Study of Loading Rate Effects on Characteristics of Negative Skin Friction for Pile Groups

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ABSTRACT

Using FLAC^{3D}, a three-dimensional 3×3 pile group and a single pile were analyzed numerically. Loading rate was controlled by compiling FISH sentences, by which can analysis the characteristics of negative skin friction of pile groups influenced by loading rate. Firstly, it was proved that using this paper's numerical model to study the negative skin friction of pile foundation is correctness by the comparison with the numerical model built on literature. Then, the drag-load and down-drag of pile groups and single pile which influenced by loading rate were studied; the influencing factors, such as step loading or direct loading, pile head load, the sequence of applying pile head load and surface load were discussed. Finally, it was proved by comparison with the results of model test results that numerical analysis method is reliable for engineering calculation. The results showed that, the drag-load and down-drag of pile become smaller with the slowing of loading rate, and tend to a stable value gradually at last; The negative skin friction of pile groups influenced by the load sequence, the negative skin friction obtained by surface load applying after pile head load larger than surface load applying before pile head load, while simultaneous applying surface load and pile head load is in the middle.

KEYWORDS: pile foundation; negative skin friction; drag-load; neutral plane; loading rate; numerical analysis

INTRODUCTION

Negative skin friction (negSF) may occur by downward vertical soil stress near the pile transferred to the pile shaft when the soil next to a pile settles more than the pile under surface load or groundwater lowering conditions. The development of additional compressive force (drag-load) in a pile and excessive pile settlement (down-drag) could cause many engineering problems, such as, foundation yield or failure, pile damage, uneven settlement of structure etc.

Recently, much research was done on negSF of pile foundations. Johanessen & Bjerrum (1965) have put forward effective stress method to calculate negSF, which was also widely adopted by Domestic and Foreign codes at present. Shibata et al. (1977, 1982) studied on negSF of pile groups by model test, the arrangement of pile groups, surface load and asphalt coating which influence the efficiency of pile groups were discussed. Chow et al. (1996) built a numerical model for pile groups under negSF using FEM, and pointed out that the effect of soil slip at the pile-soil interface was a key factor affecting pile groups behaviour. Shen & Teh (2002) built a theoretical calculation model based on variational method and most low potential energy principle, and calculated results were compared with field measured results. Lee et al. (2002, 2004) studied on drag-load, down-drag and the efficiency of pile groups under negSF by FEM using ABAQUS, and surface load, the friction coefficient of pile-soil interface, the arrangement of pile groups and the spacing of piles which affecting the results were discussed. Jeong et al. (2004) discussed the drag-load influenced by the slip of pile-soil interface, pile head load etc by ABAQUS. Sun et al. (2004) studied on the negSF calculation method of single pile on the collapsible loess foundation, and pointed out that the settlement velocity of soil was one of important influence factors for the characteristics of negSF. Comodromos & Bareka (2005) studied on drag-load and neutral plane of single pile in layered soil influenced by the sequence of applying pile head load and surface load using FLAC3D software. Wang et al. (2000, 2005) built a negSF calculation method for single pile under layered soil using Biot consolidation theory, Fredholm integral equation and Laplace changing method. Xia et al. (2007) studied on field test and numerical analysis on neutral plane, drag-load and the settlement of soil under different pile head load considering time effect. Authors (2008) studied on the negSF of pile groups on saturated clay considering the interaction of pile head load and surface load, coupled effect of surface load and soil consolidation. Drag-load, neutral plane of different position of pile on pile groups and the settlement of different layer soil variation of consolidation time were discussed. Poulos (2008) put forward the design method of pile foundation under negSF, and discussed on the characteristics negSF influenced by residual stress of pile, pile head load and the efficiency of pile groups.

Obviously, there was little literature on the analysis of negSF of pile groups considering loading rate. In this paper, the drag-load and down-drag of pile groups and single pile which influenced by loading rate were studied; the influencing factors, such as step loading or direct loading, pile head load, the sequence of applying pile head load and surface load were discussed. Finally, it was proved by comparison with the results of model test example that numerical analysis method is reliability on engineering calculation.

NUMERICAL MODELING AND VERIFICATION

Numerical Model Built and Its Parameter Selection

Model pile embedded on viscosity soil with pile length L equal to 20 m, pile diameter D equal to 0.5 m of concrete single pile (SP) and 3×3 pile groups (PG) with pile spacing S equal to 2.5D were built by FLAC3D. Owing to symmetry, only half of a whole mesh for single pile and a quarter of a whole mesh for pile groups were used in the 3D simulation. The geometric model, typical finite difference meshes and model size were showed in Figure 1. Pile and soil material properties used in the analysis were showed in Table 1. As the elastic modulus of pile was much larger than soil, pile model using Isotropic elastic model, soil model using Mohr-Coulomb model. The interface of pile-soil use Mohr-Coulomb model (kn, ks choose 107 kPa/m, cohesion ca equal to 0 and internal friction angle φ equal to 16.7°, which the same to the friction coefficient equal to 0.3.). For both single pile and pile groups, the whole dimension of the grid was 30 m in the x and y directions and 25 m deep. The lateral sides of the mesh were taken far enough from the piles to avoid any boundary effect. Upper boundary condition was free boundary, side boundary condition was level direction sliding support boundary (level direction constrained, vertical direction free), bottom boundary condition was vertical direction sliding support boundary (level direction free, vertical direction constrained). Groundwater table was assumed on the ground surface.

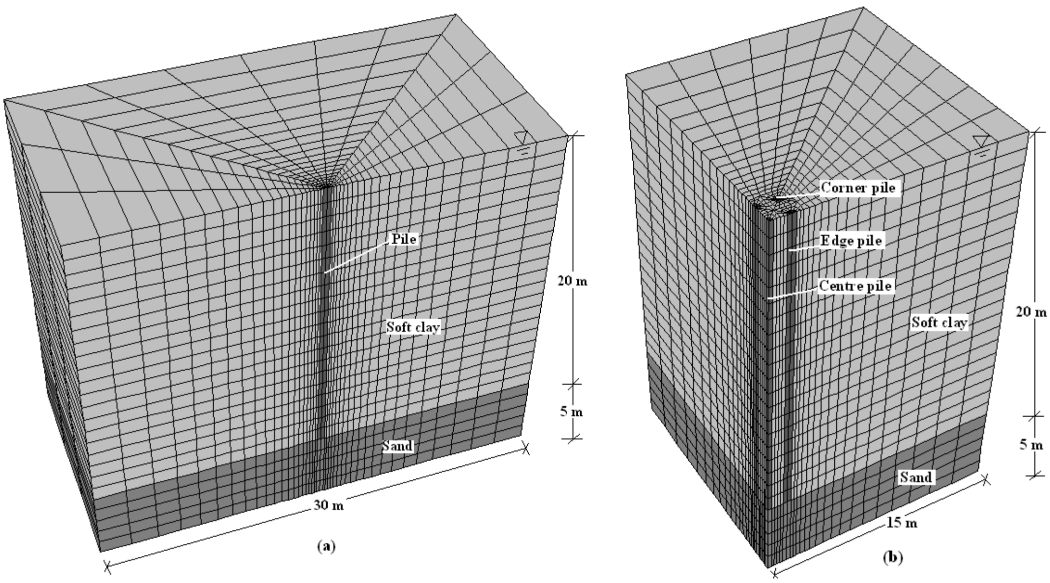

Figure 1: The geometric model, typical finite difference meshes and model size for single pile (a) and 3×3 pile groups (b)

Table 1: Pile and soil material properties used in the analysis

Material	Model	E /MPa	υ	c /kPa	φ / °	ϕ / °	K_0	γ /kN/m³
Concrete pile	Isotropic elastic	20,000	0.2				1.0	25
Soft clay	Mohr-Coulomb	5	0.3	3	20	0.1	0.65	18
Sand		50	0.3	0.1	45	10	0.5	20

Numerical Model Verification

Single pile model was calculated with assuming the elastic modulus of pile Ep was 2 GPa and poisson's ratio υ was 0.3, other parameters were chose the same to Table 1 on section 2.1. Through the comparison between the numerical model of this paper and the numerical model built on literature to prove that study on the negSF of pile foundation is correctness through this paper's numerical model. Figure 2 showed that when surface load (S.L.) equal to 50 kPa, the drag-load distributions along pile depth were in good agreement between the results obtained by this paper and the results obtained by literature (after Lee et al. and after Comodromos & Bareka).

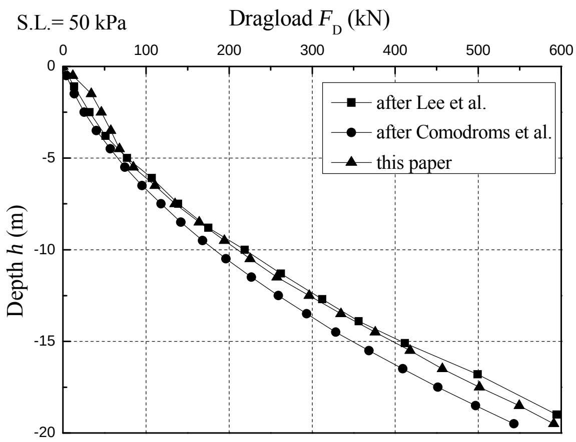

Figure 2: The comparison of drag-load distributions between this paper and on literature (SP, S.L. = 50 kPa)

INFLUENCE FACTOR ANALYSIS

Analysis of Drag-load Influenced by Loading Rate

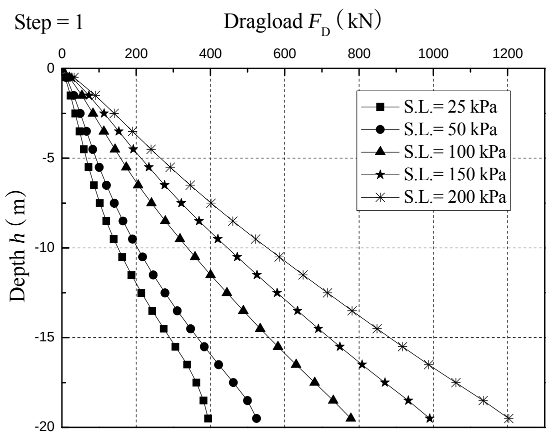

Figure 3: Curves of drag-load of pile versus surface loads (The corner pile (P_c) in 3×3 pile groups)

Take corner pile (Pc) in 3×3 pile groups for example, Figure 3 shows that when surface loading rate equal to 1 step, the variation of drag-load distributions along pile depth were uniform under different surface loads (S.L.), and increased with the improving of surface load.

Take single pile under 200 kPa surface load for example, Figure 4(a) shows that the drag-load distributions along pile depth decrease with the slowing of loading rate, and tend to a stable value at last. Take 3×3 pile groups and single pile under 25 kPa surface load for example, Figure 4(b) showed that the drag-load of each position pile obtained when surface loading rate equal to 20000 steps were slightly smaller than the results obtained when surface loading rate equal to 1 step. The drag-load of single pile were larger than that of corner pile, larger than edge pile and larger than interior pile, because of the influence of shadowing of each pile (the efficiency of pile groups).

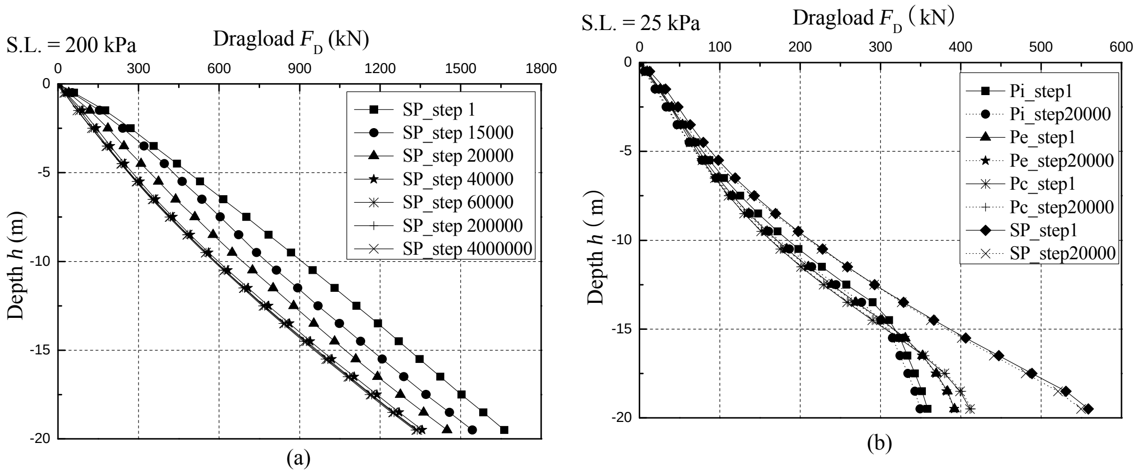

Figure 4: Curves of drag-load of pile versus loading rate (a) single pile, (b) pile groups and single pile

Analysis of the axial force of pile influenced by loading mode

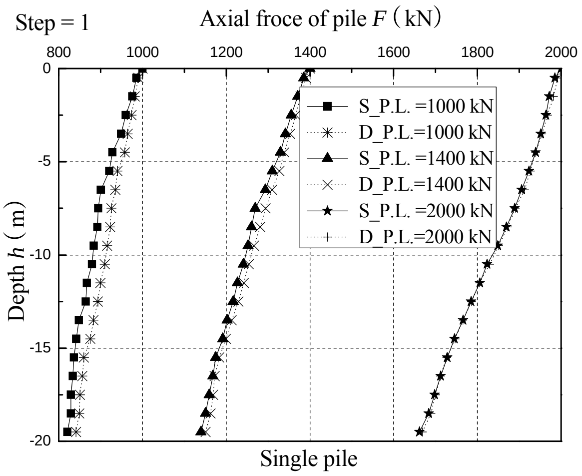

Figure 5: Curves of the axial force of pile versus loading mode of pile head (SP, step loading (S_P.L.) or direct loading (D_P.L.))

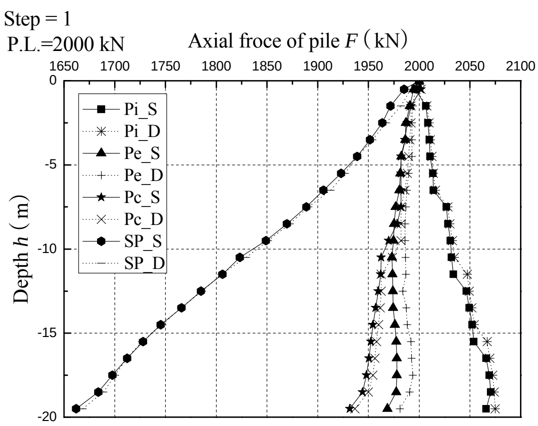

Figure 6: Curves of the axial force of pile versus loading mode of pile head (PG and SP, P.L. = 2000 kN)

Take single pile under pile head load (P.L.) for example. Figure 5 shows that the axial force of pile were difference under step loading (200 kN for each step) or direct loading when pile head loading rate equal to 1 step. The results obtained by direct loading model were slightly larger than the results obtained by step loading model, while the difference becomes little with the increasing of load grade and the results tend to equal at last.

Take 3×3 pile groups and single pile under 2000 kN pile head load for example. Figure 6 shows that the drag-load get by direct loading model were slightly larger than the results get by step loading (200 kN for each step) model when pile head loading rate equal to 1 step. As the influencing of shadowing of each pile in groups (the efficiency of pile groups), side friction of single pile were larger than that of piles in groups; Side friction of corner pile in groups were larger than that of edge pile in groups. Upper part of interior pile in groups was subjected by negSF, which caused the axial force of pile become larger along pile depth. It is because the neighboring pile head load caused the settlement of surrounding soil, while the settlement of soil caused the negSF in the upper part of interior pile.

Analysis of the Axial Force of Pile

Influenced by the Interaction of Pile Head Load and Surface Load

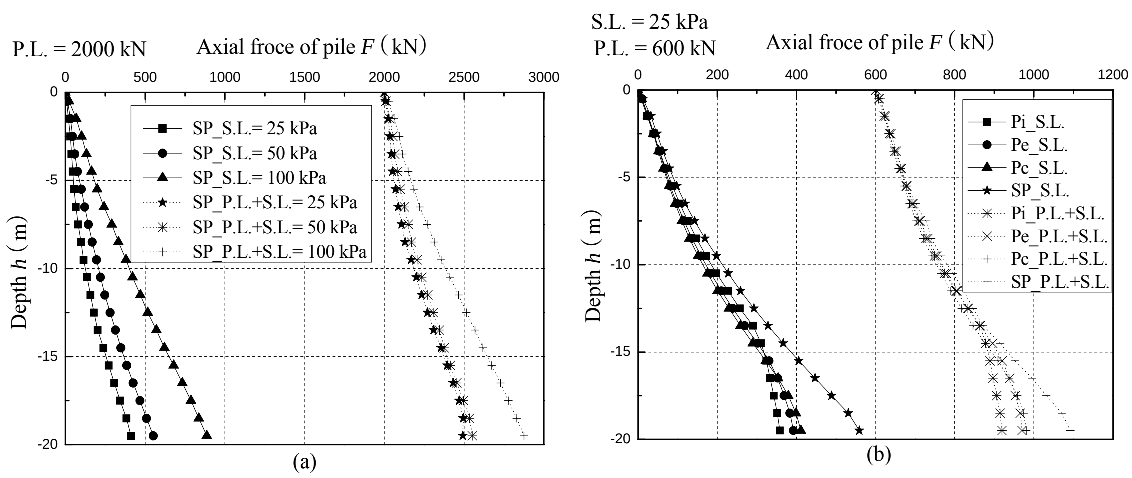

Figure 7: The comparison of the axial force of piles under surface load between pile head load and no pile head load (*a*) single pile, (*b*) pile groups and single pile

Figure 7(a) shows that the axial force of single pile caused by surface load after no pile head load or 2000 kN pile head load were almost equal. Figure 7(b) shows that the distribution of the axial force of position piles in 3×3 pile groups and single pile caused by 25 kPa surface load after no pile head load or 600 kN pile head load were uniform. So, in the condition of applied pile head load before surface load, the axial force of pile distributions along pile depth were uniform, and the negSF value caused by surface load were almost equal.

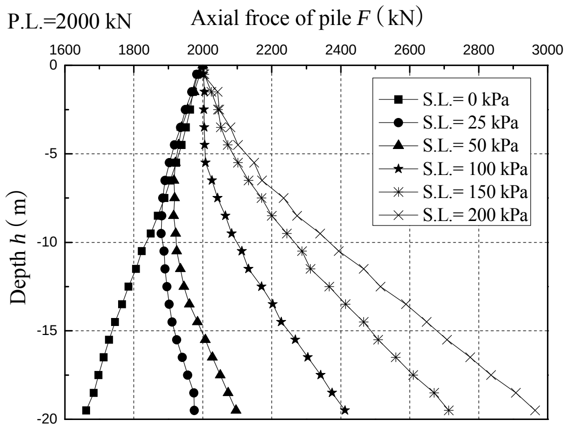

Figure 8: Curves of the axial force of pile under pile head load (P.L. = 2000 kN) influenced by surface load

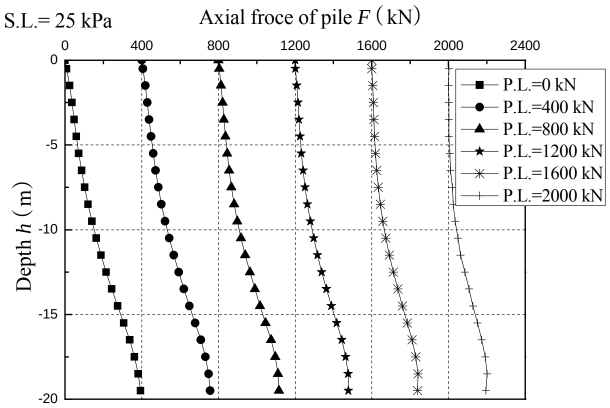

Figure 9: Curves of the axial force of pile and pile head load under pervious surface load

Figure 8 shows that applied 2000 kN pile head load after different surface load, the axial force of pile distributions along pile depth were different. The value of surface load grade influenced the axial force of pile distributions along pile depth directly. With the increasing of surface load, the side friction of pile changed from positive to negative, and reached to maximum value at last. It is showed in picture that the axial force of pile distributions along pile depth changed from decrease to increase.

Figure 9 shows that the axial force of pile distributions along pile depth under applied step pile head loading (200 kN for each step) after 25 kPa surface load vary uniformly, while the value of drag-load which caused by surface load decreases with the increasing of pile head load grade.

Figure 10 shows that when only pile head load and without surface load (a) is applied, the axial force of pile becomes smaller along pile depth; when both pile head load and surface load (b, c, d) were applied, the axial force of pile becomes larger along pile depth. It was because the side friction of pile shaft was positive skin friction without surface load applied, while the side friction of pile shaft was negative skin friction with surface load applied. It was also shown that the distributions of drag-load influenced by load sequence significantly. The drag-load obtained by surface load applying before pile head load (b) smaller than the drag-load obtained by surface load applying after pile head load (c), while the drag-load obtained by simultaneous applying surface load and pile head load (d) was in the middle, corresponding different down-drag equal to 13.77 mm, 16.44 mm and 14.38 mm, respectively. It was because that when surface load apply first, part of soil can provide positive friction after settlement finished. This conclusion was the same obtained on literature (after Comodromos & Bareka).

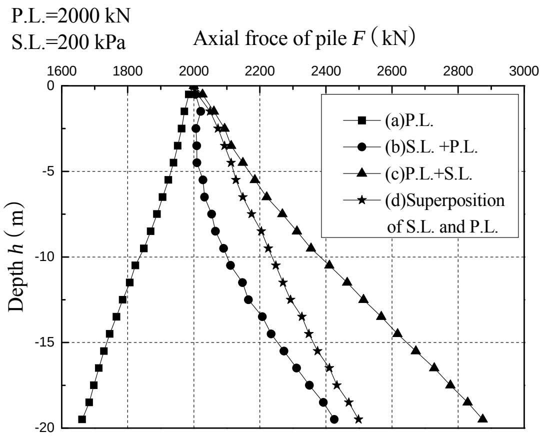

Figure 10: Curves of the axial force of pile along pile depth and load sequence (P.L. = 2000 kN and S.L. = 200 kPa)

EXPERIMENTAL VERIFICATION

Model test results obtained by authors (2008) was analyzed by FLAC3D in order to prove that using numerical analysis method to study pile groups under negSF considering loading rate is reliable and accurate. In order to simulate model test conditions better, the size and parameters of numerical model were chose the same to model test conditions. Pile and pile cap model use Isotropic elastic model, surrounding and bearing layer soil model use Mohr-Coulomb model. The interface of pile-soil use Mohr-Coulomb model (Use formula (1) which was suggested by the standard of FLAC3D to determining the value of k_n and k_s, chose 5.75×10^7 Pa/m and 4.02×10^7 Pa/m, respectively. Choose cohesion c_a equal to 0 and internal friction angle φ equal to 30.5°, which the same to the friction coefficient equal to 0.35.). The geometric model, typical finite difference meshes and model size are shown in Figure 11. Pile and soil material properties used in the analysis are shown in Table 2. Upper boundary condition was free boundary, side boundary condition was level direction sliding support boundary (level direction constrained, vertical direction free), bottom boundary condition was vertical direction sliding support boundary (level direction free, vertical direction constrained). Groundwater table was assumed on the ground surface as the surrounding soils were saturated or near saturated clay. After surface load finished, coupled effect of surface load and soil consolidation were considered. Choose the vertical permeability coefficient of clay k_v equal to 1.57×10^{-7} cm/s, the horizontal permeability coefficient of clay k_h equal to 1.78×10^{-7} cm/s.

Table 2: Pile and soil material properties used in the analysis

	K /MPa	G /MPa	c /kPa	φ / °	γ /kN/m³	K_0
Pile	1.52×10^4	5.83×10^3			11.6	1.0
Pile cap	1.52×10^4	5.83×10^3			11.6	1.0
Clay	1.767	0.183	7.0	19.1	17.4	0.82
Silt	1.474	0.491	16.16	33.9	13.9	0.54
Sand	16.08	7.423	0	30.0	14.7	0.43

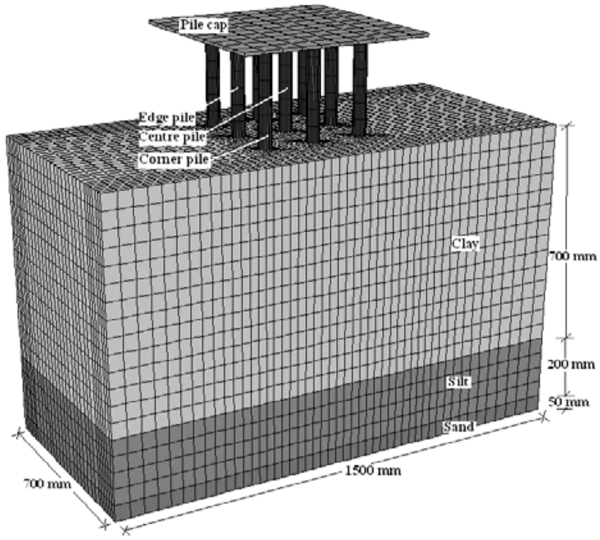

Figure 11: The geometric model, typical finite difference meshes and model size for model test

$$k_n, k_s = \max\left[\frac{(K + 4/3G)}{\Delta z_{\min}}\right] \quad (1)$$

Figures 12 and 13 show that the curves of pile head load and the settlement of pile top (Q-s curves), the curves of pile head load and pile tip resistance which were obtained by numerical simulation were similar to that obtained by experimental results. The relationships were nearly linear, which means that piles were working under elastic stage. The pile tip resistance of corner pile in groups was larger than that of edge pile and larger than that of interior pile under the same load grade conditions. The results obtained by numerical simulation were larger than that obtained by experimental. It may be because the bearing soil parameters, such as elastic modulus, bulk density, used in numerical simulation (which was measured in laboratory) were smaller than those of the actual values.

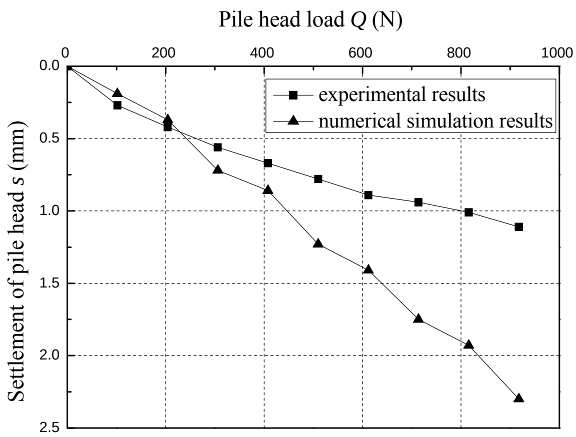

Figure 12: Comparisons on the curves of pile head load and pile head settlement

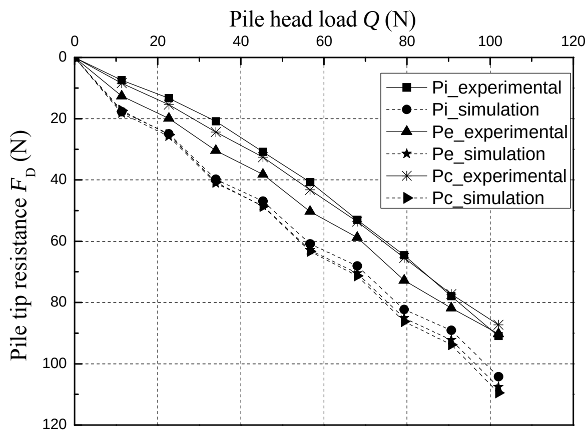

Figure 13: Comparisons on the curves of pile head load and pile tip resistance

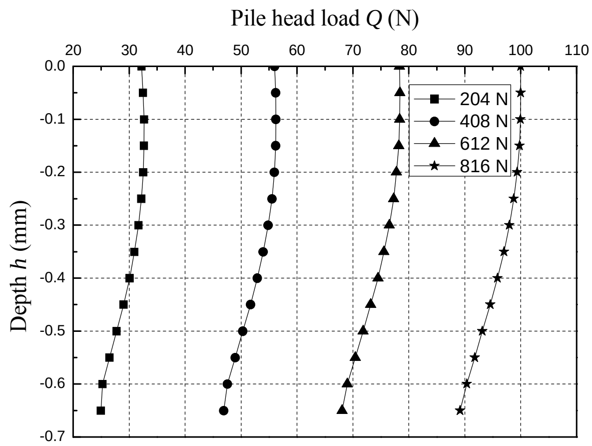

Figure 14: Curves of pile head load and the axial force of pile shaft

Figure 14 showed that the axial force of pile distributions along pile depth under different pile head load grade were uniformly, and decreased along pile depth. It belongs to typical friction and end-bearing pile form.

The axial force of pile distributions along pile depth under 5.1 kPa surface load and 918 kN pile head load after 24 h consolidation were showed in Table 3. It was showed that the axial force of pile which obtained by numerical simulation were smaller than that of experimental results, the neutral plane which obtained by numerical simulation were lower than that of experimental results. It may be because the surrounding soil parameters, such as elastic modulus, bulk density, used in numerical simulation (which was measured in laboratory) were smaller than that of actual values. The drag-load of corner pile in groups was larger than that of edge pile and larger than that of interior pile under the same load grade and consolidation time conditions.

Table 3: Comparisons on the results of maximum axial force of pile and neutral plane position by numerical simulation and experimental (24 h consolidation)

	Axial force of pile /N			Neutral plane /m		
	Pi	Pe	Pc	Pi	Pe	Pc
Measured	173.4	173.0	184.9	-0.25	-0.25	-0.25
Simulation	121.1	126.6	128.3	-0.6	-0.45	-0.40

CONCLUSIONS

Following conclusions can be drawn from the results of the numerical analyses presented.

(1) It was proved that study on the negative skin friction of pile foundation considering the influence of loading rate is feasible through numerical analysis by comparison with the literature on model tests, while the usefulness of the numerical model was expanded significantly by selection of parameters.

(2) The drag-load and down-drag were influenced by the loading rate and loading mode of pile head load or surface load. Negative skin friction will be decreased with the lowing of loading rate, and tend to an stable

value at last. The drag-load caused by step loading mode were slightly larger than that caused by direct loading mode, the difference become less with the increasing of load grade, and tend to equal at last.

(3) The distributions of drag-load were influenced by load sequence of pile head load and surface load significantly. The drag-load obtained by surface load applying before pile head load smaller than the drag-load obtained by surface load applying after pile head load, while the drag-load obtained by simultaneous applying surface load and pile head load was in the middle, corresponding different down-drag equal to 13.77 mm, 16.44 mm and 14.38 mm, respectively.

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