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Pile head displacements with different cross sectional shapes under lateral loading and unloading in granular soils

P. Vahabkashi* **and A. Rahai**

Department of Civil Engineering, Amir Kabir University of Technology, Tehran, Iran.

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Cross sectional shapes;
Dissipated energy.

Abstract. Piles in structural foundations that are used to load transmissions from the main structure to the bed are generally subjected to lateral loads. In order to study the effect of concrete pile geometry on its structural behavior, several models with different shapes and dimensions were selected and analyzed, assuming nonlinear behavior for soil. The behavior of the pile models was studied, evaluated and tabulated using numerical analysis under different conditions, such as changes in the pile geometry and shape, and soil properties. Therefore, the displacements of pile heads situated in granular soil, with different compaction levels, under a lateral load, were studied in loading and unloading cycles. The dissipated energy was calculated based on pile head displacements in different load steps in the first and second cycles of loading. The "performance index" is defined as the ratio of dissipated energy to the maximum pile head displacement, and these two factors effects on different pile model behavior were compared, concurrently. It was observed that piles with rectangular cross sections and smaller width have the maximum dissipation of energy, and the minimum displacement occurs in dense soil.

1. Introduction

Pile behavior under lateral loads should be investigated, considering those parameters which influence it effectively, such as pile geometry and rigidity, pile connections to caps whether hinged or fixed, and soil properties. Stress distribution in soil surrounding the pile under lateral loads is not uniform, and its formation also depends on the soil behavior model.

Gazetas and Gerolymos (2005) [1,2] studied the results of comparing the 4-spring Winkler model and the finite element method, for both rigid and flexible caisson foundations, and recommended the Winkler model, due to its simplicity and generalization capability for inelastic soil. Reese and Van Impe (2001) [3] studied pile behavior assuming five different conditions and methods: both pile and soil in continuous elastic, pile in elastic behavior and soil in semi-infinite space, pile under rigid conditions and soil under non-elastic conditions, the CLM (Characteristic Load Method) and the $p-y$ curve method. Brown and Shie (1990, 1991) [4,5] and Trochanis et al. (1991) [6] 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.

According to research by Greimann et al. (1987) [7], performed on SPI (Soil-Pile Interaction) in the abutment of single span bridges, an analytic algorithm was used, based on a developed non-linear finite element method, to compute the stresses and

*. *Corresponding author. Mobile: +98 912 1432893;*
Fax: +98 21 66509003
E-mail addresses: Vahabkashi@aut.ac.ir (P. Vahabkashi); Rahai@aut.ac.ir (A. Rahai)

internal forces in piles. In this analysis, to model the pile, beam-column elements with nonlinear geometry and materials were used. Also, to model the soil, nonlinear springs were applied and a modified model was introduced to define a tangential stiffness in non-linear spring elements. Several numerical examples are presented for evaluating the validity of the mentioned model. In 2001, another survey was performed by Ellis and Springman [8] in which the effect of soil-pile interaction on the behavior of piles under the abutment of a single span bridge in plane-strain state was studied. In this study, a series of geotechnical experiments were carried out on some piles situated in soft clay. The test results were compared with the above-mentioned numerical analysis. The structural behavior of some elements (especially piles) did not match the plane strain assumptions, hence, some other methods were proposed, and their validity was examined by experiment. Finally, it was demonstrated that side abutments and the soil around them should also be modeled in 3D space.

Several analytical methods have been developed to analyze the response of laterally loaded piles, including the elastic continuum [9,10], finite element [11], elastic subgrade reaction [12-14], and $p - y$ [15,16] methods. The choice of a constitutive model depends on several factors, but, in general, it is related to the type of analysis that the user intends to undertake the expected precision of predictions and knowledge of the soil [17].

In a study by Movemen (2005) [18], a pile model was analyzed, based on the displacement control method, using FLAC 3D software, to evaluate the pile response and the lateral pressure caused by the slope of the soil surface around the abutment in a transitional failure mode. The soil under the surface layer had low strength as a liquefied soil layer. This study included investigation of kinematic loads and soil 3D displacement effects on the responses of pile or pile groups [2×2] subjected to lateral pressure. The results prove that the proposed displacement method can be used for designing the piles which are under lateral soil displacement or can be applied to the analysis of soil-pile stability. Analytical results show the important effect of soil and pile parameters and the relative stiffness between soil and pile on failure models.

Piles are often embedded in layered soils, such as a clay layer overlying the rock. The stiffness of soil can 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 (1963) [14] and Pise (1982) [10] can be used for piles in layered soils under small service loads, the stiffness of soil is still required to be 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 the 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 for initial calculation of pile bearing capacity [19].

Ashour et al. (2004) [20] 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 the pile and layered soil (sand and/or clay). Pile reaction is characterized by three-dimensional soil-pile interaction, which is then transformed into its equivalent one-dimensional beam on an elastic foundation and the related parameter (modulus of subgrade reaction, E_s) variation along the pile length. In a pile group, the interaction between piles is 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 piles differs along the length of the pile and changes from one soil layer to another in the soil profile.

Pile flexibility, which causes energy dissipation during an earthquake, is dependent on the pile head displacement that should be limited to provide appropriate conditions for the structure leaning on the piles. Therefore, the separate study of dissipated energy and pile head displacement does not show the proper behavior of piles. In this study, we have endeavored to investigate the energy dissipation and displacement of the pile head concurrently to find the most suitable cross section, having maximum energy dissipation and minimum pile head displacement.

2. Analysis method

In this study, several models of circular and rectangular piles with different geometries in granular soil with various compactions have been investigated, and the analysis results are presented based on the assumptions below:

1. The nonlinear analysis of 3D models is performed using the Mohr-Coulomb criteria for soil behavior and soil-pile interaction.
2. The behavior of pile material is modeled as elastic isotropic.
3. The behavior of the soil surrounding the piles, which has 100 mm thickness, is modeled using the "Interface Element". FLAC 3D provides interfaces that are characterized by Coulomb sliding. Friction angle and cohesion parameters are defined in order

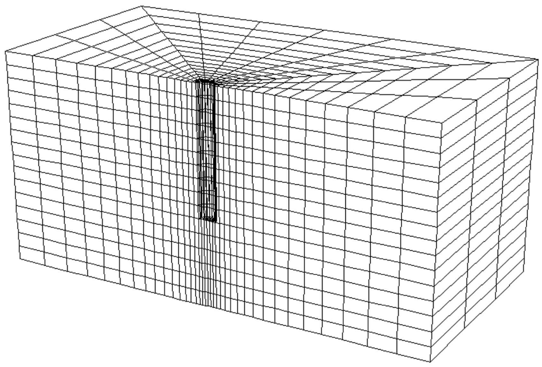


Figure 1. Gridding of piles and surrounding soil.

to calculate the values of sliding, penetration or separation of two surfaces. These parameters are considered as 67 percent of the main values, based on previous studies [21,22].

4. To minimize boundary condition effects in analysis, the geometry of soil meshes surrounding the piles is modified based on stress variation in boundary zones. The finite difference mesh is shown in Figure 1.
5. 3D numerical analysis of piles is performed under incremental cyclic loading with two loading and unloading cycles. For some models, the increment load in the first cycle is 31.25 kN, and in the second cycle is 62.5 kN. Also, maximum load is 125 kN in the first cycle and 250 kN in the second cycle. For other models, the increment load is 62.5 kN in the first cycle, and 125 kN in the second cycle. Maximum load is 250 kN and 500 kN in the first and second cycles, respectively. More details of different model characteristics are shown in Table 1.
6. In order to minimize the analysis process, only half of each model is analyzed, due to the symmetry.
7. The analysis is performed based on the finite difference method using FLAC 3D software. In order to obtain an appropriate grid space value in the vertical direction, which has a significant impact on the numerical analysis results, an initial value of 900 mm (equal to 1/10 pile's length) has been chosen, and with its reduction in sequential analyses, a proper grid space of 150 mm has been acquired.

3. The validity of the analytical method

To validate the analytical procedure, the experimental results for pre-casted piles, used and tested under lateral static cyclic loading in the Fajr II site, are chosen and analyzed with numerical models. The aforementioned site is located in Mahshahr, Khuzestan Province, near the Persian Gulf, southwest Iran, where the Fajr II petrochemical site is located. The results of the lateral load test of pile No.12, which is shown in Figure 2, have been considered in this study. Further information is available in a case study investigating driven pile behavior by Hosseinzadeh Attar and Fakharian (2013) [23]. These circular hollow section concrete piles have an outer diameter of 450 mm, a thickness equal to 90 mm, and a length of 21 m. The compressive strength and elastic modulus of concrete are 80 MPa and 44000 MPa, respectively. The region's soil is layered and its characteristics are listed in Table 2. Lateral static loading results are also shown in Figure 3.

The resulting values for lateral displacement of pile heads in 3D analysis, under the first cycle of loading and unloading, are shown and compared with the experimental real scale data in Figure 4. As shown in this figure, the analytical and experimental results have acceptable agreement. The relative difference between numerical analysis and experimental results has been calculated for various steps of loading. Results show a 4.2% difference in maximum load case, and the average difference in various loading steps is 30%. This is due to the fact that the beginning of nonlinearity in soil behavior occurs under lower steps of loading, relative to analytical results. As the aim of this study is to compare pile behavior in various models, and the absolute values of results in the middle steps of loading have not been considered, the existing difference has no major impact on the conclusion and when making inferences.

4. Specifications of the numerical models

This study is performed using pile models with cross-shaped, circular and rectangular cross sections, as shown in Figure 5. Pile length is 9 meters, and the diameter or width of cross sections are 600 mm

Table 1. Fajr II site's soil layer characteristics.

No.	Layer	Depth (m)	Thickness (m)	γ (kN/m^3)	E_s (MPa)	V	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; E_s: Modulus of Elasticity;

V: Poisson's Ratio; C: Cohesion; ϕ: Angle of internal friction.

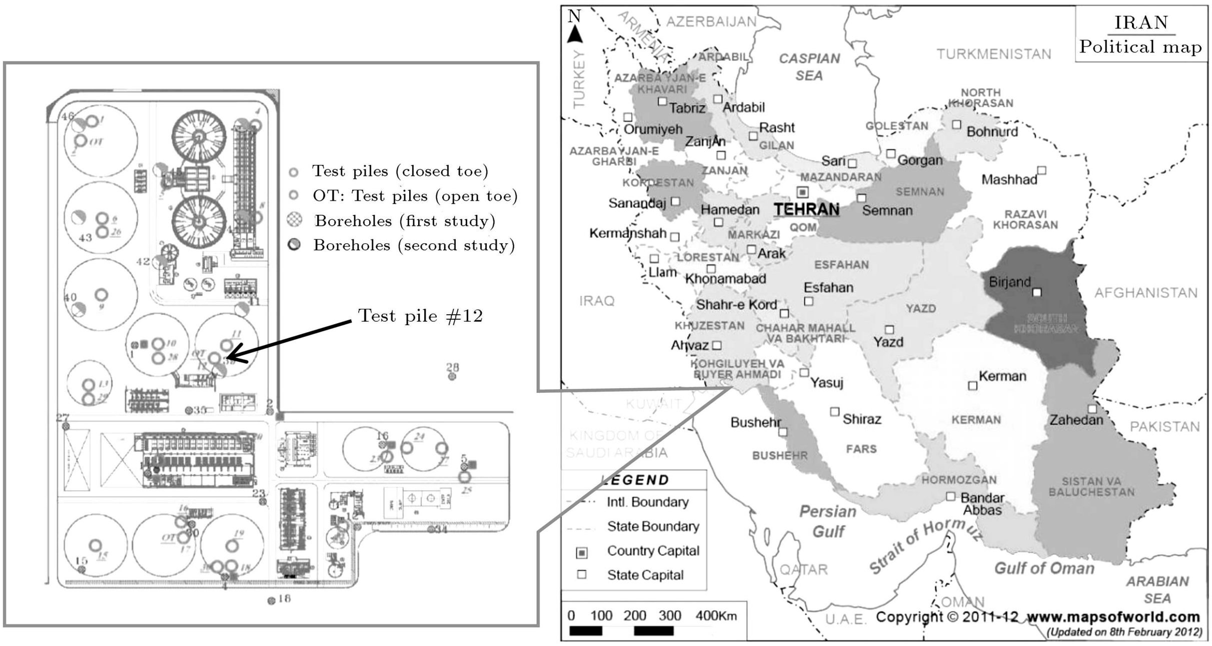


Figure 2. Location of test pile no.12 in Fajr II site, Mahshahr, Iran.

Table 2. Specifications of pile models and the soil around them; K_s = Coefficient of horizontal subgrade reaction.

No.	Cross-section	B (mm)	H (mm)	$I*10^{-8}$ (mm^4)	C (kPa)	ϕ	Dr (%)	γ (kN/m^3)	V	E_s (MPa)	K_s (MN/m^3)	$V_{\max}$ (kN)
1	Circle	600	—	63.58	10	36	80	21.3	0.3	65	175	250
2	Square	600	600	108	10	36	80	21.3	0.3	65	175	250
3	Rectangular	300	1200	432	10	36	80	21.3	0.3	65	175	250
4	Rectangular	1200	300	27	10	36	80	21.3	0.3	65	175	250
5	Rectangular	300	1200	432	10	36	80	21.3	0.3	65	175	500
6	Rectangular	1200	300	27	10	36	80	21.3	0.3	65	175	500
7	Rectangular	600	1200	864	10	36	80	21.3	0.3	65	175	500
8	Rectangular	1200	600	216	10	36	80	21.3	0.3	65	175	500
9	Cross shape	300	1200	452.25	10	36	80	21.3	0.3	65	175	500
10	Cross shape	600	1200	972	10	36	80	21.3	0.3	65	175	500
11	Circle	600	—	63.58	1	24	20	15.3	0.35	10	16	250
12	Square	600	600	108	1	24	20	15.3	0.35	10	16	250
13	Rectangular	300	1200	432	1	24	20	15.3	0.35	10	16	250
14	Rectangular	1200	300	27	1	24	20	15.3	0.35	10	16	250
15	Rectangular	300	1200	432	1	24	20	15.3	0.35	10	16	500
16	Rectangular 1	200	300	27	1	24	20	15.3	0.35	10	16	500
17	Rectangular	600	1200	864	1	24	20	15.3	0.35	10	16	500
18	Rectangular	1200	600	216	1	24	20	15.3	0.35	10	16	500
19	Cross shape	300	1200	452.25	1	24	20	15.3	0.35	10	16	500
20	Cross shape	600	1200	972	1	24	20	15.3	0.35	10	16	500

and 1200 mm. Soil is assumed to be homogeneous and is modeled in X, Y and Z directions up to a 15 m distance from the pile head. These models have been completed in low compacted and high compacted granular soil. The soil properties mentioned in Table 1 are obtained from the test results of 2 different regional soils. Other geometrical and mechanical properties are also presented in Table 1.

Loading is applied as a uniform horizontal stress on the pile head joints at every step of load increase,

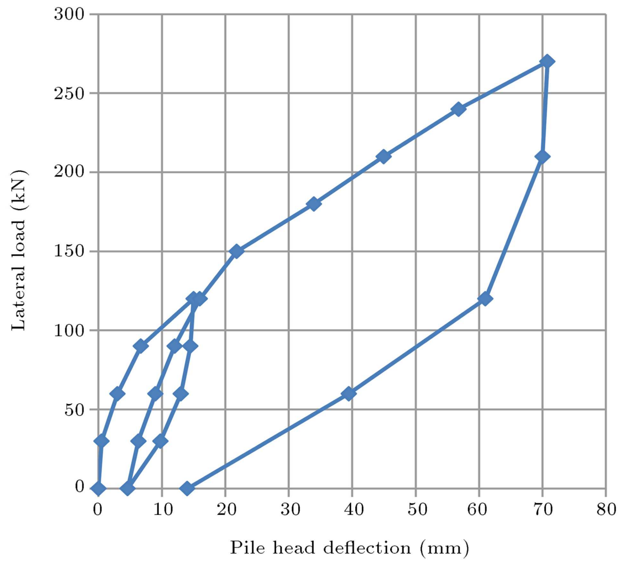


Figure 3. Results of the lateral static cyclic loading.

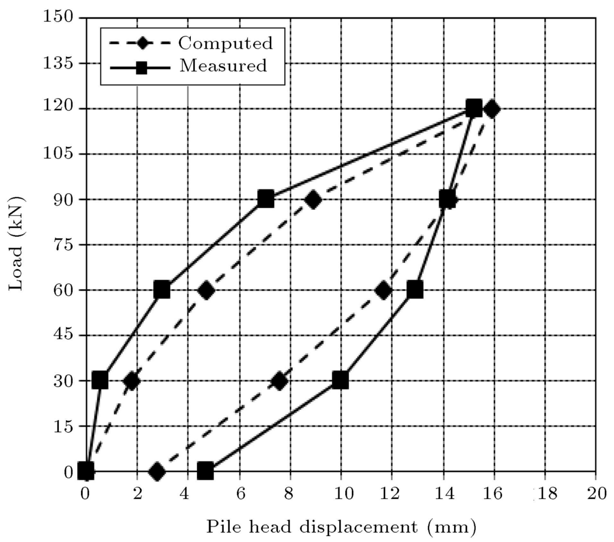


Figure 4. Comparison of pile head displacement in analytical and experimental models in first loading cycle.

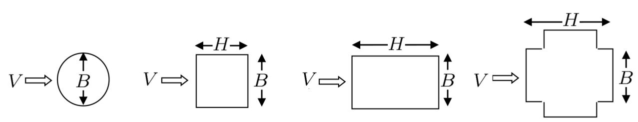


Figure 5. Pile cross section shapes.

and is performed by applying a primary stress on the pile head.

In order to have the same compaction of the soil against piles with different geometric shape, the width or diagonal of the load conveying surface should be chosen as equal. Obviously, in this case, pile stiffness would not be similar. However, due to the same load, by comparison of pile head displacement in the load direction under various states, the stiffness of the set of soil and pile would be comparable.

5. Result and discussions

The area under the loading and unloading curve presents the value of dissipated energy, which is produced due to nonlinearity in the soil behavior, and it is used to compare pile behavior.

The dissipated energy is obtained based on pile head displacements at different load steps of the first and second cycles of loading (Tables 3 and 4, Figure 6).

To compare the pile behavior under 250 kN and 500 kN loads, and to study the effect of replacing a 600*1200 mm pile with two of 300*1200, the displacements of the 600*1200 mm pile under 500 kN loads are scaled by a factor of 0.5. The numbers of scaled models are accompanied by an index of "s".

According to the soil type (low or high compacted) and the maximum load value (250 kN and 500 kN), four groups are classified: group one includes models 1 to 4 and scaled models 7 and 8; group two contains models 5 to 10; group three contains models 11 to 14 and scaled models 17 and 18; and finally, group four contains models 15 to 20. The comparison results are shown in Figure 6. Despite the fact that more displacement in the pile and soil increases the dissipation of transmitting energy from the bed to the main structure, large displacement of pile head causes large displacement and serious problems for the main structure. So, piles which dissipate more energy with smaller displacements have more appropriate behavior. For a concurrent comparison of maximum pile head displacement and the dissipation of energy in different models, the "performance index", "k", is defined as the ratio of dissipated energy to maximum displacement. The greater "performance index" shows the more appropriate behavior of the pile. These values are presented in Tables 5 and 6, and also in Figures 7(c), (d) and 8(c), (d).

According to the analytical results, in models of the first group, the maximum dissipation of energy is obtained for models #1 and #3. The maximum pile head displacement of model #1 is 41% greater than model #3. Thus, model #3 has better behavior in this group.

A comparison of scaled models #7 and #8 with models #3 and #4 shows that using piles with larger dimensions results in better behavior. For example, increasing the rectangular pile dimension from 300 to 600 mm caused an increase in the performance index from 7.5% to 53%.

In groups (2) and (4), with maximum horizontal force of 500 kN, it is shown that the maximum value of dissipated energy, both in low and high compacted soil, occurs in rectangular cross section piles with dimension ratios of 0.25. But, due to the large pile head displacement in low compacted

Table 3. Values of pile head displacement (mm) for different cross sections under cyclic loading with a maximum horizontal force of 250 kN and increment loads of 31.25 kN in the first cycle and 62.5 kN in the second cycle.

Model no.	Load (kN)																
	0	31.25	62.5	93.75	125	93.75	62.5	31.25	0	62.5	125	187.5	250	187.5	125	62.5	0
1	0	0.434	1.018	1.665	2.359	1.935	1.460	0.917	0.288	1.229	2.411	4.080	6.026	5.075	3.965	2.661	0.542
2	0	0.358	0.861	1.432	2.040	1.691	1.303	0.828	0.301	1.053	2.078	3.421	4.925	4.193	3.199	2.080	0.813
3	0	0.344	0.799	1.286	1.810	1.442	1.018	0.570	0.110	0.920	1.836	2.927	4.092	3.302	2.370	1.415	0.201
4	0	0.285	0.627	1.061	1.584	1.306	1.022	0.723	0.379	0.941	1.593	2.805	4.264	3.703	3.076	2.256	1.224
7(S)	0	0.270	0.628	1.021	1.435	1.165	0.853	0.494	0.129	0.730	1.459	2.379	3.428	2.852	2.126	1.352	0.342
8(S)	0	0.234	0.537	0.919	1.343	1.115	0.877	0.600	0.262	0.728	1.345	2.375	3.566	3.101	2.508	1.739	0.843
11	0	2.764	6.476	11.498	17.925	15.098	11.721	7.342	1.995	10.453	18.422	36.689	64.399	57.851	48.663	33.901	6.658
12	0	2.312	5.302	8.949	13.353	10.894	7.948	4.689	1.232	7.325	13.987	25.525	40.885	35.047	27.550	18.154	5.556
13	0	1.780	3.981	6.487	9.361	7.622	5.776	4.048	2.271	5.585	9.495	16.768	25.315	21.676	17.705	13.566	8.800
14	0	2.082	5.487	10.060	16.233	14.377	11.671	8.152	3.675	8.839	16.796	35.830	62.731	57.478	48.939	37.499	18.205
17(S)	0	1.574	3.596	6.173	9.407	7.966	6.377	4.804	3.023	5.966	9.634	18.350	30.207	27.049	23.140	19.049	14.238
18(S)	0	1.765	4.490	8.358	13.858	12.078	9.678	6.457	2.548	8.136	14.577	31.606	57.038	52.141	44.633	34.160	14.245

Table 4. Values of pile head displacement (mm) for different cross sections under cyclic loading with a maximum horizontal force of 500 kN and increment loads of 62.5 kN in the first cycle and 125 kN in the second cycle.

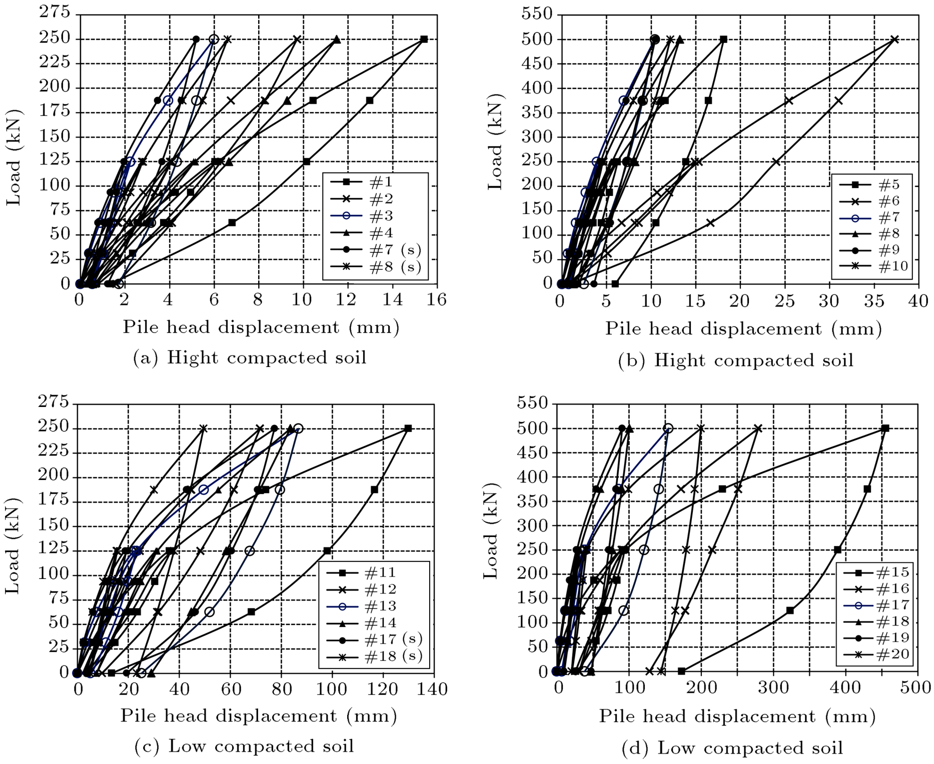
Model no.	Load (kN)																
	0	31.25	62.5	93.75	125	93.75	62.5	31.25	0	62.5	125	187.5	250	187.5	125	62.5	0
1	0	0.434	1.018	1.665	2.359	1.935	1.460	0.917	0.288	1.229	2.411	4.080	6.026	5.075	3.965	2.661	0.542
2	0	0.358	0.861	1.432	2.040	1.691	1.303	0.828	0.301	1.053	2.078	3.421	4.925	4.193	3.199	2.080	0.813
3	0	0.344	0.799	1.286	1.810	1.442	1.018	0.570	0.110	0.920	1.836	2.927	4.092	3.302	2.370	1.415	0.201
4	0	0.285	0.627	1.061	1.584	1.306	1.022	0.723	0.379	0.941	1.593	2.805	4.264	3.703	3.076	2.256	1.224
7(S)	0	0.270	0.628	1.021	1.435	1.165	0.853	0.494	0.129	0.730	1.459	2.379	3.428	2.852	2.126	1.352	0.342
8(S)	0	0.234	0.537	0.919	1.343	1.115	0.877	0.600	0.262	0.728	1.345	2.3757	3.566	3.101	2.508	1.739	0.843
11	0	2.764	6.476	11.498	17.925	15.098	11.721	7.342	1.995	10.453	18.422	36.689	64.399	57.851	48.663	33.901	6.658
12	0	2.312	5.302	8.949	13.353	10.894	7.948	4.689	1.232	7.325	13.987	25.525	40.885	35.047	27.550	18.154	5.556
13	0	1.780	3.981	6.487	9.361	7.622	5.776	4.048	2.271	5.585	9.495	16.768	25.315	21.676	17.705	13.566	8.800
14	0	2.082	5.487	10.060	16.233	14.377	11.671	8.152	3.675	8.839	16.796	35.830	62.731	57.478	48.939	37.499	18.205
17(S)	0	1.574	3.596	6.173	9.407	7.966	6.377	4.804	3.023	5.966	9.634	18.350	30.207	27.049	23.140	19.049	14.238
18(S)	0	1.765	4.490	8.358	13.858	12.078	9.678	6.457	2.548	8.136	14.577	31.606	57.038	52.141	44.633	34.160	14.245

Table 5. The performance index values, k (kN), into the cycle of loadings with a maximum horizontal force of 250 kN.

Cycle	Model											
	1	2	3	4	7(S)	8(S)	11	12	13	14	17(S)	18(S)
1	17.74	20.24	24.99	11.33	24.04	14.34	25.14	17.75	35.44	21.15	33.54	30.95
2	42.60	40.31	60.36	22.15	55.93	34.6	74.91	55.15	89.39	60.15	90.36	84.61

Table 6. The performance index values, k (kN), into the cycle of loadings with a maximum horizontal force of 500 kN.

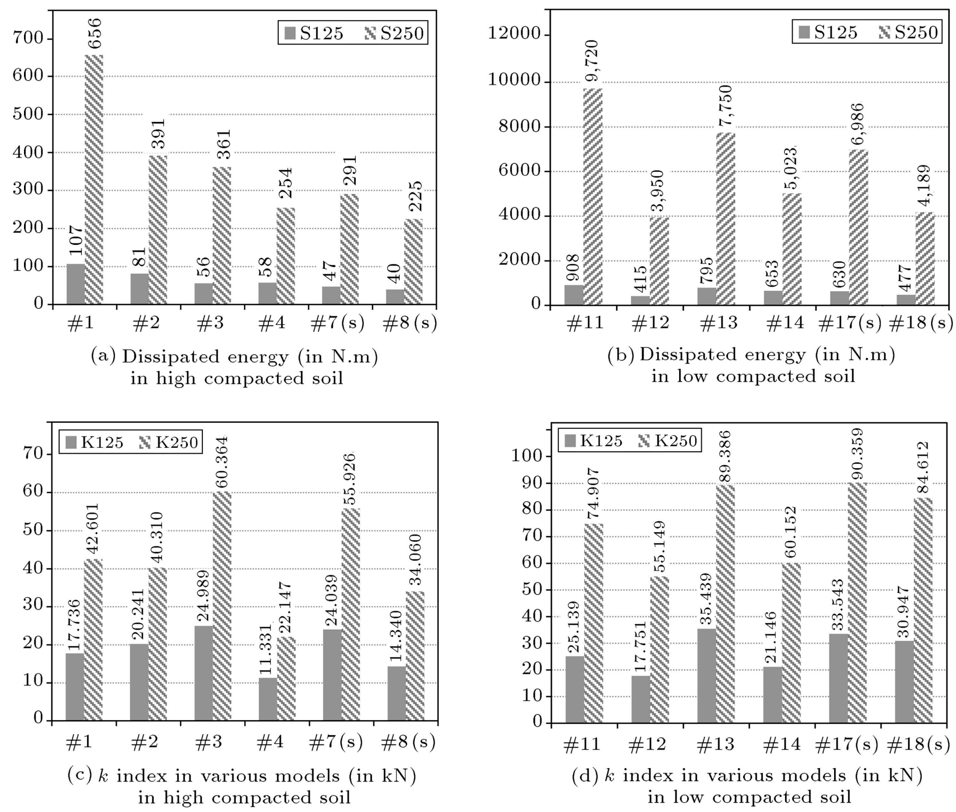
Cycle	Model											
	5	6	7	8	9	10	15	16	17	18	19	20
1	67.07	24.41	48.08	28.68	43.21	39.31	94.64	66.24	67.09	61.89	68.27	101.5
2	181.4	115.2	147.2	108.0	143.6	126.6	247.5	197.2	204.7	199.1	212.7	286.9



(a) Hight compacted soil (b) Hight compacted soil

(c) Low compacted soil (d) Low compacted soil

Figure 6. Pile head displacement with different cross sections in two cycles of loading with a maximum horizontal force of 250 kN (a,c) and 500 kN (b,d) in low and high compacted soil.



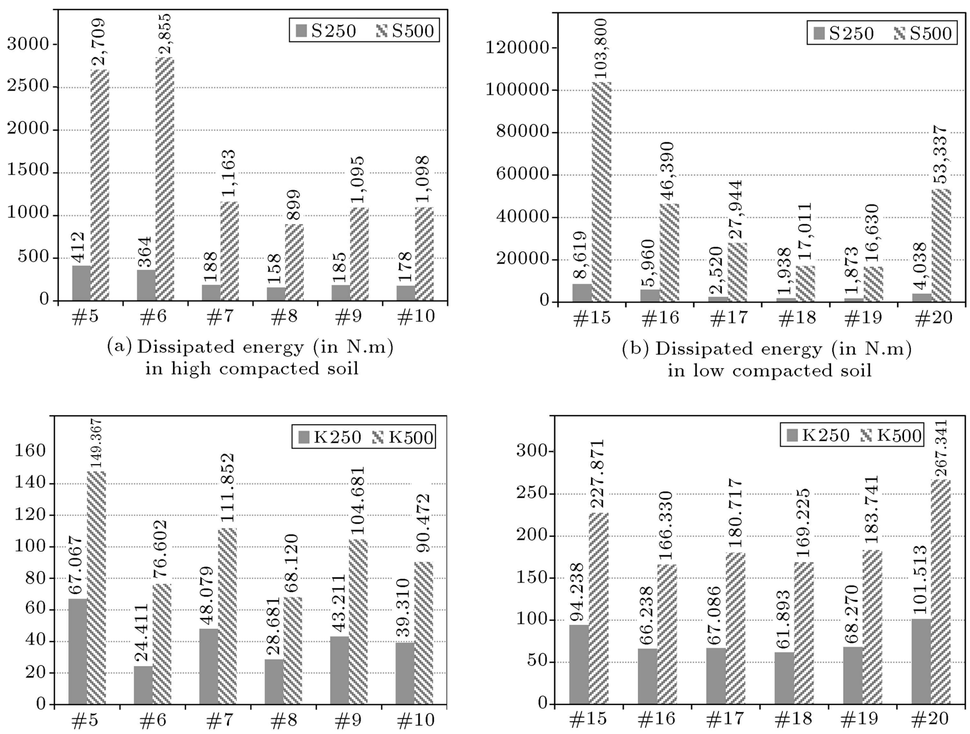
(a) Dissipated energy (in N.m) in high compacted soil

(b) Dissipated energy (in N.m) in low compacted soil

(c) k index in various models (in kN) in high compacted soil

(d) k index in various models (in kN) in low compacted soil

Figure 7. Comparison of the dissipated energy and performance index "k" in various models with different cross sections in two cycles of loading with a maximum horizontal force of 125 kN in the first cycle and maximum horizontal force of 250 kN in the second cycle in high and low compacted soil.



(a) Dissipated energy (in N.m) in high compacted soil

(b) Dissipated energy (in N.m) in low compacted soil

(c) k index in various models (in kN) in high compacted soil

(d) k index in various models (in kN) in low compacted soil

Figure 8. Comparison of the dissipated energy and performance index "k" in various models with different cross sections in two cycles of loading with a maximum horizontal force of 250 kN in the first cycle and maximum horizontal force of 500 kN in the second cycle in high and low compacted soil.

soil (314 mm), using them is not appropriate. The cross-shaped pile with a thickness of 600 mm shows the maximum performance index among the models with low compacted soil type. While the thickness of cross-shaped piles varies from 300 to 600 mm, the performance index in low compacted soil increases. However, the performance index differences of these piles in highly compacted soil are not noticeable. This means that the high compacted surrounding soil between the flanges acts as part of the pile cross section, and the performance dependence of the pile on its flange thickness decreases in this state.

In rectangular cross sections, when the perpendicular side to the force direction is the larger side, pile behavior is more flexible, and the difference between the performance indexes in low and high compacted soil has greater value. As an example, for a rectangular pile with 300*1200 mm cross sectional dimensions under a maximum lateral load of 250 kN, the difference in performance index for high and low surrounding soil compaction reaches 170 percent.

The results of the models in the third group show that the maximum dissipation of energy is obtained for model #3, but there is no noticeable difference between pile head displacements.

6. Conclusions

In this paper, the effects of the shape and geometry of piles on their behavior in granular soil under lateral loads are investigated using several numerical models. Incremental cyclic loading for the pile head are considered. The pile head displacement and the dissipation of energy in the soil and the pile are measured and compared. To compare the analytical results, different piles are categorized based on soil characteristics and loading conditions, and the performance index is defined as the ratio of dissipated energy to displacement.

According to the analysis results, the piles with a rectangular cross section where the loading is applied on the larger side of the cross section have the most suitable performance in compact soils. The dissipation of energy in different load cycles for low compacted soil is greater than for high compacted soil. The cross section shape is less influential in low compacted soil because of large pile displacements. The comparison of rectangular piles performance with different widths in compact soils demonstrates that the combination of two rectangular piles with the small width make the new pile with larger width, where loading is applied along the smaller side of section, and causes considerable improvement in pile performance. The maximum dissipation of energy with no consideration of soil condition is produced in the thin rectangular piles, which are inefficient because of large displacement on their heads.

The cross-shaped piles with 600 mm flange thickness show the most suitable performance and have the highest "performance index" in low compacted soil. Nevertheless, these piles seem to be inefficient in compact soils. The pile performance dependence on flange thickness in low compacted soil is much more than that in high compacted soil. As an explanation, the high compacted soil confined between flanges participates with the flanges and performs as part of the pile, which causes a reduction in the dependency on flange thickness.

The effect of soil compaction on the performance of piles under different conditions is not the same. The largest difference between the performances of the piles, located in compacted and loose soils, is related to rectangular piles with less width. This pile is under incremental lateral loading, with smaller maximum load along the width of the cross section. On the other hand, the soil compaction rate could be more effective on pile behavior in the case of flexible piles with increased interface area. The models with low compacted soil show more dissipation of energy ratio in relation to the models with high compacted soil.

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Biographies

Pejman Vahabkashi received a BS degree in Civil Engineering, and MS and PhD degrees in Geotechnical Engineering, from Amir Kabir University of Technology (AUT), Iran, in 1995, 1998 and 2013, respectively. He was member of a specialized compilation committee of the Iran National Building Code (structural concrete design and construction specification) for two terms, and currently teaches civil engineering courses in universities and institutes. His research interests include pile behavior, soil and structure interaction and bearing capacity of shallow and deep foundations.

Alireza Rahai received a BS degree in Civil Engineering, in 1975, from Amir Kabir University of Technology (AUT), Iran, an MS degree in Concrete & Prestressed Concrete Structures from CHEC, Paris, France, in 1977, and a PhD degree in Concrete Structures from the University of Paris, France, in 1979. He is currently President of Tehran Polytechnic, Iran, and Professor in the Civil Engineering Department of that institution. His research interests include structural concrete elements behavior and nonlinear analysis and seismic performance of reinforced concrete members.