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Lateral behavior of piles with different cross sectional shapes under lateral cyclic loads in granular layered soils

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Abstract

Piles or drilled shafts used in bridge foundation, waterfronts, and high rise buildings are generally subjected to lateral loads. In order to study the effect of concrete pile geometry on the structural behavior in layered soils, several models with different shapes and dimensions for single piles and different properties for two soil layers with variable thickness were selected and analyzed using the finite difference method. The performance of single piles situated in layered granular soil with different compaction and thicknesses were studied in two cycles of lateral loading and unloading. The applied finite difference procedure is also validated based on experimental and published results. The pile head displacement occurs due to pile's deformation and rotation. Deformation causes internal forces in pile, though rotation induces stress in surrounding soil. The pile head displacement of different models due to their overall deformation and rotation were calculated under maximum loading. For a comparison of pile head displacement due to their overall deformation and rotation in different models, the "performance index" is defined as the ratio of "displacement due to deformation" to the "total displacement".

Keywords: *Layered soils, Geometric piles, Lateral load, Cyclic load, Soil-pile interaction.*

1. Introduction

Soil-pile interaction possesses an important role in evaluating pile behavior under lateral loads. Several analytical methods have been developed to analyze the response of laterally loaded piles, including the elastic continuum [1] [2], finite element [3], elastic subgrade reaction [4] [5] [6], and p–y [7] [8] methods. In a study considering numerical solution for laterally loaded piles situated in layered soil [9], it was found out that although nonlinear p–y analysis is the most widely used design method for these piles, an elastic subgrade reaction solution is a good alternative for computing pile deflection under small working loads because of its simplicity and ease of use. Reese & Van Impe [10] studied the pile behavior assuming five different conditions and methods: both pile and soil in continuous elastic spaces, pile in elastic behavior and soil in semi-infinite space, pile as a rigid and soil in a non-elastic condition, the CLM (characteristic load method) and the p-y curve method.

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However, piles are often embedded in layered soils, such as a clay layer overlying on rock. The stiffness of soil could vary with depth, such as in sand and sedimentary rock, or remain constant with depth, such as in clay. Although the solutions proposed by Davisson and Gill [6] and Pise [2] can be used for piles in layered soils under small service loads, provided that stiffness of soil consider as constant with depth for each layer. This may not sufficiently represent the actual soil profiles, especially when soil stiffness varies with depth. The pile stress distribution depends effectively on the surrounding soil properties. Regarding soil-pile interaction and effect of soil behavior on pile, more accurate elasto-plastic models such as Mohr-Coulomb or Drucker-Prager are more suitable. Also, due to the fact that mohr-colomb parameters can be obtained from simple tests and are usually available, they are frequently used in initial calculation of piles' bearing capacity [11]. Brown and Shie [12] [13] and Trochanis et al. [14] conducted a series of 3D FEM studies on the behavior of a single pile and a pile group with the elasto-plastic soil model. These researchers used interface elements to consider pile-soil interaction. Moreover, Brown and Shie derived p-y curves from FEM data, which provide a comparison of the FEM results with the empirical design procedures in use. Kimura et al. [15] conducted a 3D FEM analysis of the ultimate behavior of laterally loaded pile groups in layered soil profiles, the soil behavior was modeled by the Drucker–Prager model and pile by nonlinear beam elements. Information about the lateral behavior of piles in layered soil profiles is very limited. Some analytical studies have been conducted by Davisson and Gill [6] and Lee and Karunaratne [16] to define the influence of pile length, the thickness of the upper layer, and the effect of relative stiffness of adjacent layers to the pile with the assumption that the response of soil is elastic. Yang and Jeremic [9] studied the effect of soil layers on pile lateral behavior, using the finite element method and nonlinear elastic-plastic soil behavior. In their research, finite element results were used to draw p-y response curves, to study the soil layering effects. According to the analysis results the layering effects are formed in two ways. The lower layers are affected by the upper layers as the upper layers are also affected by lower ones. Moreover, the layering effects are not symmetric. When the pile is laterally loaded at the head, an interface extends into the upper layer is more effective than that for the lower layer at small displacements.

Ashour et al. [17] studied the lateral behavior of pile groups in layered soils. They used the strain wedge model which was developed to analyze the response of a long flexible pile influenced by a horizontal uniform load at the top of pile and layered soil (sand and/or clay) .The pile reaction is characterized by three-dimensional soil–pile interaction which is then changed into its equivalent one-dimensional beam on elastic subgrade and the related parameter (modulus of subgrade reaction, E_s) would be variable along its length. In a pile group the interaction between the piles are based on the geometry and interaction of the mobilized passive sections of soil adjacent to the piles related to the pile spacing. Furthermore in a group the overlap of shear zones between the piles differs along the length of the pile and changes from one soil layer to another in the soil profile.

In a study by Eslami et al. [18] on pile-raft foundation systems, it has been mentioned that lateral bearing capacity of pile-groups is not significant in their vertical behavior , so they can be non-connected to foundation, but in single piles, lateral bearing capacity and its effect on piles' performance is of particular importance.

In the lateral loads, the flexibility of piles and stiffness of their surrounding soil influenced by deformation of soil and pile causes the displacement of the pile head. Pile deformation and rotation are the two factors which create a different effect on the stresses and forces in the soil and pile. Different reactions of soil layers and soil-pile interaction, which depend on the shape of the pile cross section, has effect on these two factors. In this study the behavior of piles with different cross section shapes and dimensions in soil layers with different properties, under lateral load are compared and the displacement of the pile head in above mentioned parts are computed and analyzed separately to define the pile with suitable performance in each case.

2. Analysis Method

In this study, several models of piles with circular & rectangular cross sections with different dimensions in granular layered soil are studied and the analysis results are presented based on the assumptions below:

1) The analysis is performed based on the finite difference method using FLAC 3D software.

2) The nonlinear analysis of 3D models is performed using the Mohr-Coulomb criteria for soil behavior and soil-pile interaction.

3) The behavior of the soil surrounding the piles which has 100 mm thickness is modeled using the "Interface Element". Mechanical properties are considered as 67 percent of the main values based on previous studies [19] [20].

4) The geometry of soil meshes surrounding the piles is modified based on stress variation in boundary zones to minimize undesirable boundary condition effects in the analysis. In addition, due to more effect of near soil elements to pile surface in analysis results, small dimensions contemplated for them, and elements dimensions are increasing with getting far from pile. Comparing repetitive analysis results with gradual variation of dimensions, results the appropriate ones, considering the least effect of dimensions in results. Figure 1 shows the gridding of piles and surrounding soil which is selected to minimize the analysis process.

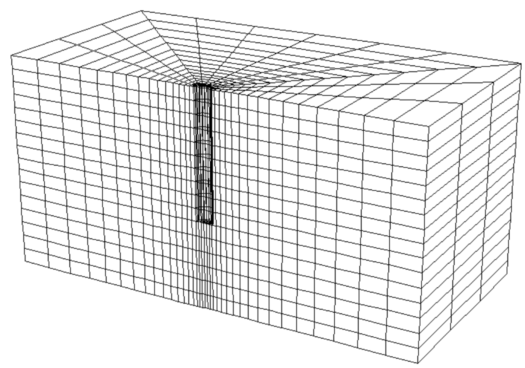


Fig. 1 Gridding of piles and surrounding soil

5) In order to minimize the analysis process, only half of each model is analyzed due to the symmetry.

6) 3D numerical analysis of piles is performed under incremental cyclic load with two loading and unloading cycles of piles with circular and rectangular cross sections. The load increment in the first cycle is 31.25kN and the maximum of this load is 125kN. The second loading cycle has been defined with a load increment equal to 62.5kN and its maximum load is 250kN. Applied loads are static and analysis is independent from loading time.

3. Validation of the Analytical Method

In order to validate the analytical procedure, the experimental results for pre-casted piles used and tested under lateral static cyclic loading in Fajr II site, are chosen and analyzed with numerical models. The aforementioned site is located in Mahshahr in Khuzestan Province near Persian Gulf, in southwest Iran where Fajr II petrochemical site is located. The results of test pile No.12, which are shown in Figure 2, are used in this study. Further information is available in a case study investigating driven piles' behavior by Hosseinzadeh Attar and Fakharian [21]. These circular cross sectional concrete piles have an outer/inner diameter of 450/270 mm, 90mm thickness and a length of 21m. Their compressive strength and the elastic modulus are 80MPa and 44000MPa, respectively. Region's soil is layered and its characteristics are listed in Table 1. Lateral static loading results are also shown in figure 3.

Table 1 Fajr II site's soil layer characteristics [21]

No.	Layer	Depth (m)	Thickness (m)	γ (kN/m³)	Es (MPa)	ν	C (kPa)	ϕ (deg.)
1	gravel	0-1	1	18-18.5	40	0.3	---	29
2	silt	1-13	12	18	10	0.4	15	5
3	sand	13-21	8	20	20	0.35	---	30

γ: Specific weight
Es: Modulus of Elasticity
ν: Poisson's Ratio
C: Cohesion
ϕ: Angle of internal friction

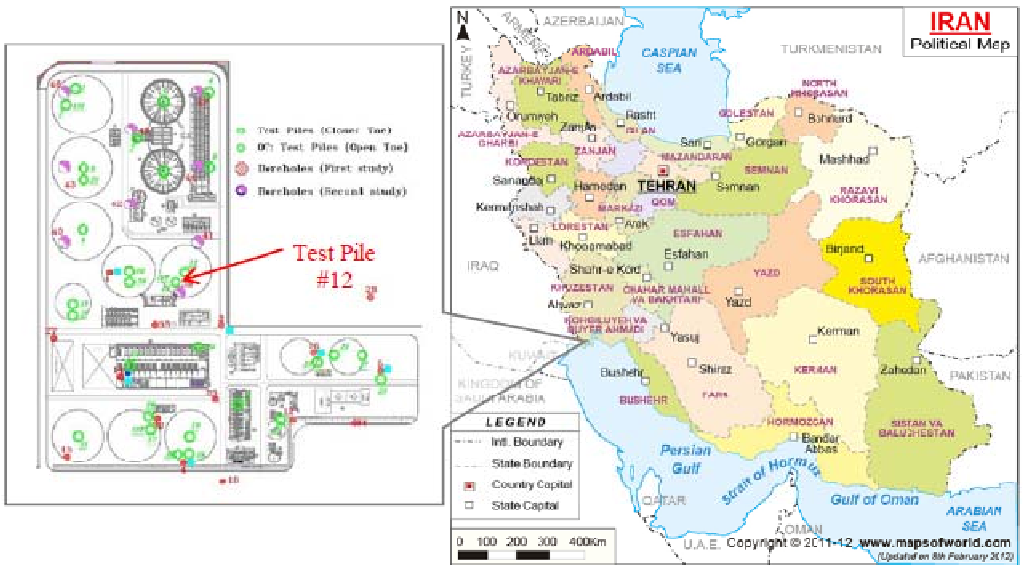


Fig. 2 Location of test pile No.12 in Fajr II site. Mahshahr, Iran [21]

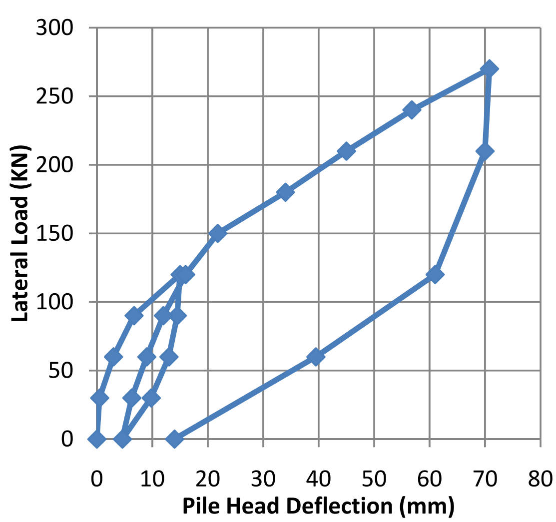


Fig. 3 Results of the lateral cyclic static loading [21]

Given values for lateral displacement of pile heads in a 3D analysis under the first cycle of loading and unloading are shown and compared with the experimental real scale data in figure 4. As it is shown in figure 4 the analytical and experimental results have acceptable correspondence. Relative difference between numerical analysis and experimental results are calculated in various steps of loading. Results show 4.2% difference in maximum load case, and the average difference in various loading steps is 30%. Obviously, the main difference occurs in middle steps of loading that were not considered in this study. According to the test results, the beginning of nonlinearity in soil behavior occurs under lower steps of loading in comparison with analytical results.

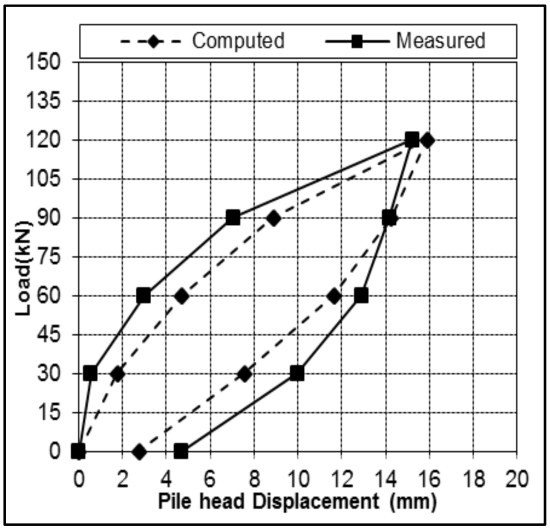


Fig. 4 Comparison of pile head displacement

4. Specifications of the Numerical Models

1) This study is performed using pile models with circular and square cross sections. The diameters of circular cross sections are 600mm and 1200mm with a length of 9m and length to diameter ratio ($\frac{L}{B}$, B: width or diameter of the section, L: the pile length) of 15 and 7.5 respectively. Selected dimensions and $\frac{L}{B}$ ratios are adopted to investigate the behavior of short and long piles. Square cross sections also have the same dimensions. The loading condition is defined as an incremental cyclic load with a maximum of 250kN for all piles.

2) The load is applied as a uniform horizontal stress on the pile head joints in every step of loading. Soil properties used in numerical analysis were obtained from test results of 3 different regions' soil. To study the effects of various compaction rates in soil layers on piles' behavior, the soil layers surrounding the pile are considered in 2 layers with different thicknesses and properties.

3) The soil was modeled in X, Y and Z directions up to a distance of 15m from the pile head with low compaction in the upper layer and high compaction granular soil in the bottom layer. The thickness of the upper layers for models were 3 m and 6 m, equal to one-third and two-thirds of the pile height. These models were also analyzed assuming a uniform soil in its total height with similar specifications and then compared with other models. Other geometrical and mechanical properties of soil layers are presented in tables 2 and 3.

Table 2 Soil layers Properties used for numerical analysis

Layer name	Soil	C (kPa)	ϕ	γ (kN/m3)	ν	Es (MPa)	Ks (MN/m3)
A	Loose Dense Sand	1	24	15.3	0.35	10	16
B	Medium Dense Sand	3.5	32	19	0.3	40	33
C	Gravel	10	36	21.3	0.3	65	175

K_s = Coefficient of lateral earth pressure

Table 3 Specification of models and the soil around them

No	Cross- sections	B(mm)	H(mm)	Elevation Layer"a"(m)	Elevation Layer"b"(m)	Elevation Layer"c"(m)
1	Circle	600	----	(-15) ~ 0	----	----
2	Square	600	600	(-15) ~ 0	----	----
3	Circle	1200	----	(-15) ~ 0	----	----
4	Square	1200	1200	(-15) ~ 0	----	----
5	Circle	600	----	----	(-15) ~ 0	----
6	Square	600	600	----	(-15) ~ 0	----
7	Circle	1200	----	----	(-15) ~ 0	----
8	Square	1200	1200	----	(-15) ~ 0	----

9	Circle	600	----	----	----	(-15) ~ 0
10	Square	600	600	----	----	(-15) ~ 0
11	Circle	1200	----	----	----	(-15) ~ 0
12	Square	1200	1200	----	----	(-15) ~ 0
13	Circle	600	----	(-3) ~ 0	(-15) ~ (-3)	----
14	Square	600	600	(-3) ~ 0	(-15) ~ (-3)	----
15	Circle	1200	----	(-3) ~ 0	(-15) ~ (-3)	----
16	Square	1200	1200	(-3) ~ 0	(-15) ~ (-3)	----
17	Circle	600	----	(-6) ~ 0	(-15) ~ (-6)	----
18	Square	600	600	(-6) ~ 0	(-15) ~ (-6)	----
19	Circle	1200	----	(-6) ~ 0	(-15) ~ (-6)	----
20	Square	1200	1200	(-6) ~ 0	(-15) ~ (-6)	----
21	Circle	600	----	(-3) ~ 0	----	(-15) ~ (-3)
22	Square	600	600	(-3) ~ 0	----	(-15) ~ (-3)
23	Circle	1200	----	(-3) ~ 0	----	(-15) ~ (-3)
24	Square	1200	1200	(-3) ~ 0	----	(-15) ~ (-3)
25	Circle	600	----	(-6) ~ 0	----	(-15) ~ (-6)
26	Square	600	600	(-6) ~ 0	----	(-15) ~ (-6)
27	Circle	1200	----	(-6) ~ 0	----	(-15) ~ (-6)
28	Square	1200	1200	(-6) ~ 0	----	(-15) ~ (-6)
29	Circle	600	----	----	(-3) ~ 0	(-15) ~ (-3)
30	Square	600	600	----	(-3) ~ 0	(-15) ~ (-3)
31	Circle	1200	----	----	(-3) ~ 0	(-15) ~ (-3)
32	Square	1200	1200	----	(-3) ~ 0	(-15) ~ (-3)
33	Circle	600	----	----	(-6) ~ 0	(-15) ~ (-6)
34	Square	600	600	----	(-6) ~ 0	(-15) ~ (-6)
35	Circle	1200	----	----	(-6) ~ 0	(-15) ~ (-6)
36	Square	1200	1200	----	(-6) ~ 0	(-15) ~ (-6)

5- Evaluation of the results

The investigated variable in the analysis is the pile head displacement due to the piles' overall deformation and rotation.

In compared models in each group, the sides that are pressed into the soil have similar width or diameter. In this condition, bending stiffness of the pile with square cross section and the pile with circular cross section are not the same and the stiffness of pile with square cross section is 1.7 times larger than pile with circular cross section. Part of the "pile head displacement" caused by pile rotation, generally depends on soil stiffness; and part of the "pile head displacement" caused by its deformation generally depends on the pile stiffness.

Moreover the displacement due to rotation only creates stress in soil, but displacements due to deformation represent the internal force in the pile element. Therefore, the separation of these two parts which create the pile head displacement together is necessary to investigate stresses and internal forces in pile head and soil. According to the difference of the bending stiffness of piles, in order to compare the models, two parts of pile head displacement due to pile rotation and deformation were separated.

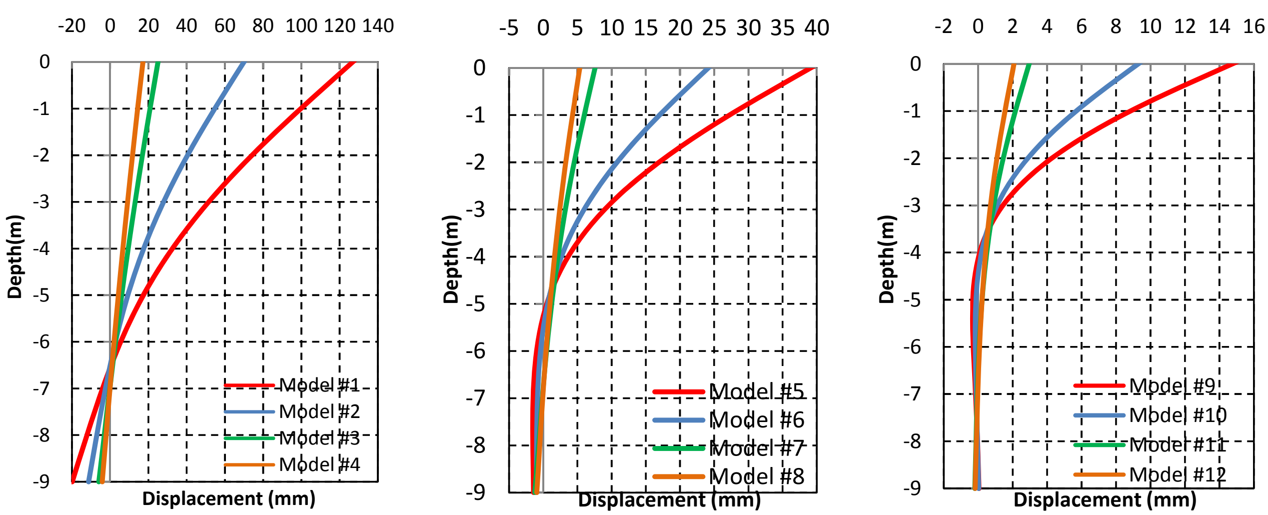
The (i) index ($i = \frac{\Delta d}{\Delta t}$, Δd: displacement due to deformation, Δt: overall displacement) has been selected as an index for comparison of the behavior of various models. By comparing the (i) index in models, the effect of pile cross-section shape is evaluated in layered soils with various thickness and stiffness values. The pile length (L) is divided into 10 equal parts in order to calculate the displacement due to pile deformation. Then, the displacement of each point is extracted from the results of the analysis. Based on the obtained coordinates for the piles, the deformation curves are estimated using a sixth-order equation. The equation of the tangent line is obtained at the confluence of the curve with vertical axis (initial position of pile). The displacement due to pile deformation is calculated by subtracting the corresponding values obtained from the deformation curve and the tangent line at the pile head. These values have been extracted at the maximum load on the pile head. The overall displacement and the displacement due to deformation at the pile head are given in Tables 4 and 5. Figures 5 and 6 show the deformation curves and the (i) index for various models.

Table 4 The overall displacement at the pile head in various models

Model	Displacement	Model	Displacement	Model	Displacement	Model	Displacement
1#	127.0	10#	9.3	19#	20.7	28#	11.2
2#	70.0	11#	3.0	20#	13.6	29#	32.4
3#	25.1	12#	2.1	21#	57.7	30#	20.3
4#	17.1	13#	74.4	22#	35.2	31#	5.3
5#	39.1	14#	44.7	23#	8.0	32#	3.7
6#	24.1	15#	11.9	24#	5.5	33#	38.6
7#	7.6	16#	8.2	25#	103.1	34#	24.0
8#	5.3	17#	112.4	26#	59.1	35#	7.0
9#	14.7	18#	64.3	27#	16.9	36#	4.9

Table 5 The displacement due to deformation at the pile head in various models

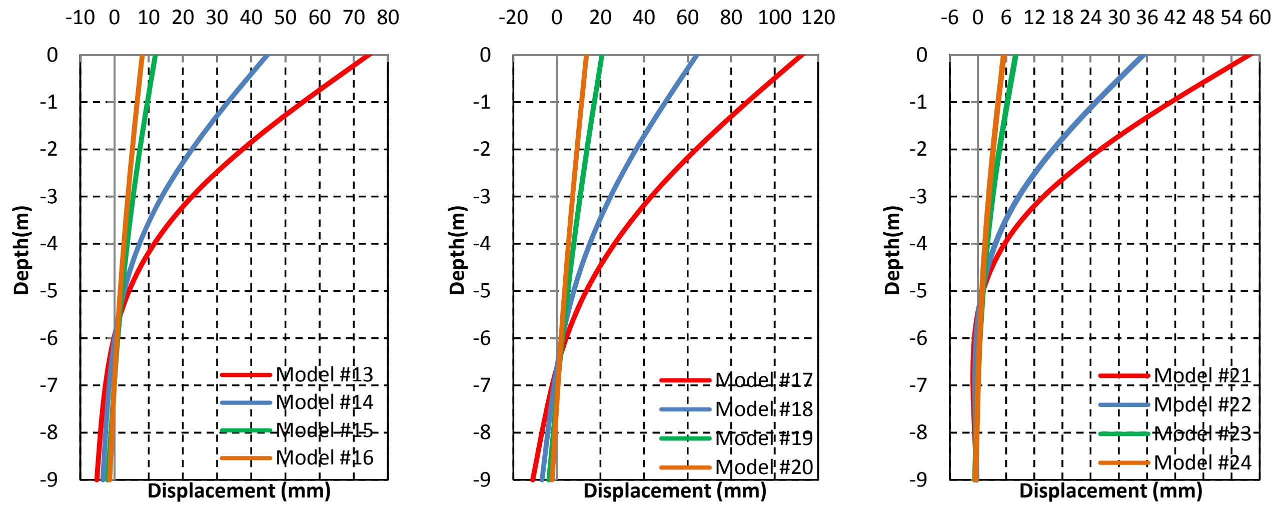
Model	Displacement	Model	Displacement	Model	Displacement	Model	Displacement
1#	64.9	10#	7.9	19#	5.7	28#	4.2
2#	35.8	11#	2.3	20#	3.4	29#	26.5
3#	4.7	12#	1.4	21#	47.3	30#	16.8
4#	2.6	13#	54.8	22#	29.6	31#	3.8
5#	30.7	14#	32.7	23#	5.3	32#	2.3
6#	18.9	15#	4.9	24#	3.2	33#	33.8
7#	3.5	16#	2.9	25#	84.3	34#	19.9
8#	2.1	17#	71.4	26#	47.2	35#	4.3
9#	12.1	18#	39.8	27#	7.1	36#	2.6



(a) Pile group with whole length buried in layer "a"

(b) Pile group with whole length buried in layer "b"

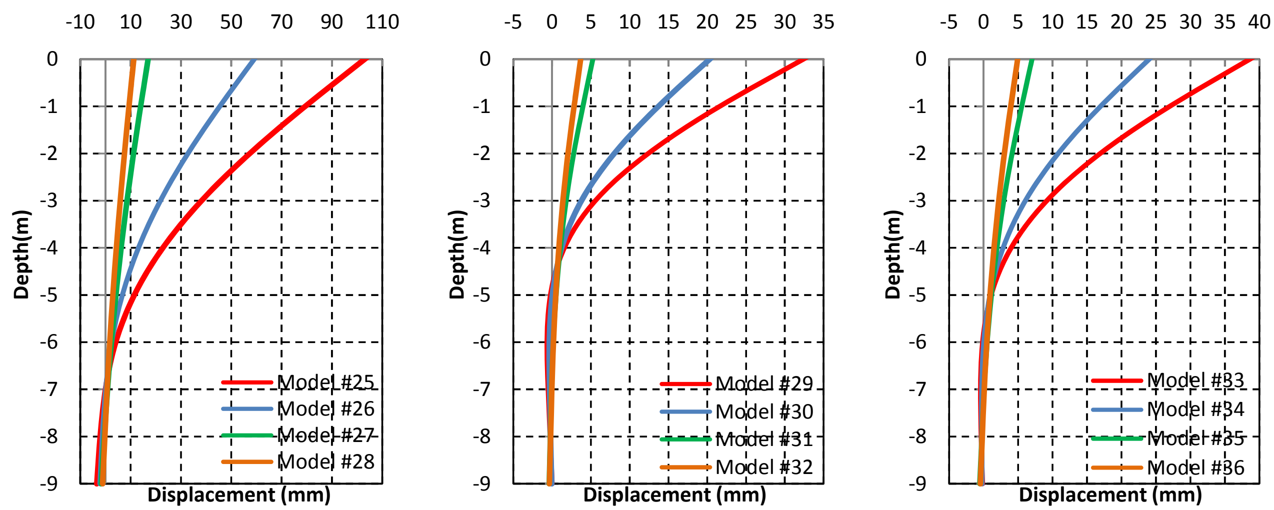
(c) Pile group with whole length buried in layer "c"



d)Pile group with1/3 length buried in layer "a" and 2/3 length buried in layer "b"

(e)Pile group with 2/3 length buried in layer "a" and 1/3 length buried in layer "b"

(f)Pile group with 1/3 length buried in layer "a" and 2/3 length buried in layer "c"

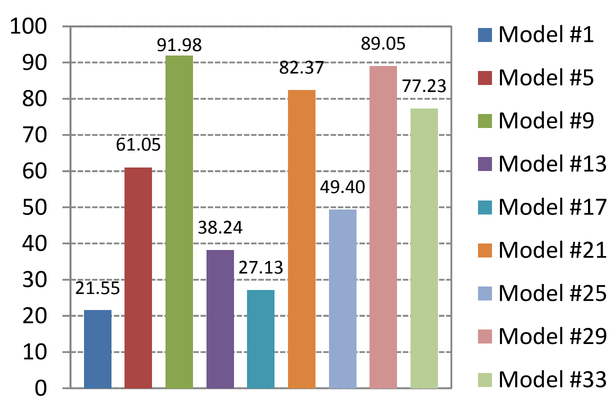


(g) Pile group with 2/3 length buried in layer "a" and 1/3 length buried in layer "c"

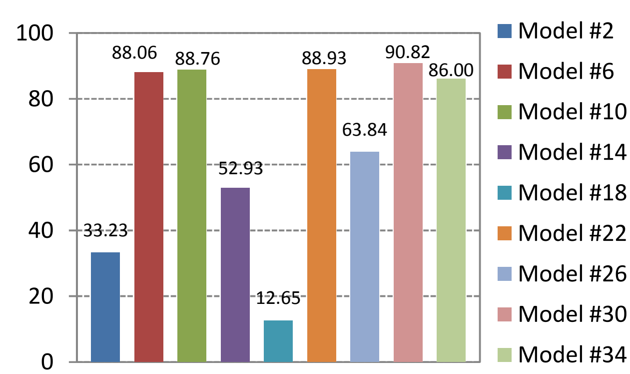
(h) Pile group with 1/3 length buried in layer "b" and 2/3 length buried in layer "c"

(i) Pile group with 2/3 length buried in layer "b" and 1/3 length buried in layer "c"

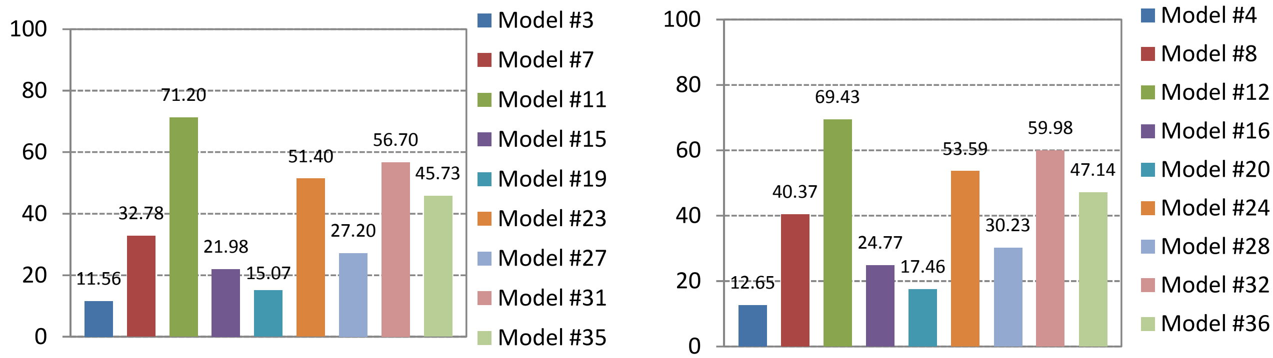
Fig.5 Deformation curves for various models, in groups with similar soil layers (specified in table 3)



(a) Pile group with circular cross section (D=600mm)



(b)Pile group with square cross section (B=600mm)



(c) Pile group with circular cross section (D=1200mm) (d) Pile group with square cross section (B=1200mm)

Fig.6 (i) Index for various models

The models were classified in different groups based on the following conditions:

A) Various cross-section shapes with the same $\frac{L}{B}$ ratio.

B) Various conditions of the layers in various models with the same pile cross-sections.

C) Different $\frac{L}{B}$ ratios of the same cross-section shapes and layers in the models.

The defined index is compared in different categories. By comparing the square and circular piles with a width or diameter of 1200mm, it has been observed that the (i) index has more sensitivity to soil layer characteristics and their thicknesses. In other words, the soil conditions (thickness and characteristics of the layers) are more effective in providing supporting conditions for reducing the pile-tip rotation in the case of square piles.

The efficiency was similar in square and circular piles, by decreasing the pile cross-section dimension to 600 mm. The average difference of (i) index is 0.34% between the two cross sections with a dimension of 600 mm. Its value is increased to 6.2% between the two cross sections with a dimension of 1200 mm.

By increasing the $\frac{L}{B}$ ratio, the rigidity of the compact soil mass is decreased and their dependency on soil stiffness is reduced. Therefore, the differences between piles' behavior is decreased in piles with various cross-section shapes. In the piles with square cross sections having larger dimensions, greater volume of passive soil will be situated in front of the upper portion and the back of the lower portion of the pile. But due to the raise in pile bending stiffness, passive soil has less effect on pile behavior. Therefore, the comparison of the indices in the piles with a dimension of 1200 mm has received more attention. The following results were obtained:

- Cross-sectional shape's influence when soil is changing from compact (type c) to loose (type a) in upper layer with a thickness of one-third of pile's length, in comparison with the state that whole length of pile is embedded in compact soil is not significant. In this condition by reducing soil density in upper layer the (i) index difference will reduce from 9% (Models #11 and #12) to 7.5% (Models #23 and #24). When upper layer thickness is equal to two-third of pile's length, by changing soil characteristics, pile cross section shape has more influence on reduction of (i) index. As the difference of (i) index in circular and square models reaches 2.4% (Models #19 and #20). Also this difference reaches 3.7% (Models #3 and #4) when soil is loose in all height of pile. It means the influence of soil density variations in middle third layer is more than variations in upper or lower third layers.
- Most variations of (i) index due to variations of cross-sectional shape, in piles with a dimension of 600 mm, would happen when soil in lower layer is compact and in middle and upper layer is medium compact (Models #33 and #34). According to deflection curves of these models, it's observed that in lower layer, curves are coincident, it means that support conditions to avoid pile's tip rotation in both states has been provided and there is no dependence to pile's stiffness. But in the upper part, square pile's displacement is reduced and pile stiffness and its interaction with soil has more influence.

Comparing the analysis results of piles with circular and square cross sections with same width and diameter, shows that soil-pile interaction under lateral load depends on pile cross section shape. Also, soil layers properties can change the amount of this influence.

As a result, exact investigation of pile behavior under lateral load –considering its interdependence on active volume surrounding soil that is preventing pile displacement– should perform in 3D analysis and simultaneous modeling of pile and surrounding soil, considering pile-soil interaction.

6- Conclusion

In the present research on laterally loaded piles, the effects of piles' cross sectional shapes on their behavior in layered granular soils is investigated. The piles' loading and unloading are in step-loading pattern. The considered variable in the analysis is pile's head displacement due to their deformation and general rotation. For the analysis and comparison of results, different piles are categorized in groups with similar cross sectional shapes and dimensions (diameter or width). Also, a comparison index is defined as the ratio of "displacement due to deformation" to "total displacement".

It is observed that the considered index has more sensitivity to soil layer characteristics and their thicknesses in square and circular cross sectional shapes with larger dimensions. This means that soil conditions such as thickness and characteristics of the soil layers are more effective on fixity of tip and reduction of pile rotation in the square piles with larger aspects.

The compact soil mass in front of the top section of the pile and behind the lower section of the pile is greater in the square cross section piles. Therefore by increasing the cross section dimensions and pile stiffness and reducing their dependence on the stiffness of soil, changes in soil characteristics will cause less impact on the behavior of piles.

The pile cross section is more influential when soil characteristics change in two-third of the soil layer adjacent to the top of the pile than one-thirds of the upper layer. As the cross sectional shape is changed, the volume of the active soil in the front and back of pile is changed. Therefore, the degree of fixity of pile tip is more dependent on the lower layer of the soil. While in the piles with the same cross sectional shape, the pile end conditions are similar and total displacement and rotation tendency is more dependent on the upper soil layer. Thus, the upper soil layer conditions are more influential in the analysis results.

In the circular and square piles, by loosening the upper layer of the soil, the deformation portion into total displacements is reduced. This reduction is more significant in piles with larger cross-sectional dimensions, because as the soil stiffness of the upper soil layer is reduced, bending stiffness of pile is the determining factor in its deformation and rotation. Rotation is more effective in this case. Also pile's end fixity is reduced due to reduction of upper layer's stiffness. This behavior is caused by less fixity of square piles in loose soil. By increasing the soil stiffness or cross sectional dimension, the behavior of piles with different cross sectional shapes would be more different.

In conclusion, results show that circular and square cross section pile behavior with width or diameter equal to 600 mm are similar. Also, it's observed that when diameter or width is equal to 1200 mm, pile behavior difference appears between square and circular cross sections, and square cross section results in less pile head displacement. Also due to reduction of deformation portion in total displacement, internal forces decrease. Therefore in large dimensions, despite the convenient execution of circular piles, square piles is recommended due to its better performance.

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