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## THE MECHANISM OF THE EFFECTS OF INCREASING THE LENGTH OF THE PILES UNDER LATERAL LOADS IN SAND

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### SAMMARY

In many projects, piles are designed and installed as the ultimate solution in 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. Pile group is a particular type of deep foundations which is mostly and widely utilized in coastal and offshore structures, and sustains vertical and lateral loads.

Noting the lateral load exerted on the structure, the effect of loading on the behavior of pile should be analyzed using an appropriate method. In this article, a 4x4 pile group with piles of 100 cm diameter and 10, 15-m in length with center-to-center spacing of 3 times the diameter are modeled using the Plaxis 3D Foundation, which uses the finite element method, and the Mohr-Coulomb model, and the behavior of the piles driven in sand and subjected to loading is studied.

Taking the results, the mechanism of the pile group behavior under vertical, lateral, adjacent structures loads and bending moment is calculated, and displacement in the x-direction, y-direction, and along the length, bending moment, and bearing capacity along the length of the pile have been obtained for each pile

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

### INTRODUCTION

It is for centuries that 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 so as to transfer the compression, tension or lateral loads 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:

- Due to technological advances, nowadays the use of pile foundations is more economical and feasible than was in the past.
- 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 [1].

The horizontal displacements of the soil opposite the laterally loaded pile is more than the vertical displacements, and these displacements decrease with increasing the depth; and the displacement of a pile group consisting of two piles, one oblique and another vertical, is smaller than the displacement of a pile group consisting of two vertical piles [2]. When the distance between piles increases, bearing capacity of the pile group increases [3]. The deviation of a laterally loaded pile group is 2 times the deviation of a single pile at the same load level [4].

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 [5]. The lateral resistance of a long flexible pile decreases when the water level changes from horizontal to sloping [6]. Lateral load resistance depends on the spacing of the piles, and as this spacing decreases, the reciprocal effect of group gradually gains importance [6]. 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 [7].

## 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 [8].

## NUMERICAL MODELING

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 and 15 m in length, 100-cm in diameter, and center-to-center spacing of 3 time 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. Noting that 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 its top plate free. Moreover, in the Plaxis 3D Foundation program

there are distinct options for applying horizontal and vertical boundary conditions which can be put to use. Figure (1) illustrates an example of the plan related to arrangement of piles and direction of the loads.

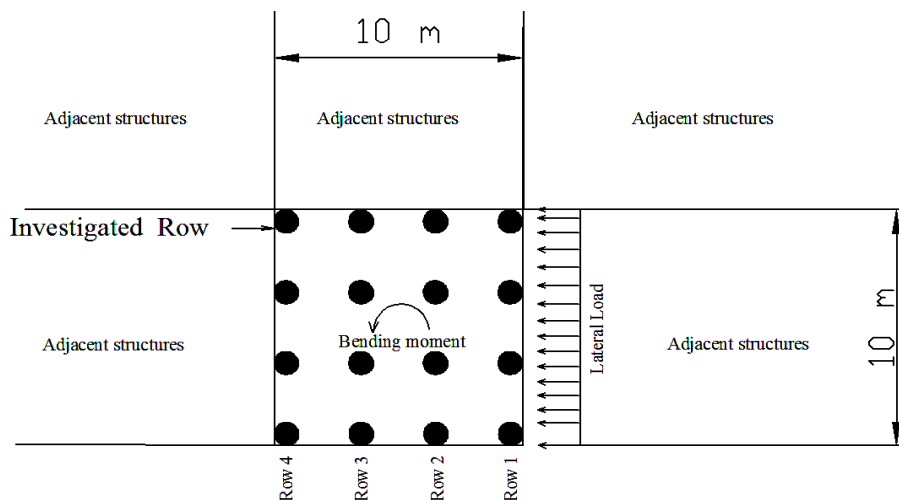


Figure 1. Arrangement of piles and directions of the load plan.

### SOIL, PILE AND PILE CAP PROPERTIES

To model the problem, a soil with the properties given in Table (1) 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 (2).

Table 1. Soil properties

material	E(kN/m <sup>2</sup> )	$\nu$	C(kN/m <sup>2</sup> )	$\phi$	(kN/m <sup>3</sup> ) $\gamma$	$\psi$
sand	10000	0.35	0.0	28	17	0.0

Table 2. Pile and pile cap properties

Parameter material	BxL(m)	h (m)	D (m)	E (kN/m <sup>2</sup> )	$\nu$	(kN/m <sup>3</sup> ) $\gamma$
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) and (3).

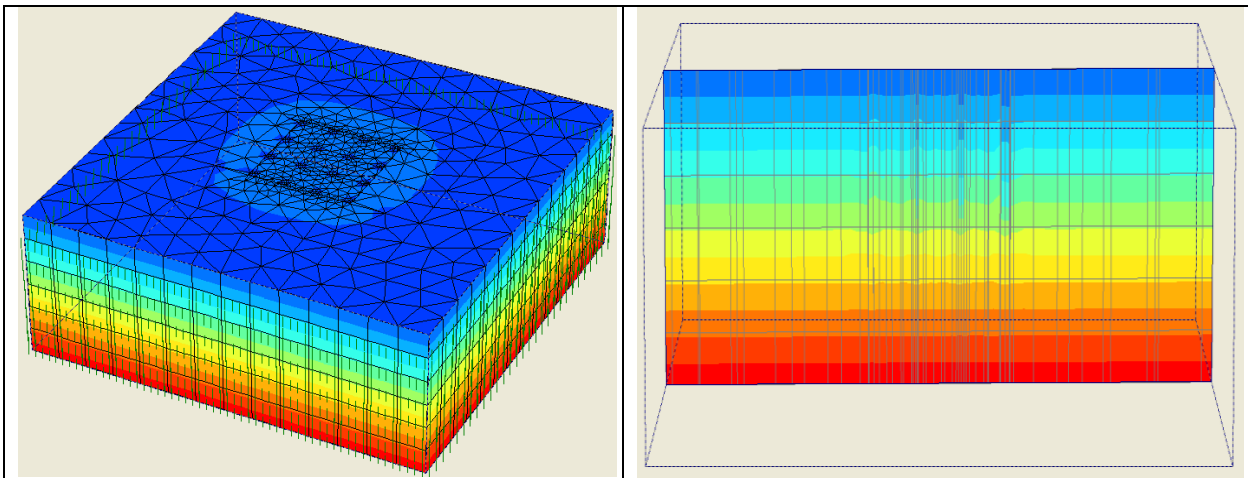


Figure 2. Three and two dimensional residual stresses of sand in initial phase.

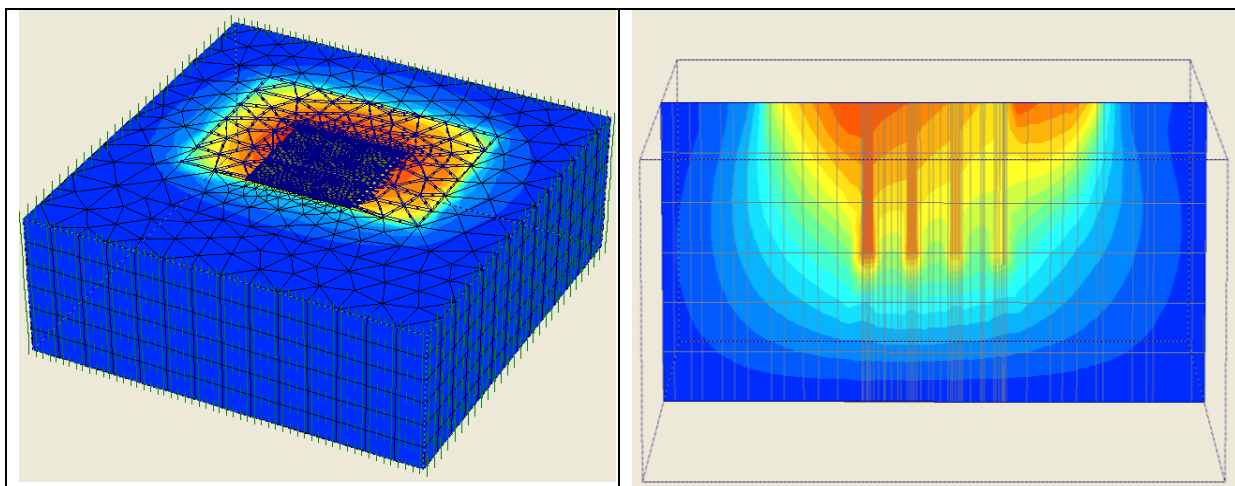


Figure 3. Three and two dimensional residual stresses of sand in loading phase

## 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  $300 \text{ kN/m}^2$ , the exerted lateral load  $900 \text{ kN/m}$ , the adjacent structures loads  $225 \text{ kN/m}^2$ , and the imposed bending moment on the structure  $24000 \text{ kN.m}$  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 the Mohr-Coulomb model. The applied loads to the piles are shown in Figures (4) and (5). 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 are attained.

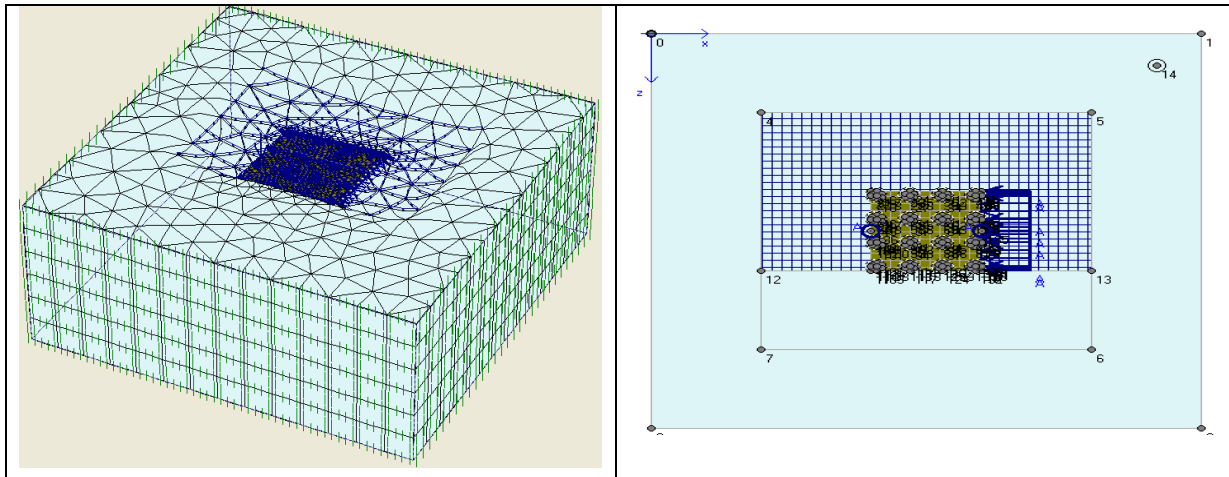


Figure 4. Applied loads to piles

### DISPLACEMENT ALONG THE LENGTH OF THE PILE IN VERTICAL DIRECTION

Figure (5) shows the vertical displacement of the first row of the pile group with lengths of 15m. It is observed that in each pile group, as moving to the depth below the ground surface, the displacement along the length of the pile decreases. In other words, the value of axial strain decreases as moving away from the loading. The value of this displacement at the top, the middle and the bottom of the pile is specified in Table (3).

Figure (6) shows displacement of pile bottom in group with length 10 - 15 meter in vertical direction. Shows that in pile group with increasing length, displacement of pile bottom decreased. Moreover, by comparing the two 15 m and 10 m pile lengths in Figure (7), it is observed that with increasing the length, the displacement of the pile in vertical direction decreases 38%. The reason is that when pile length is increased, the contact surfaces between pile wall and soil leads to increased friction, which causes the displacement to decrease. Therefore, with increasing the length in the group, displacement along the length of the piles, in the vertical direction, decreases.

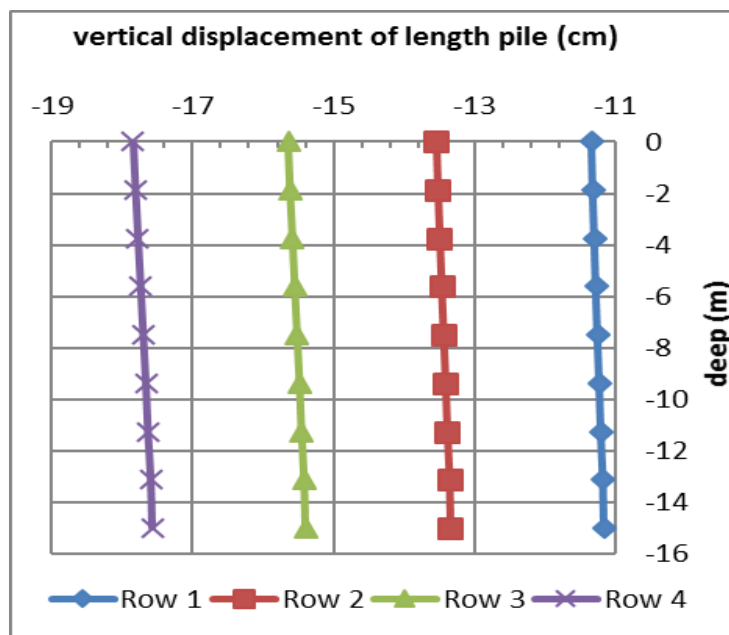


Figure 5. Displacement of pile in group

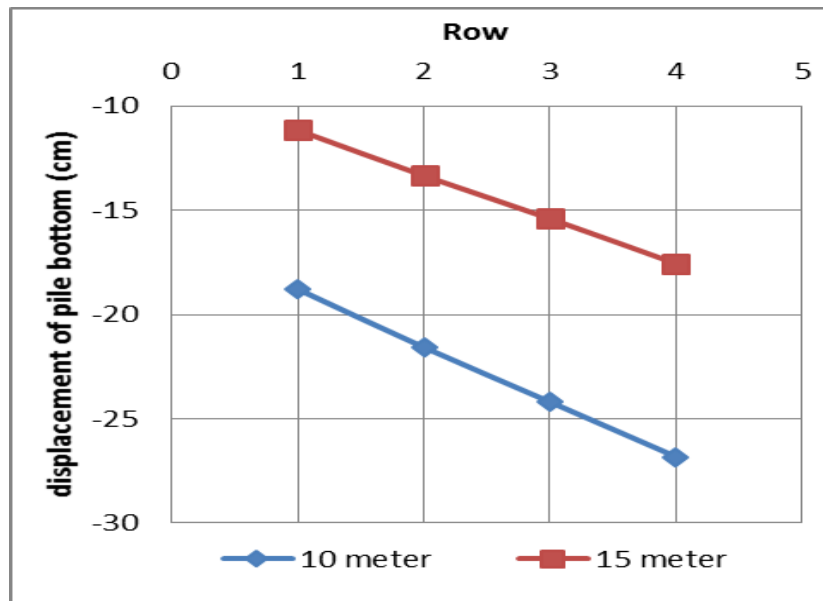


Figure 6. Vertical displacement pile bottom In 10 &15 meter

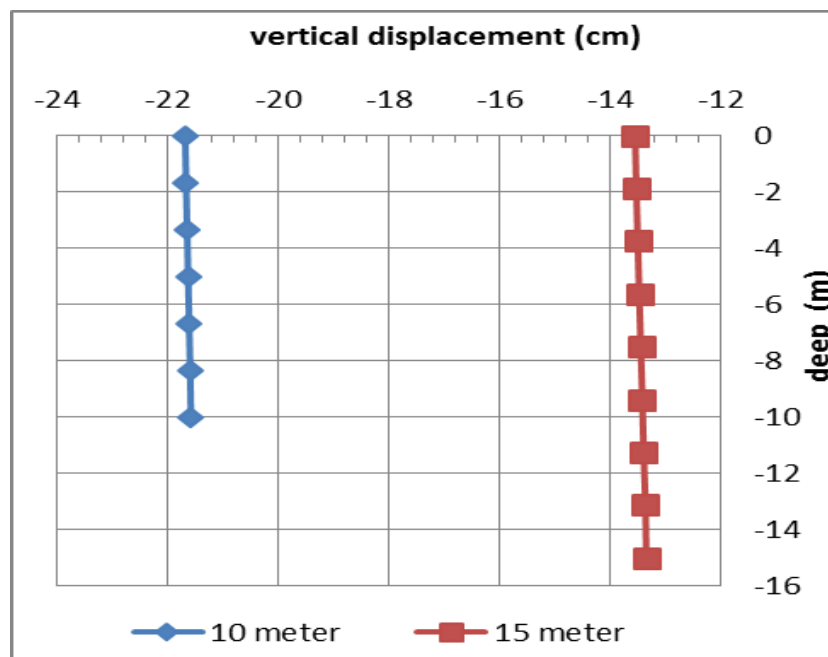


Figure 7. Compare displacement of pile in group 10 &15 meter

Table 3. Displacement values in length of pile at top, middle and bottom of pile group

Displacement / Pile	Top of the pile cm	Middle of the pile(cm)	Bottom of the pile(cm)
10 METER	-21.69	-21.62	-21.55
15METER	-13.54	-13.44	-13.34

BENDING MOMENT ALONG THE LENGTH OF THE PILE

Figure (8) shows the variations of bending moment curve of the pile head in 10 m and 15 m pile groups. According to the figure, it is observed that piles with lengths of 15 m resist larger bending moment as compared to piles with lengths of 10 m. In Figure (9) By comparing the curves of piles of 10 m and 15 m in length, it is observed that, in 15 m piles as compared to 10 m piles, with increasing the length, the value of bending moment at the ground surface increases 63%; and also as moving to the depth below it keeps increasing.

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 (4).  $[E]$  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 Table (5), and are directly proportional to the length of the pile and increase with increasing the pile length.

Noting this theoretical equation, it is also observed that with increasing the pile length, the values of coefficients increase, and since they are directly proportional to the created bending moment in pile, bending moment increases; thus, it can be inferred that with increasing the length, the value of bending moment in the pile increases. In Equation 3  $X$  is pile spring.

Table 4.  $n_h$

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

Table 5.  $A_M$  and  $B_M$

Z	$A_M$	$B_M$	Z	$A_M$	$B_M$
0.00	0.00	1	0.9	0.69	0.88
0.1	0.1	1	1	0.72	0.85
0.2	0.19	0.99	1.2	0.76	0.77
0.3	0.29	0.99	1.4	0.77	0.66
0.4	0.37	0.98	1.6	0.74	0.59
0.5	0.45	0.97	1.8	0.69	0.49
0.6	0.53	0.96	2	0.62	0.4
0.7	0.59	0.93	3	0.22	0.05
0.8	0.64	0.91	4	0.00	0.04

$$M = [P_1 T] A_M + M_1 B_M \tag{1}$$

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

$$Z = \frac{X}{T} \tag{3}$$

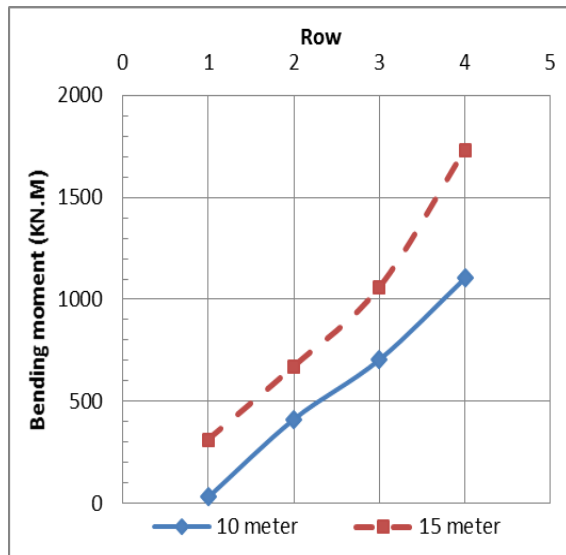


Figure 8. Bending moment in pile head

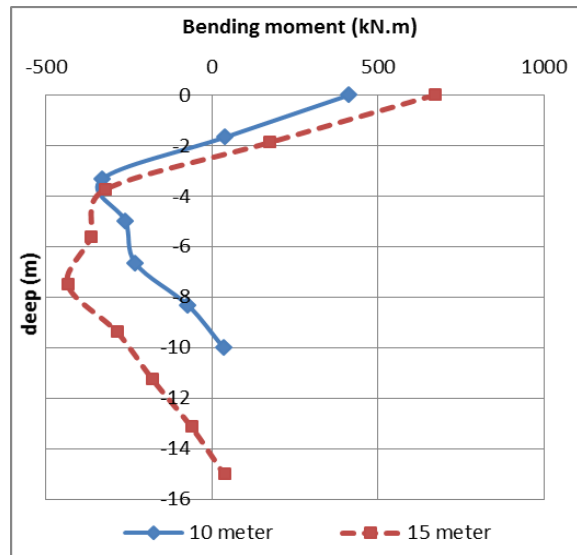


Figure 9. Compare bending moment in pile

### VARIATIONS OF PILE GROUP AXIAL FORCE WITH INCREASING THE LENGTH

Figure (10) shows the variations of axial force curve of the pile head. According to the figure, it is observed that, in both groups, the value of axial force increases from the first row to the fourth, which is due to the available bending moment that, as a result of rotation, the right side of the foundation is subjected to uplifting force and its left side to downward force.

It is also observed that, in all four rows, the value of axial force at the pile bottom in pile group of 15 m in length is more that in pile group of 10 m in length. By comparing the curves of piles of 15 m and 10 m in length as shown in Figure (11), it is observed that with increasing the length, axial force increases 14% as compared to 10 m pile.

Increasing the length leads to increased interlock between the soil and the pile; therefore, this increased interlock causes the axial force of the pile to increase. Thus, with increasing the pile length, the created axial force in pile increases.

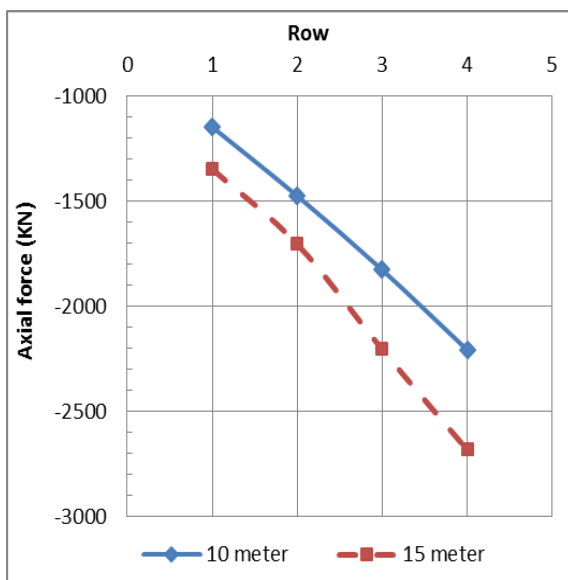


Figure 10. Bearing capacity of pile head

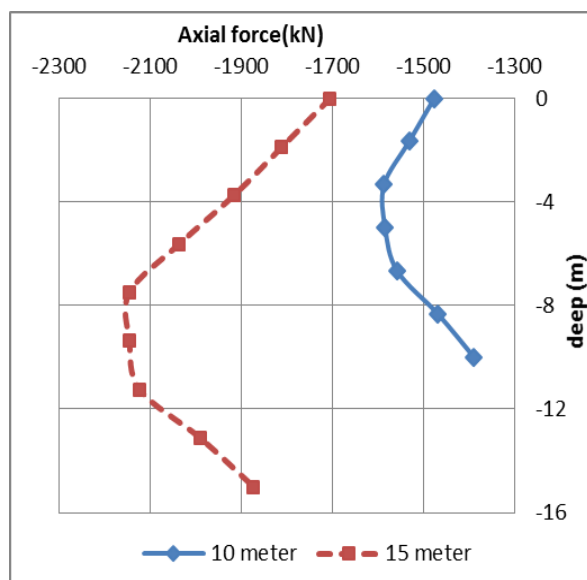


Figure 11. Compare bearing capacity of pile length



LATERAL DISPLACEMENT OF PILE GROUP IN THE X-DIRECTION

Figure (12) shows the lateral displacement curve of the pile head in pile group of 10 and 15 m. According to the figure, it is observed that, as moving away from lateral loading, the value of displacement in rows progressively decreases; moreover, the value of lateral displacement of pile head in pile group of 15 m in length is more than of 10 m in length. In addition, Figure (13) shows that with increasing the length, lateral displacement along the length of the pile increases.

This process can also be observed in Equation (4). This equation is Matlock & Reese Equation and shows the lateral displacement along the length of the pile.  $[M_1]$  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 (4).  $[E]$  is the modulus of elasticity,  $[I]$  is the moment of inertia of pile, and  $[A_Y, B_Y]$  are coefficients which are obtainable from the related Table (6), and are directly proportional to the length of the pile and increase with increasing the pile length. According to this equation, it is also observed that with increasing the pile length the value of lateral displacement increases.

$$X = A_Y \left[ \frac{P_1 T^3}{EI} \right] + B_Y \left[ \frac{M_1 T^2}{EI} \right] \tag{4}$$

Table 6.  $A_Y$  and  $B_Y$

Z	$A_Y$	$B_Y$	Z	$A_Y$	$B_Y$
0.00	2.43	1.62	0.9	1.08	0.44
0.1	2.27	1.45	1	0.96	0.36
0.2	2.11	1.29	1.2	0.73	0.22
0.3	1.95	1.14	1.4	0.54	0.11
0.4	1.79	1	1.6	1.38	0.029
0.5	1.64	0.78	1.8	0.24	-0.03
0.6	1.49	0.75	2	0.14	-0.07
0.7	1.35	0.64	3	-0.07	-0.089
0.8	1.21	0.54	4	-0.05	-0.028

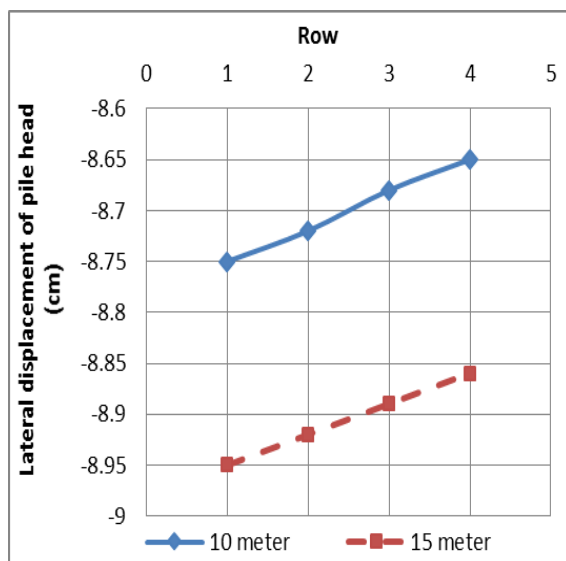


Figure 12. Lateral displacement of pile head

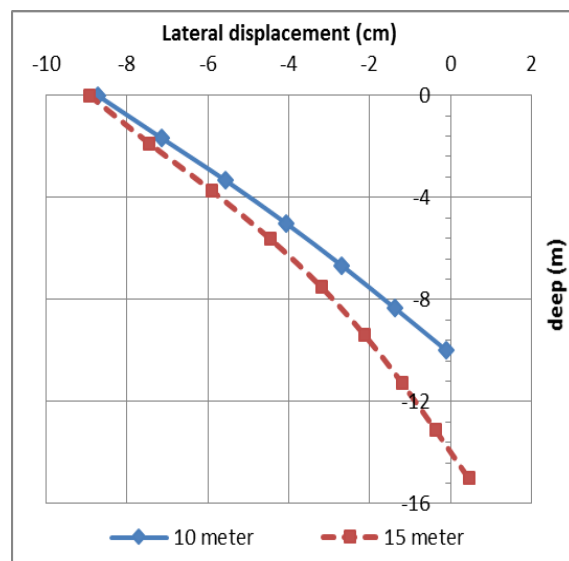


Figure 13. Compare lateral displacement Pile length

## CONCLUSION

The operation of deep foundations has attracted the attention of many researchers. Furthermore, noting the importance of composite loads and the exerted bending moment on the pile group, in this article, this subject has been precisely studied. For this reason, two pile groups with lengths of 10 m and 15 m subjected to composite loads and bending moment in sand were studied and analyzed using numerical modeling, and considering the assessment driven from the achieved results, it was observed that with increasing the length of the piles, the contact surfaces between the pile and the soil increases, and so the pile becomes difficult to move in the soil, causing the vertical displacement along the length of the pile to decrease.

Furthermore, friction between the pile and the soil leads to increased bearing capacity of the piles. Considering the results, it was observed that with increasing the length of the piles, lateral displacement increases, and since displacement is directly proportional to bending moment, bending moment also increases with increasing the pile length.

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