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The Behavior and Optimization Analysis of Double-row Piles in Different Forms

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ABSTRACT

As a foundation pit support, double-row piles can effectively control soil deformation, improve construction speed and reduce project cost. Most of the existing studies focus on vertical double-row piles, while there are fewer reports on inclined-vertical double-row piles. Inclined piles are able to convert part of the horizontal load into axial load, thus providing better resistance to horizontal load. In this paper, the working behavior of double-row piles with different forms in sand is investigated by numerical simulation. The results show that the working behavior of the inclined front row or inclined rear row is different and the supporting effect is affected by the inclination angle and direction. Comparisons of the overturning stability of double row piles indicate that double-row piles with the front row inclined and the rear row vertical have a better anti-overturning stability. Finally, inclined backward-vertical double-row piles are optimized and analyzed and the design parameters, such as row spacing, pile spacing and pile length, are discussed.

KEYWORDS: Double-row piles, Model test, Numerical simulation, Supporting effect, Anti-overturning stability, Optimization analysis.

INTRODUCTION

With the increase of urban population and acceleration of urbanization, underground space should be developed and utilized reasonably. At present, underground projects in big cities must solve the problems of the complex surrounding environment, complicated underground pipe networks and narrow construction sites. To ensure the safety of the foundation pit, the support structure should be used for protection. Compared to other systems, row piles offer advantages in deformation control, speed improvement and cost reduction, but single-row cantilever piles represent a statically determined structure, which needs to be embedded into the bottom of the foundation pit to a sufficient depth in order to maintain stability under the action of earth pressure, where the pile displacement and soil deformation are large, while double-row piles have rigid coupling beams connecting the front and rear row piles to form a statically indeterminate structural system. Compared with the drawing structure, the system of double-row piles is simple and has a less environmental impact. Compared with braced support, double-row piles have no internal rods and provide a wider working surface. Therefore, double-row piles have better economic and social benefits than other supports.

Double-row piles are developed in the late 1980s (Yu et al., 1997) by moving the single-row cantilever piles backward at intervals and then connecting the front and rear row piles with crossbeams. At present, studies on double-row piles are mainly focused on experimental research and

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numerical simulation. He et al. (1996) carried out tests on double-row piles and the same changing law was observed in model test and *in-situ* test. Many scholars have studied the mechanical properties and parameter optimization of double-row piles. Zhao et al. (2017) analyzed the characteristics of double-row piles and discussed the calculation model. Cao et al. (2018) equated the pile-soil as a planar truss structure and proposed an improved calculation model. Khadidja Sekhri et al. (2020) carried out nonlinear static analysis to discuss the lateral capacity of the pile-soil system under lateral loading. Ren et al. (2018) simulated the excavation process of deep foundation pit and proposed the concept of unequal length double-row piles. In order to improve the mechanical performance of double-row piles and seek more reasonable supporting forms, some scholars have analyzed inclined piles. Gang and Ruo-xu (2010) carried out a model test on inclined single-row piles to study the working behavior at different inclined angles. By using three-dimensional finite elements, Li et al. (2009) analyzed the support structure of multi-row piles and revealed the relationship among the lateral displacement, the internal force, the soil settlement and the inclined angle. Xu et al. (2010) studied the displacement and internal force of plum-shaped double-row piles at different inclined angles, row spacings and pile spacings. Maeda et al. (2013) obtained the horizontal displacement and bending deformation of inclined piles by centrifugal tests. Huang et al. (2020) analyzed the influence of inclination angle, diameter and length on the support effect of the front row pile. However, there are few studies on inclined-vertical double-row piles. In this paper, the working mechanism of double-row piles in different forms will be investigated by numerical simulation and the anti-overturning stability will be calculated.

Verification of Numerical Simulation Results

The Finite Element Software

Plaxis is a large-scale finite element software and has powerful modeling, calculation and post-processing functions.The software can consider nonlinear, time-dependent behavior and interaction of soil-structure and automatically generate element grids to simulate complicated problems. Its operation is simple and clear. Reliability and rationality have been verified by model tests.

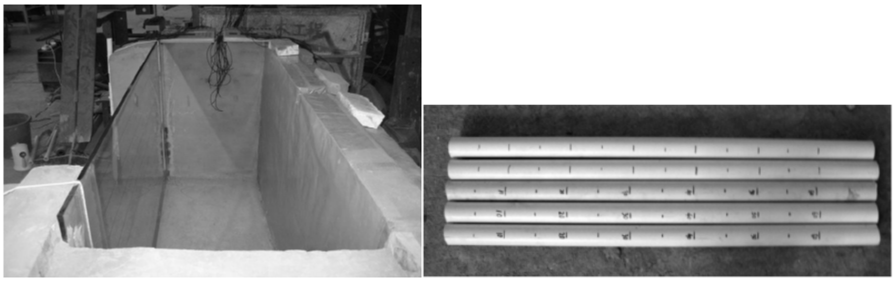
Overview of Laboratory Model Tests

Gang and Ruo-xu(2010) conducted a model test on single-row piles with inclination angles of 0º,10º and 20º, in which pile displacements, bending moments and soil settlements are measured. The model device in the test consisted of a model tank, model piles, sandy soil and a measurement system. The model tank is a cube of 2.0m*0.62m*1.1m (length*width*height) and the overall diagram is shown in Figure 1. One long side of the model tank is 12 mm tempered glass and the other three sides are brick masonry surfaces. In order to eliminate the friction between sand and brick wall and reduce the influence of the boundary effect, a double-layer plastic sheet was pasted on the inner wall of the model tank, so that the plastic sheets can slide relatively to each other.

The model piles were PVC pipes, 700mm in length, 32mm in diameter and 2mm in pipe wall, while the density was 18 kN/m^3. The diagram of model piles is shown in Figure1(b). The model test was carried out in sandy soil and the natural dry density of sand was 1.600 g/cm^3, the natural void ratio $e=0.659$, the maximum void ratio $e_{max}=0.874$ and the minimum void ratio $e_{min}=0.615$. Through direct shear test and compactness test, the following parameters were obtained: $\varphi=35.2°$, $c=0$ kPa and $D_r=0.830$ (Gang and Ruo-xu, 2010).

In the model test, the pile spacing is 3*D* (*D* is pile diameter) and a beam with the cross-section of 30mm*80mm connected the pile tops, before the test, putting them into the model tank and filling the sand like rain. Later, the sand should be excavated step by step and the readings of dial indicator and strain gauge should be recorded every 5 cm of the excavation until the pile top displacements or soil settlements reach a state of failure.

Xu et al. (2010) had done the large scale model tests with the same equipment and materials to compare the support performance of rectangular arrangement and plum-shaped arrangement of double-row piles. He et al. (1996) analyzed the internal force, deformation and soil pressure distribution characteristics of the double-row piles, and compared the model test with the field measured data. The results showed that by setting the appropriate scale, the model test could accurately reflect the field measured results.



(a) Model tank (b) Model piles

Figure (1): The schematic diagram of model device (Gang and Ruo-xu, 2010)

Based on the model test, a 1:1 three-dimensional numerical model is established by using plaxis^{3D} software. The single-row piles with inclination angles of 0º,10º and 20º are shown in Figure 2 and the simulation parameters are shown in Table 1 according to the model test. A 10-node tetrahedral element and an embedded structural unit are adopted for the soil and piles, which can calculate shear and normal spring parameters on the pile-soil contact surface and automatically simulate the pile-soil interaction. In the simulation, Mohr-Coulomb (M-C) elastic-plastic model is used to simulate sandy soil, which can reflect the soil settlement caused by excavation and the influence of lateral earth pressure on the pile. The linear elastic constitutive model is used to simulate the pile structure as the pile deformation can not reach the plastic range.

(a) Single-row vertical piles (b) Single-row inclined piles

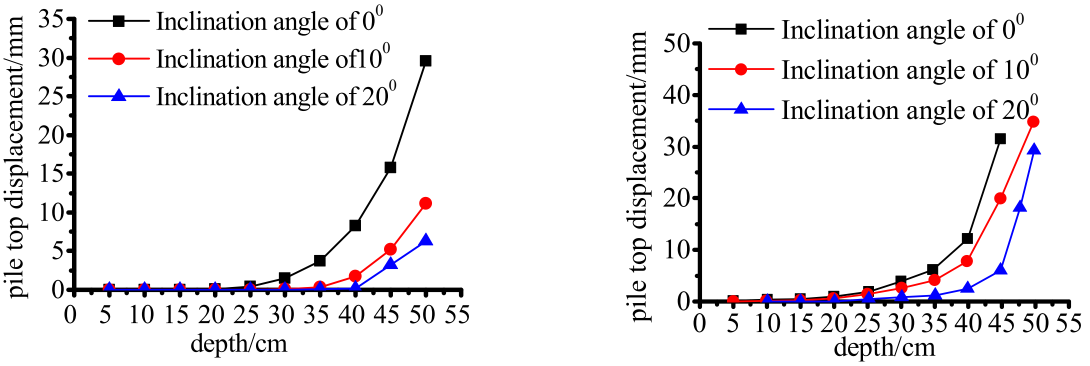
Figure (2):The model of single-row piles (Gang and Ruo-xu, 2010)

Table 1. Material parameters

Material	Poisson's ratio	Modulus of elasticity (MPa)	Internal friction angle (º)	Cohesive force (kPa)
Crown beam	0.3	5000	—	—
PVC pipe pile	0.36	300	—	—
Coarse sand	0.32	25	35.2	0

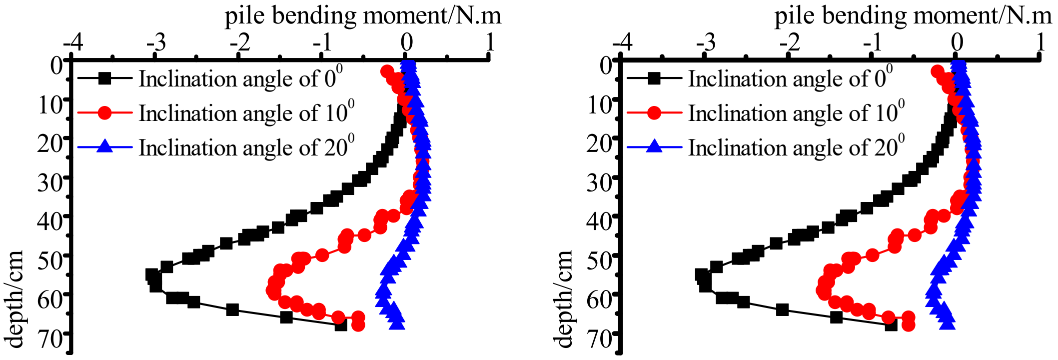
Comparison Results

Figures 3 and 4 illustrate the results of the numerical simulations compared with the laboratory tests. In the numerical simulation, the elastic model was used to simulate the piles to ensure that the specified excavation depth could be reached, and the connection between the crown beam and the pile top was completely rigid, which would result in the simulated pile top displacement being slightly lower than the laboratory test results. However, both the numerical simulation and the laboratory test results show similar trends in pile top displacement and pile bending moment, which indicates that it is feasible to use numerical simulation for the analysis of row pile support.



(a) Simulation result (b) Model test result (Gang and Ruo-xu, 2010)

Figure (3): Comparison of the horizontal displacement on pile top



(a) Simulation result (b) Model test result (Gang and Ruo-xu, 2010)

Figure (4): Comparison of pile bending moments

Simulation Results of Double-row Piles

Analysis of Double-row Piles

Currently, double-row vertical piles are more widely used, but inclined piles have obvious advantages in resisting horizontal loads (Kong et al., 2011), because they can convert part of horizontal load into axial load and improve the horizontal bearing capacity. In recent years, inclined piles have been widely used in bridge, wharf, coastal and harbor projects. It is necessary to research the form of double-row piles.

To discuss the working mechanism of different forms of double-row piles and the characteristics of soil deformation, the above model parameters will be used for modeling and analysis. The forms of double-row piles are shown in Table 2 and their internal force and deformation in sandy soil are analyzed by the Plaxis^{3D} software. According to the reference (Yang et al., 2014), at present, only piles with inclined angles of less than 7° can be constructed in China. Zhang (2017) considered that inclined angles within 10°~12° are beneficial in controlling cost, materials and construction. The inclined angles in Table 2 are not larger than 10°.

The pile spacing is 3*D* and a crown beam connects the same row piles. The row spacing is 4*D* and there is a crossbeam to connect the front and rear row piles. Other parameters are the same as in the case of single-row piles (*D* is pile diameter in the paper).

The pile spacing in this paper is the pile top spacing, but the inclined direction of the pile is perpendicular to the boundary of the foundation pit; so is the spacing of pile top or pile bottom.

Table 2. Working conditions of double-row piles

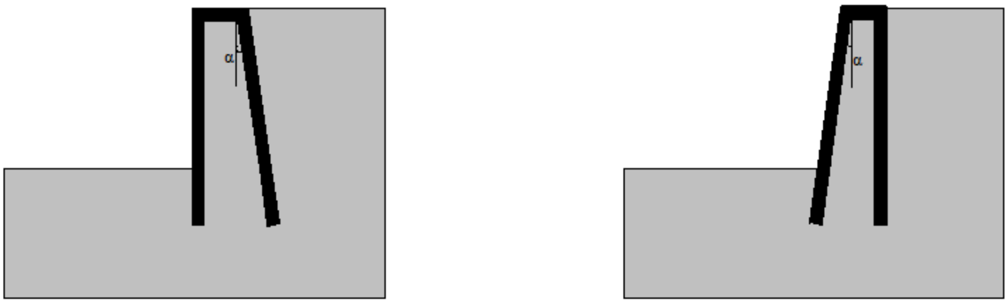
Working condition	Front row pile				Rear row pile				Note
	Length/ cm	Diameter/ cm	Wall thickness/ cm	Angle	Length/ cm	Diameter/ cm	Wall thickness/ cm	Angle	
1	70	3.2	0.2	0º	70	3.2	0.2	0º	all vertical
2	70	3.2	0.2	0º	70.3	3.2	0.2	5º	rear inclined
3	70	3.2	0.2	0º	71.0	3.2	0.2	10º	rear inclined
4	70	3.2	0.2	0º	70.3	3.2	0.2	-5º	rear inclined
5	70	3.2	0.2	0º	71.0	3.2	0.2	-10º	rear inclined
6	70.3	3.2	0.2	5º	70	3.2	0.2	0º	front inclined
7	71.0	3.2	0.2	10º	70	3.2	0.2	0º	front inclined

Note: Due to the limitation of pile row spacing, the inclined angle of the rear row piles in working condition 3 is 7.8º.

Pile Displacement of Different Forms of Double-row Piles

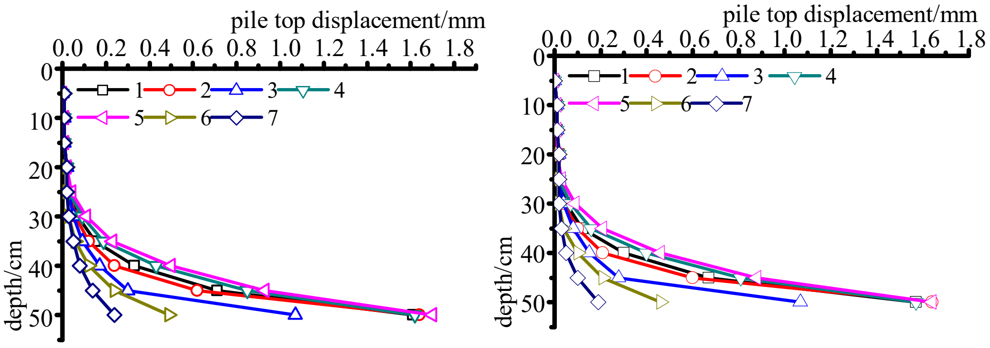
Different forms of double-row piles are shown in Figure 5. According to the model test and preliminary judgment, the maximum excavation depth in the simulation is about 50 cm and the depth of excavation compared to the length of piles is 5/7. The simulation results are shown in Figures 6-8.

(a) Double-row vertical piles (b) Vertical-inclined backward double-row piles



(c) Vertical-inclined inward double-row piles (d) Inclined backward-vertical double-row piles

Figure (5): Different forms of double-row piles

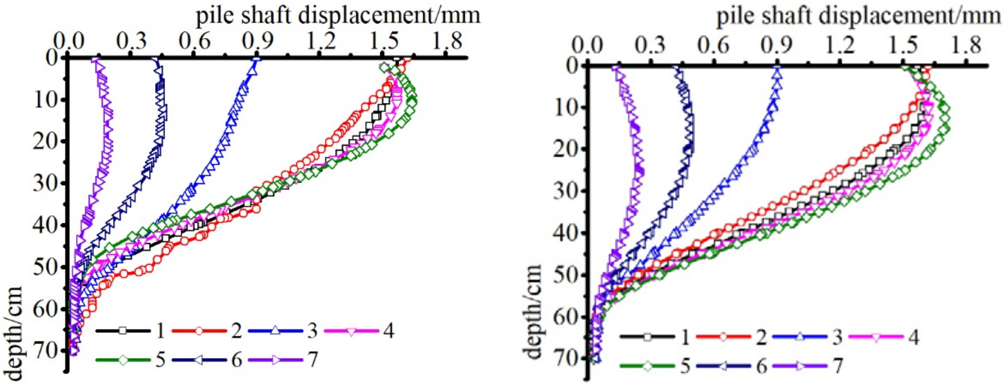


(a) Front row piles   (b) Rear row piles

Figure (6): The change of pile top displacement with excavation depth for different working conditions

Because the front and rear row piles are connected by the crossbeams, the top horizontal displacements of them are the same. When the excavation depth is shallow, the top horizontal displacements of front and rear row piles are small and there is little difference in each working condition. With the excavation depth increased, the top displacements gradually increased, but their increasing rates are different. In Figure 6 (a) and Figure 6 (b), the top horizontal displacement of vertical-inclined inward double-row piles is the largest and has no obvious correlation with the inclined angle. The top horizontal displacement of the inclined backward-vertical double-row pile is the least and decreased with pile inclination. In Figure 6 (a), the maximum value of top horizontal displacement of the front row piles is 1.70 mm and the minimum value is 0.24 mm; compared with the former, the latter decreased by 86%. Similarly, in Figure 6 (b), the maximum and minimum top horizontal displacements of the rear row piles are 1.64 mm and 0.19 mm, where the latter is 88% less than the former.

Figure 7 shows the shaft horizontal displacement of front and rear row piles. It can be seen that the shaft horizontal displacements decrease gradually with the pile length and tend to be consistently below the bottom of the foundation pit. The shaft horizontal displacements of front row are slightly larger than those of rear row and the maximum horizontal displacements of them are all located at the upper part. In Figure 7 (a) and Figure 7 (b), the shaft horizontal displacement of the inclined backward-vertical double-row piles is the least and that of the vertical-inclined inward double-row piles is the largest. With the inclined angle increased, the former decreases, but the latter increases, because the rear row of vertical-inclined inward double-row piles mainly played a role of pulling anchor, where with the inclined angle increase, the anchorage effect will reduce. In Figure 7 (a), the maximum and minimum shaft horizontal displacements of front row piles are 1.75 mm and 0.25 mm; the former is 7 times larger than the latter. In Figure 7 (b), the maximum and minimum shaft horizontal displacements of rear row piles are 1.7 mm and 0.2 mm, where the difference between them is 8.5 times.



(a) Front row piles   (b) Rear row piles

Figure (7): The change of shaft displacement with pile depth for different working conditions

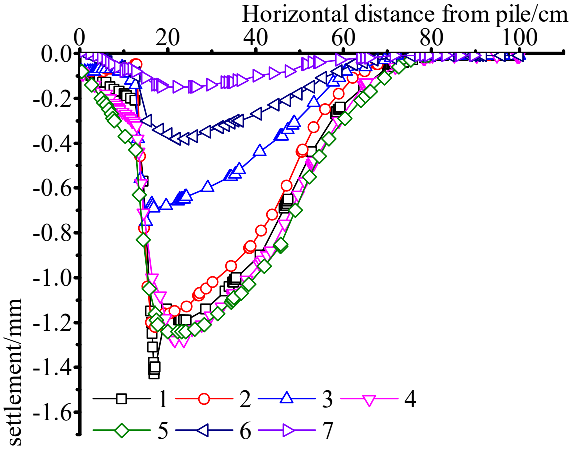


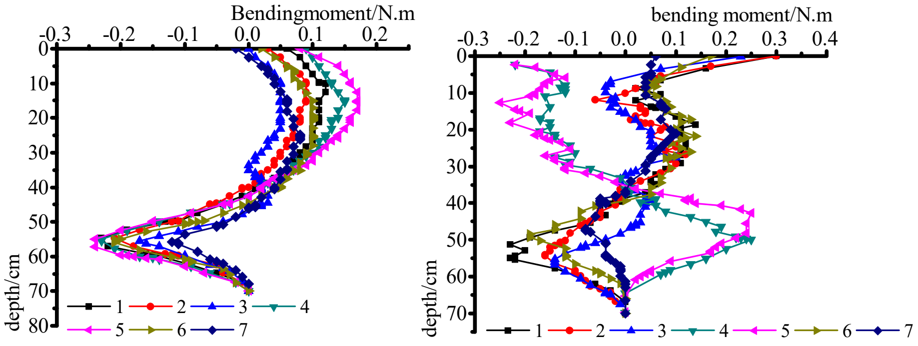
Figure (8): Ground settlement for different working conditions

Figure 8 shows the ground settlement around the foundation pit, which is an important index for the supporting system. It can be seen from the curves that the ground settlements around the foundation pit mainly occur within 20D from the front row piles, but the maximum settlement of each working condition mainly occurs about 5D~7D from it. The settlement curve in working conditions 6 or 7 looks like a groove and it is similar to the ground settlement caused by the internal bracing support, while the others look like a triangle and the settlement is much larger than that of working conditions 6 or 7. The maximum and minimum values in Figure 8 are about 1.3 mm and 0.15 mm, the latter being much smaller than the former.

Bending Moment of Different Forms of Double-row Piles

In Figure 9 (a), the change of bending moment in each working condition is similar and the positions of the maximum positive and negative bending moments are close. The maximum positive bending moments appear at the depth of about 5D below the ground and the maximum negative bending moments are in the depth of about 2D below the bottom of the foundation pit. The bending moment of working condition 4 or 5 is large and that of working condition 3 or 7 is small, but the maximum positive and negative bending moments in working condition 7 are close. In Figure 9 (b), the bending moments of rear row piles in working conditions 4 and 5 are different from the others, which further indicates that the working behavior of vertical-inclined inward double-row piles is different.The maximum positive and negative bending moments in working conditions 4 and 5 are large and their positions are near the pile top and the foundation pit, respectively. There are two reverse bending points in working conditions 4 and 5 and three reverse bending points in other working conditions.

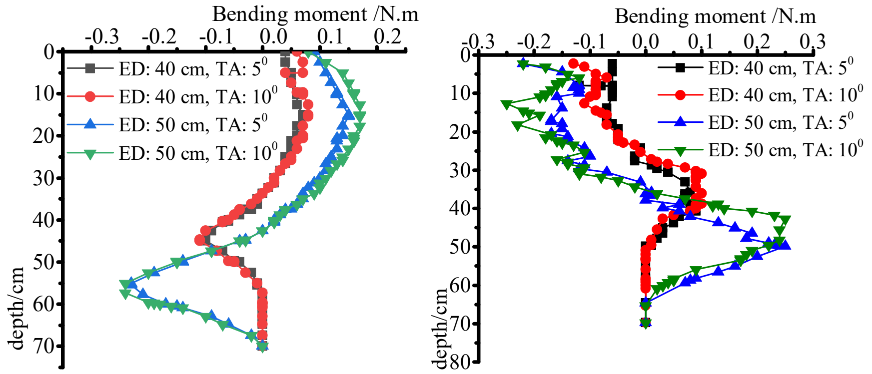
It can be seen that the crossbeams of double-row piles constrain the lateral deformation of front and rear row piles and their bending moment is less than that of single-row piles, which is equivalent to adding a restraint force to prevent deformation and a bending moment to stop the rotation of double-row piles.



(a) Front row piles

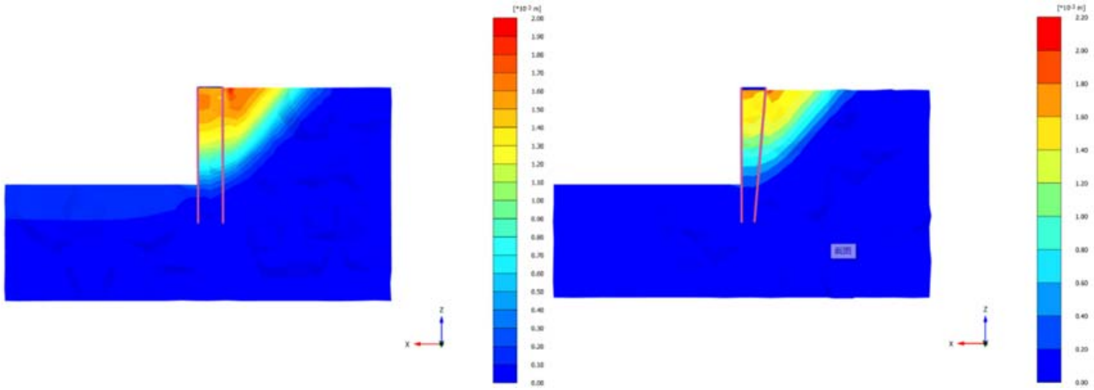
(b) Rear row piles

Figure (9): The bending moments of pile shaft after excavation for different working conditions



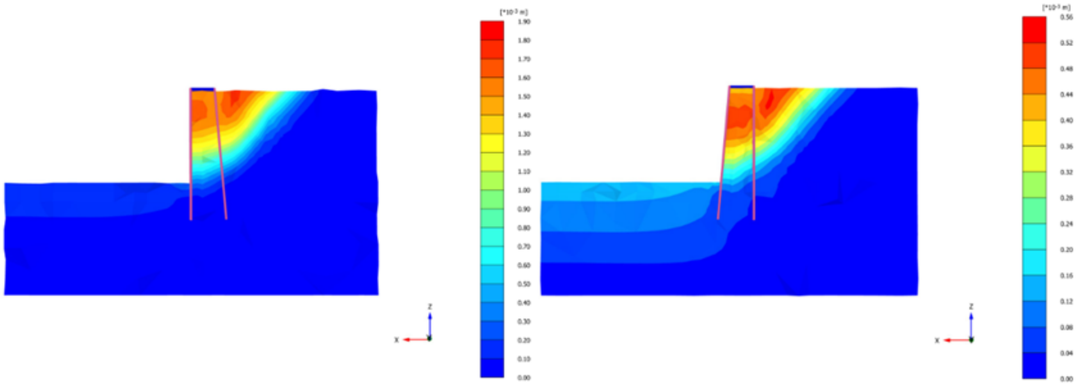
(a) Front row piles (b) Rear row piles

Figure (10): The bending moments in conditions 4 and 5 for different excavation depths (EDs) and tilt angles (TAs)



(a) Double row vertical piles (the maximum displacement is 1.955mm)

(b) Vertical-inclined backward double row piles (the maximum displacement is 2.091mm)



(c) Vertical-inclined inward double row piles (the maximum displacement is 1.884mm)

(d) Inclined backward-vertical double row piles (the maximum displacement is 0.535mm)

Figure (11): Total soil displacement around the foundation pit

To better understand the internal force of vertical-inclined inward double-row piles, the bending moments of working conditions 4 and 5 in different excavation depths are compared in Figure 10. The results show that the bending moment of the vertical-inclined inward double-row piles is not related to pile inclination angle, but increases rapidly with the excavation depth and the positions of inflection points move down.Because most of the rear row piles are located beyond the potential slip plane,under the action of soil pressure, the bending direction of the front and rear row piles is different. As the overturning force increases, the bending moment is increased.

Anti-overturning Stability of Double-row Piles

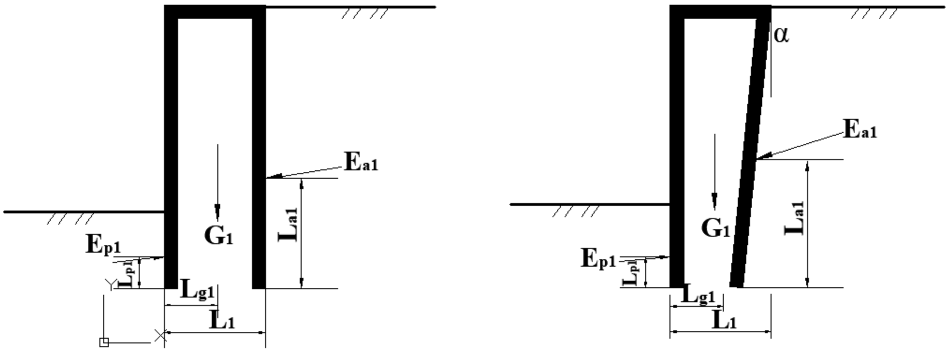
Total Soil Displacement around the Foundation Pit

According to the above analysis, the soil displacements around the foundation pit in working conditions 1, 2, 4 and 5 are large, but the soil displacement value of working condition 4 or 5 is close. For ease of comparison, the total soil displacements in working conditions 1, 2, 4 and 6 are shown in Figure 11. It means that the soil displacement caused by double-row vertical piles and double-row piles with an inclined angle of 5° are compared.

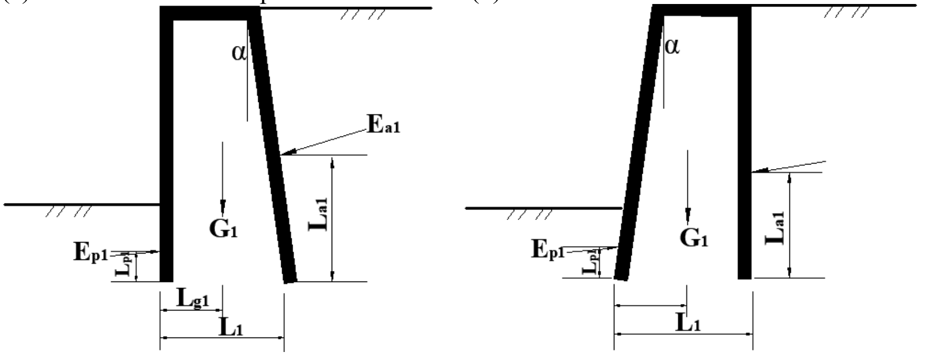
Figure 11 indicates that the affected areas around the foundation pit in working conditions 1, 2, 4 and 6 are close, but the maximum displacement value and scope are different. In Figure 11 (b), the soil displacement value is the largest, while the scope of the maximum displacement is small. In Figure 11 (d), the maximum displacement value is less than 1/3 that of the others, but there is a slight disturbance below the bottom of the foundation pit.

Calculation of Anti-overturning Stability

The internal force and deformation of double-row piles are widely researched, while there is little research on the anti-overturning stability of double-row piles. After excavation is completed, double-row piles tend to overturn around the bottom of front row piles. For the whole system, the main overturning force comes from the active soil pressure acting on the rear row piles, while the anti-overturning forces are the total weight of pile-soil and the passive soil pressure acting on the front row piles. The soil pressure in front and rear row piles is considered to cancel each other as calculating the anti-overturning stability. Based on the retaining wall theory, the calculation model in working conditions 1, 2, 4 and 6 is shown in Figure 12.



(a) Double-row vertical piles (b) Vertical-inclined backward double-row piles



(c) Vertical-inclined inward double-row piles (d) Inclined backward-vertical double-row piles

Figure (12): Anti-overturning calculation model of double-row piles

The anti-overturning stability coefficients in the figure are:

$$k_a = \frac{E_{p1}\cos\delta L_{p1} + G_1 L_{g1} + E_{a1}\sin\delta L_1}{E_{a1}\cos\delta L_{a1}} \tag{1}$$

$$k_b = \frac{E_{p2}\cos\delta L_{p2} + G_2 L_{g2} + E_{a2}\sin(\delta - \alpha)L_2}{E_{a2}\cos(\delta - \alpha)L_{a2}} \tag{2}$$

$$k_c = \frac{E_{p3}\cos\delta L_{p3} + G_3 L_{g3} + E_{a3}\sin(\delta + \alpha)L_3}{E_{a3}\cos(\delta + \alpha)L_{a3}} \tag{3}$$

$$k_d = \frac{E_{p4}\cos(\delta - \alpha)L_{p4} + G_4 L_{g4} + E_{a4}\sin\delta L_4}{E_{a4}\cos\delta L_{a4}} \tag{4}$$

where, E_a, E_p—the active and passive soil pressure; L_a, L_p—the distance from active and passive soil pressure to the bottom of front row piles;

G—the total weight of pile-soil;

L_g—the distance from the total weight to the bottom of front row piles;

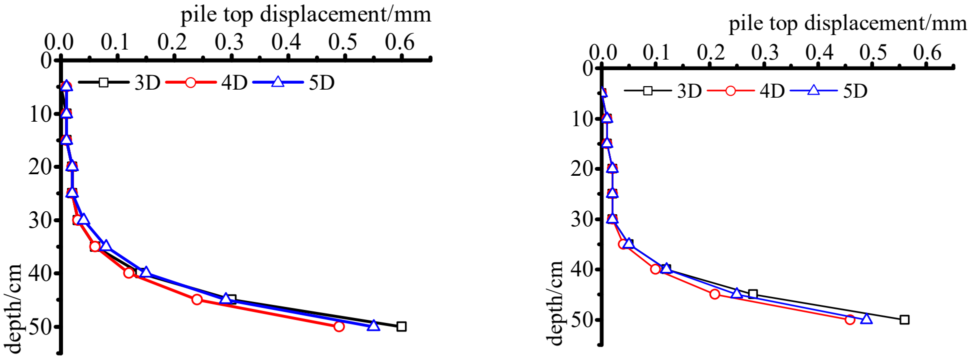
L_1—the horizontal distance from the bottom of front row piles to the active soil pressure;

α—the inclined pile angle, here 5°;

δ—the friction angle between pile and soil, according to the literature (Li Guangxin et al., 2016), it is $\varphi/2$ (φ ist he soil internal friction angle).

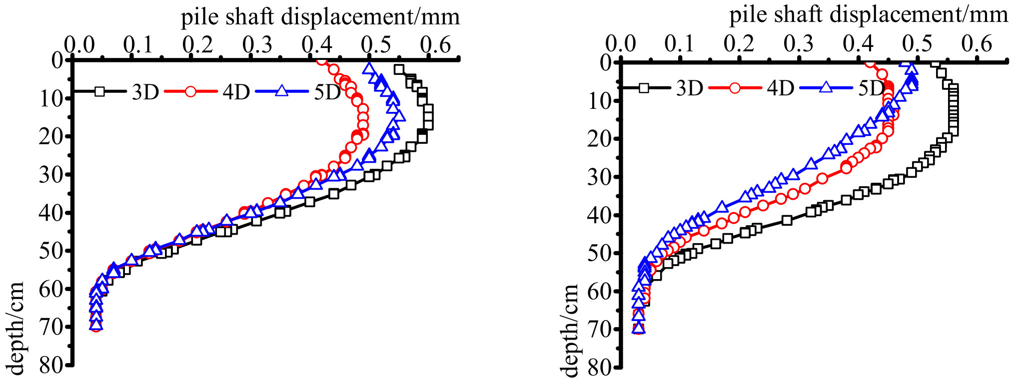
By substituting pile-soil parameters into the above formulae, the results obtained are:

$k_a = 1.60$, $k_b = 1.69$, $k_c = 1.57$, $k_d = 2.05$; the order is $k_c < k_a < k_b < k_d$. Therefore, the anti-overturning stability of the inclined backward-vertical double-row piles is larger than that of the others, which is in accordance with the numerical simulation results.



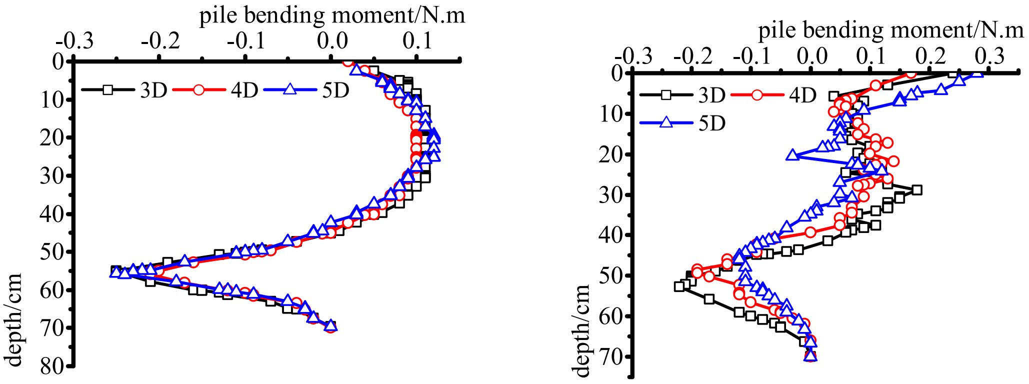
(a) Pile top displacement of the front row

(b) Pile top displacement of the rear row



(c) Pile shaft displacement of the front row

(d) Pile shaft displacement of the rear row



(e) Pile bending moments of the front row

(f) Pile bending moments of the rear row

Figure (13): Simulation results of three row spacings for different pile displacements (Legend: 3D; 4D; 5D)

Analysis of Anti-overturning Stability

The front and rear row piles are connected by the crossbeams and form a rigid frame, but the supporting effect of each working condition is different. Because the rear row piles in working condition 2 tend to the direction of soil sliding, the active soil pressure and overturning moment on it are small, so the vertical-inclined backward double-row piles are less likely to overturn. However, if the rear row piles change the angle from backward to inward, the working behaviors will change. The rear row piles in working condition 4 act as a pulling anchor, with the active soil pressure increasing, causing a tendency to overturn and the anti-overturning stability to decline. However, if the front row piles incline backward, the tilt piles act as supports for the rear vertical piles, which can further control the pile displacement and soil settlement. Therefore, the anti-overturning stability of the inclined backward-vertical double-row piles is better, which meets the conclusions of the documents (Xu Yuan et al., 2010).

Optimization Analysis of Inclined Backward-Vertical Double-row Piles

According to the results of simulation and calculation, inclined backward-vertical double-row piles have great advantages in controlling pile displacement, bending moments and soil settlement and have a high anti-overturning stability. Theoretically, the greater the inclined angle is, the better is the supporting effect. However, inclined backward-vertical double-row piles with a tilted angle of 5° are more feasible, because the inclined pile can be constructed in China with a maximum angle of less than 7°. The optimization analysis of inclined backward-vertical double-row piles will be analyzed in the paper.

Influence of Row Spacing

Row spacing of double-row piles is an important design parameter, which affects many interaction parts, such as the front row pile, the rear row pile, soil in piles and the crossbeam. The soil pressure will change with the variation of pile row spacing. Many scholars have studied the row spacing of double-row vertical piles, Peng Wenxiang et al.(2018) carried out a model test on double-row vertical piles with 2D, 3D, 4D and 5D row spacing (D is the pile diameter) and studied the optimal row spacing and the internal forces of front and rear row piles. Sun Tao et al.(2012) used Plaxis software to discuss the row spacing of double-row vertical piles and compared it with the engineering monitoring data.

In order to analyze the row spacing of inclined backward-vertical double-row piles, a numerical model with row spacings of 3D, 4D and 5D (D is the pile diameter) is established and the simulated results are shown in Figure 13.

According to Figure 13, the pile top displacements of the three row spacings all increase with the excavation depth and the increasing trends of front and rear row piles are the same, but the top displacement of the front row is slightly larger than that of the rear row. In Figure 13 (a) and Figure 13 (b), the order of pile top displacement is 4D<5D<3D, which indicates that the pile top displacements of front and rear rows do not increase with the row spacing, because the inclined backward-vertical double-row piles will be affected by the soil pressure in piles. For the row spacing of 3D, the soil pressure in piles is low and the supporting system is equivalent to a single-row pile to bear active soil pressure. For the row spacing of 4D, the soil pressure in piles increases and offsets part of the active soil pressure and the top horizontal displacement decreases. However, for the row spacing of 5D, the soil pressure in piles continues increasing and will affect the stability of the front row piles, under the action of crossbeams, where the top horizontal displacements of front and rear rows piles all increase.

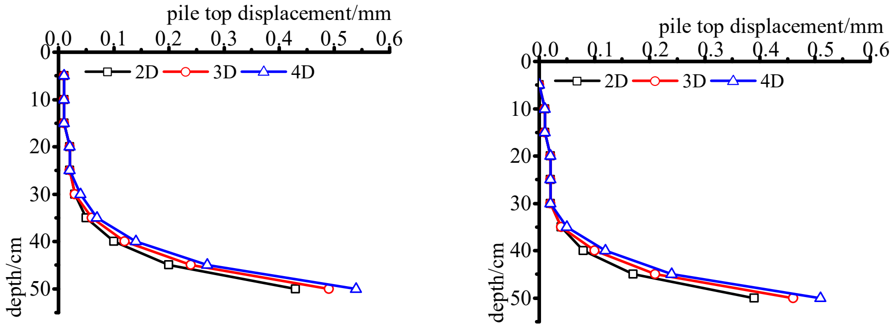
Figure 13 (c) and Figure 13 (d) indicate that the shaft horizontal displacements of piles decrease with the pile depth and tend to be consistently below the bottom of the foundation pit. The order of the front row pile is 4D<5D<3D and that of the rear row pile is 5D<4D<3D. The shaft horizontal displacements of front and rear row piles are mainly affected by the distribution of soil pressure in piles. In Figure 13, the maximum shaft horizontal displacements are not on the pile top, but at about the position of 1/3 of the excavation depth.

In Figure 13 (e), the bending moments of front row piles are the same and the maximum negative bending moments are greater than the maximum positive bending moments. In Figure 13 (f), the maximum positive and negative bending moments in the row spacings of 3D and 4D are close, but in the row spacing of 5D, there is a fluctuation, because the rear row piles mainly bear the active soil pressure and transmit it to the front row piles. With the increase of pile depth, the soil pressure in piles altered, resulting in bending moment changes and the reverse bending points move up. The positions of the maximum positive bending moments are different, where the front row piles are at 1/2 of the excavation depth, but the rear row piles are at the pile top, while those of the maximum negative bending moments are all near the bottom of the foundation pit.

Therefore, the reasonable row spacing of the inclined backward-vertical double-row piles in this case is 4D.

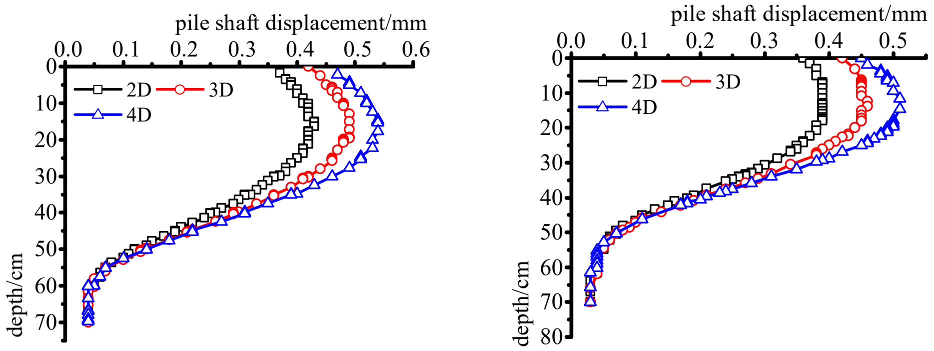
Influence of Pile Spacing

By changing the space of front and rear row piles simultaneously and taken as 2D, 3D and 4D, respectively (D is the pile diameter), the simulation results are obtained and shown in Figure 14.



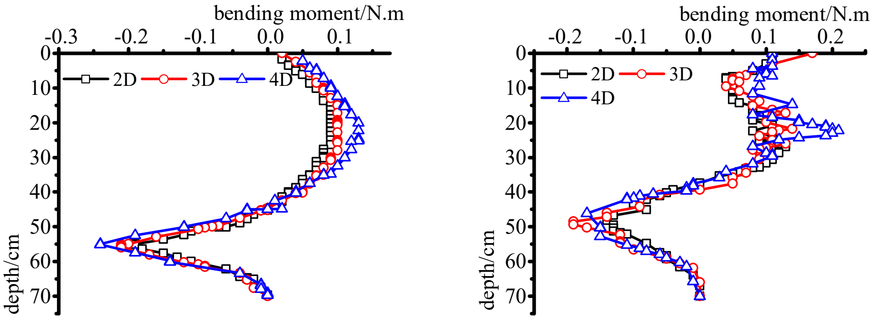
(a) Pile top displacement of the front row

(b) Pile top displacement of the rear row



(c) Pile shaft displacement of the front row

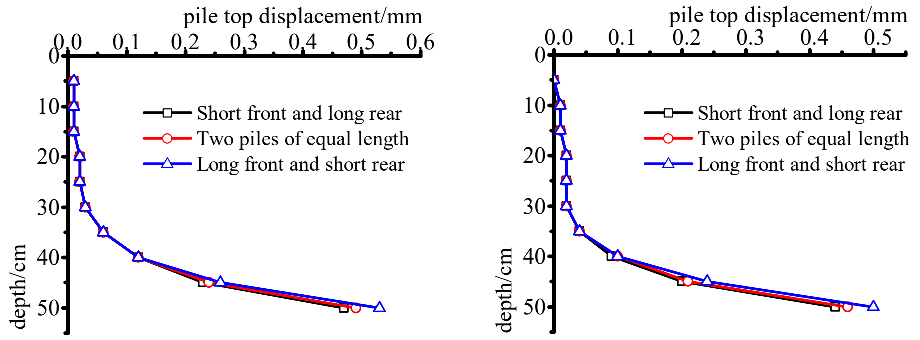
(d) Pile shaft displacement of the rear row



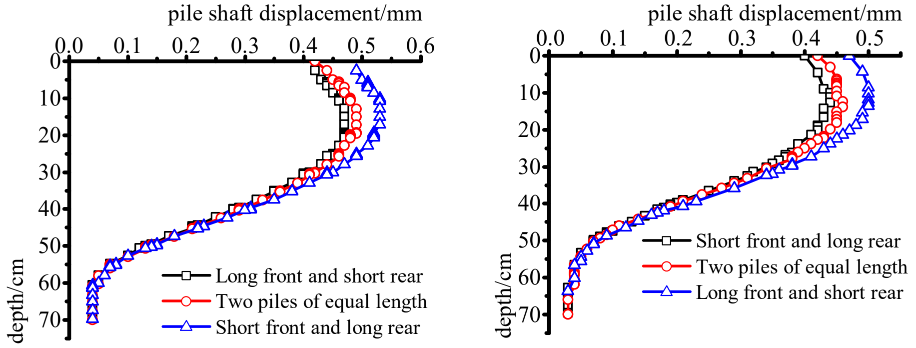
(e) Pile bending moment of the front row

(f) Pile bending moment of the rear row

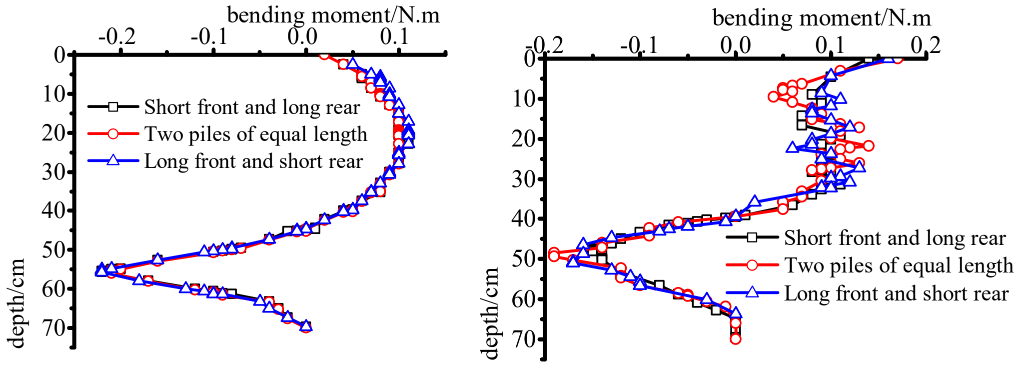
Figure (14): Simulation results of three pile spacings for different pile displacements (Legend: 2D; 3D; 4D)



(a) pile top displacement of front row (b) pile top displacement of rear row



(c) pile shaft displacement of front row (d) pile shaft displacement of rear row



(e) pile bending moment of front row (f) pile bending moment of rear row

Figure (15): Simulation results of pile length change

In Figure 14 (a) and Figure 14 (b), the pile top horizontal displacements of front and rear row piles increase with the excavation depth and the order is 2D<3D<4D. The reason is that the soil in front or rear row piles will be extruded with the increase of pile spacing; once the soil arching effect can not be formed, the overall stiffness will decline and cause the top horizontal displacement to increase.

In Figure 14 (c) and Figure 14 (d), the shaft horizontal displacements of front and rear row piles all increase with the pile spacing, but this is more obvious when the pile spacing varied from 2D to 3D. The shaft horizontal displacement of the front row pile is larger than that of the rear row pile. With the pile depth increasing, the shaft horizontal displacement gradually decreased and tended to be consistent near the bottom of the foundation pit. The inclined backward-vertical double-row piles should have a sufficient burial depth, because the passive soil pressure on the front row pile has an obvious restraint effect on the shaft displacement.

The maximum shaft displacements of front and rear row piles are all located at 1/3 of the excavation depth.

In Figure 14 (e) and Figure 14 (f), the bending moments of front and rear row piles in spacings 2D and 3D are close, but the bending moments of the rear row piles in spacing 4D fluctuated greatly, which means that the soil pressure is unstable in spacing 4D. The maximum positive bending moments are located at 1/2 of the excavation depth and the maximum negative bending moments are near the bottom of the foundation pit. The reversed point positions of them are the same; therefore, changing the pile spacing can not change the distribution form of soil pressure in front and rear row piles.

According to the above analysis, for the inclined backward-vertical double-row piles, a reasonable pile spacing should be chosen, because the pile horizontal displacements increase with the pile spacing, but if the pile spacing is too small, the material consumption will increase. In this case, the pile spacing of 3D is more economical and reasonable, because the horizontal displacements in pile spacing of 2D and 3D are small and their positive and negative bending moments are close.

Influence of Pile Length

To analyze the influence of pile length, the rear row piles will be extended or shortened 2D and the simulation results are shown in Figure 15.

In Figure 15 (a) and Figure 15 (b), the top horizontal displacements of front and rear row piles gradually increase with the excavation depth, but the combination of long front and short rear row piles is the largest. The combination of two piles of equal length is in the middle and the combination of short front and long rear row piles is the least. The reason is the active soil pressure mainly acting on the rear row piles; if it is extended, the stiffness of double-row piles will increase resulting in the pile top displacement decrease.

In Figure 15 (c) and Figure 15 (d), the shaft horizontal displacements of front row piles are slightly larger than those of rear row piles.With the short rear row piles, the shaft horizontal displacements increase, but the increasing trend is more obvious in the combination of long front and short rear row piles. The maximum shaft displacements of front and rear row piles are at 1/3 of the excavation depth and tend to be the same at 4/5 of the excavation depth.

In Figure 15 (e) and Figure 15 (f), the bending moments of front and rear row piles in different combinations are the same and have a little relationship with the length of rear row piles, but the bending moments of rear row piles are fluctuant, which means that the working mechanism of rear row piles is more complex. The location of the maximum positive and negative bending moments are different; the front row piles are located at 1/2 of the excavation depth and below the foundation pit, respectively, but the rear row piles are located at the pile top and near the bottom of the foundation pit, respectively. In this case, the combination of short front and long rear row piles was more reasonable, because it is more effective to control the pile displacements.

CONCLUSIONS

Double-row piles have been widely used in foundation pits. In this paper, the working behavior of double-row piles in different forms is investigated by numerical simulation. The pile internal force and displacement during the excavation of sandy soil pit are compared and the anti-overturning stabilities are calculated. Finally, the inclined backward-vertical double-row piles are optimized and analyzed. The main conclusions are summarized as follows:

(1) The form of double-row piles impacts their support effect. Compared with the traditional double-row vertical piles, the vertical-inclined backward or inclined backward-vertical double-row piles have advantages in controlling pile displacement and soil settlement, but with the inclination angle increasing, the ability of vertical-inclined inward double-row piles to control pile displacement and soil settlement reduces. The simulation results show that the inclined backward-vertical double-row piles have the best support effect.

(2) The bending moments of the front row piles have similar trends in all working conditions. However, the rear row of vertical-inclined inward double-row piles has an anchoring effect and the bending moments are obviously different from the others. In each working condition, the bending moment has a little relationship with the inclination angle, but when the excavation depth increases rapidly, the reverse bending points move down.

(3) The soil displacements around the foundation pit in conditions 1, 2, 4 and 6 are compared.The soil

influence range is similar, but its maximum displacement scope and values are different.The maximum displacement scope of vertical-inclined backward double-row piles is small, but the maximum displacement value of the inclined backward-vertical double-row piles is only about 1/3 of the others. Based on the retaining wall theory, the anti-overturning stability coefficients are calculated. The results show that the anti-overturning stability of inclined backward-vertical double-row piles is the best.

(4) Considering construction technology and project cost, the inclined backward-vertical double-row piles with the tilt angle of 5° are more feasible. The design parameters of inclined backward-vertical double-row piles are discussed. The pile displacement and bending moment varied with row spacing, pile spacing and pile length. Results show that the inclined backward-vertical double-row piles with a row spacing of 4D, a pile spacing of 3D and the combination of short front and long rear row piles are reasonable. Under such conditions, the pile displacement is small and the maximum positive and negative bending moments of front and rear row piles are relatively close.

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