. Bending moment in pile head and Bending moment in pile length

Equation 1 is a theoretical equation of bending moment from the equations by Matlock & Reese in which [M_1] is the initial bending moment, [P_1] the force, [T] the stiffness coefficient, which is obtained from Equation 2, and [n_h] modulus of subgrade reaction, which is obtained from table 5. [E] is the modulus of elasticity, [I] is the moment of inertia of pile, and [A_M, B_M] are coefficients which are obtainable from the related tables, and are directly proportional to the length of the pile. With this theoretical equation, it is also observed that with increasing the spacing of the piles, the value of force increases, and since they are directly proportional to the created bending moment in pile, bending moment likewise increases according to the equation; thus, it can be inferred that with increasing the spacing of the piles, the value of bending moment increases.

Table 5. n_h

Density	LOOSE	NORMAL	DENSE
1-Terzaghi (1955) n_h (lb/in^3)	2.6-7.7	7.7-26	26-51
2-Reese et al (1974) (lb/in^3)	Static and cyclic loading		
n_h	20	60	125

$$M = [P_1 T] A_M + M_1 B_M \quad [1]$$

$$T = \sqrt[5]{\frac{EI}{n_h}} \quad [2]$$

CONCLUSION

The operation of deep foundations has attracted the attention of many researchers. Moreover, noting the importance of composite loads, adjacent structures loads and the exerted bending moment on the pile group, in this article, this subject has been precisely studied, and its findings have been analyzed. For this reason, 3 pile groups with pile lengths of 10 m and distances of 2-3-4 times the diameter under composite loads, adjacent structures loads and bending moment in sand were studied using numerical modeling, and considering the assessment driven from the obtained results, it was observed that with increasing the spacing of the piles, displacement in the vertical direction increases. It was also observed that with increasing the distance from 2 times the diameter to 4 times the diameter, not only do the force resistance and the bearing capacity of the piles increase, but also their lateral displacement in the x-direction decreases. On the other hand, with increasing the center-to-center spacing of piles, the rotation point of piles, in each group, progressively nears the ground surface. By studying bending moment according to the equations by Matlock & Reese, it was observed that the increased bearing capacity leads to increased bending moment. Therefore, with increasing the distance, it is observed that the created bending moment in piles increases.

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