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Research Article

Simulation Analysis of the Effect of Pile Spacing on the Compressive Load-Bearing Performance of CEP Double Piles

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Under the action of vertical pressure, the variation of pile spacing affects the bearing performance of concrete expanded-plate (CEP) double pile and the damaged state of soil around the pile. In this study, finite element simulation analysis is performed by ANSYS software, and six sets of semisectional double pile models with different pile spacings and one set of semisectional monopile models with the same specifications are established after applying the vertical pressure to the model pile. The mapping method is used for the pile-soil model meshing, the model adopts the contact type of rigid and flexible bodies, and the simulation analysis adopts the way of applying surface load and loading step-by-step. The displacement distribution, load-displacement curve, stress cloud, and shear stress curve are collated to obtain the displacement and stress change law of pile-soil under different pile spacings and then determine the effect of the changes in pile spacing on the CEP double pile. Meanwhile, the CEP double pile model is compared with the monopile model to determine their similarities and differences. Finally, a reasonable range of pile spacing for CEP double piles is provided. It further improves the research theory of CEP group pile compressive load-bearing capacity and provides the theoretical basis for its design and application in practical engineering.

1. Introduction

Concrete expanded-plate (CEP) piles have been widely used in practical engineering because of their high economic efficiency, good load-bearing performance, and small and uniform settlement [1]. Compared with straight-hole piles, CEP piles add bearing discs at the pile position, which can flexibly set the position and parameters of the bearing discs, change the pile bearing condition, and increase the contact area between the pile and the soil, significantly improving the pile bearing capacity and stability. From the current situation of domestic and foreign research, the study on CEP monopiles performed by domestic and foreign scholars has been perfected [2–4]. Many influencing factors of CEP monopiles on the load-bearing performance and the intrinsic mechanism have been studied in depth [5], whereas research on the CEP group piles is still in the primary stage; however, most of the piles in practical engineering appear in the form of group piles [6, 7], and CEP piles are gradually used in high-rise buildings, bridges, deep-sea platforms, and other projects, and many factors, such as environment and geological conditions, influence these construction facilities. The requirements for their bearing performance are gradually improved [8, 9]. Therefore, an in-depth study on the load-bearing performance [10, 11] of CEP group piles must be conducted to meet the needs of actual projects. Under the action of vertical pressure, the neighboring piles will interact with one another when the pile spacing is small, and the change in pile spacing affects the damage state and bearing performance of the soil around the CEP group pile. This study takes CEP double pile as the research object, the pile spacing as a single variable, and ANSYS finite element software is used to establish six groups of semisectional double pile models with different pile spacings and one group of semisectional single pile models with the same specifications [10]. The displacement and stress change law of the CEP double pile and soil body under the action of vertical pressure is obtained through collated analysis, and the damage state and bearing capacity [12–14] change trend of the soil body around the pile of CEP double pile are derived. Their similarities and differences are also determined by comparing them with the monopile model [15]. Finally, the best pile spacing design principle that affects the compressive bearing performance of CEP double piles is given to provide the theoretical basis for further improving the design of CEP group pile bearing capacity under vertical load.

2. ANSYS Finite Element Modeling

2.1. Constitutive Model and Material Parameters. Due to the complex force situation in the soil in the actual project, the Duncan–Chang model in the nonlinear elastic model is chosen for the soil, which meets the DP yield criterion. The elastic-plastic model can reflect the main force characteristics of concrete and is used as the principal structure model of the CEP double pile. The interaction between the pile and the soil specifically influences the structure's stress and displacement. The finite unit method is used, which can consider the nonlinear stress-strain relationship on the interaction contact surface and improve the accuracy of the calculation results. The hyperbolic model is used for the contact surface.

In ANSYS finite element simulation and analysis, according to the preliminary experimental study and simulation analysis of CEP monopiles, the CEP double pile is made of C30 concrete material and the soil is made of powdered clay according to the site investigation report [16] to ensure that the simulation matches the actual elements [17]. The specific material parameters are shown in Table 1.

2.2. Model Determination and Model Dimensions. For a more intuitive observation of displacement distributions, stress clouds, and other related data [18], the model piles used in this simulation are semisectional piles because they are symmetrical structures. To ensure the feasibility and convenience of applying the research results of this thesis to the actual project, the dimensions of the established model pile should be consistent with the actual project, and the modeling is completed by using a 1 : 1 scale. The pile dimensions are set as follows: the pile length $L = 9200$ mm, the pile diameter $d = 500$ mm, the disk height is 932 mm, the disk overhang diameter $R = 828$ mm, the upper slope angle of the disk $\alpha = 35^{\circ}$, and the lower slope angle of the disk $\beta = 20^{\circ}$. The model pile specifications are shown in Figure 1. In this ANSYS simulation, seven groups of model piles were set up (including six groups of CEP double pile model and one group of single pile model as a comparison), and all the piles have the same specifications. The first six groups took the pile spacing as a single variable. The piles are numbered MS1–MS6, and the pile spacing is 2984, 3398, 3812, 4226, 5054, and 5882 mm in order, which are 1, 1.5, 2, 2.5, 3.5, and 4.5 times the circling pick diameter, respectively. The CEP monopile model of the same specification is set for comparison and numbered as MD.

2.3. Double Pile Modeling

2.3.1. Pile-Soil Model Establishment. The MS1 model pile is taken as an example. Key points are established on the basis of the aforementioned dimensional data. MS1 is rotated 180° after the key points are connected to obtain a semisectional model pile. To prevent the simulation results from being affected by the small soil size, the soil size is designed to be $12000\,\mathrm{mm} \times 10000\,\mathrm{mm} \times 8000\,\mathrm{mm}$, and the model pile is merged with the soil by Boolean after gouging the soil part of the model pile in the soil. The pile-soil model is shown in Figure 2. For material parameter setting, the double-pile pile body is set to Solid 65 cells, and the soil body is set to Solid 45 cells to enable the double pile and the soil body to conform to the actual situation.

2.3.2. Mesh Delineation and Contact Surface Delineation. This simulation uses the mapping method [19], which can generate a more regular grid and improve the calculation speed significantly. The test data obtained by using this method are more consistent with the actual engineering. Figure 3 shows the model after the mesh division. The model adopts the contact type of rigid and flexible bodies and sets the CEP double pile as a rigid body and the soil body around the pile as a flexible body. To match with the actual situation, the pile and soil bodies are set as face-to-face contact, and the outer surface of the pile body is set as a rigid surface, which is set as the target surface and defined by using target170 cell, whereas the contact surface of the soil body and the pile body is set as the contact surface and defined by using contact173 unit.

2.3.3. Setting Constraints and Applying Loads. To ensure that the finite element simulation is consistent with the actual project and to prevent the pile-soil model from moving due to excessive vertical load, constraints are set for the degrees-of-freedom in each direction of the pile-soil model.

The simulation analysis adopts the way of applying surface load and loading step-by-step. To facilitate comparison with the actual project, the concentrated load is transformed equivalently into the surface load, and each step is increased by 200 kN. According to the conclusion of the preliminary research on the bearing capacity of CEP monopile and the specification requirements, we load until the ANSYS simulation analysis curve does not converge and then stop loading. According to the conclusion of the preliminary research on the bearing capacity of CEP monopile and the specification requirements [20], when the loading until the ANSYS simulation analysis curve does not converge, we stop loading, which is regarded as loading to the ultimate load at this time. The constraint case level load application position is shown in Figure 4.

Table 1: Material parameters.

Material	Density (t/mm^3)	Modulus of elasticity (MPa)	Poisson's ratio cohesion	Cohesion (MPa)	Friction angle (°)	Expansion angle (°)	Pile-soil friction coefficient
Flexible pile	2.25×10^{-9}	3.465×10^4	0.2	—	—	—	0.3
Powdered clay	1.688×10^{-9}	40	0.35	0.04355	10.7	10.7	

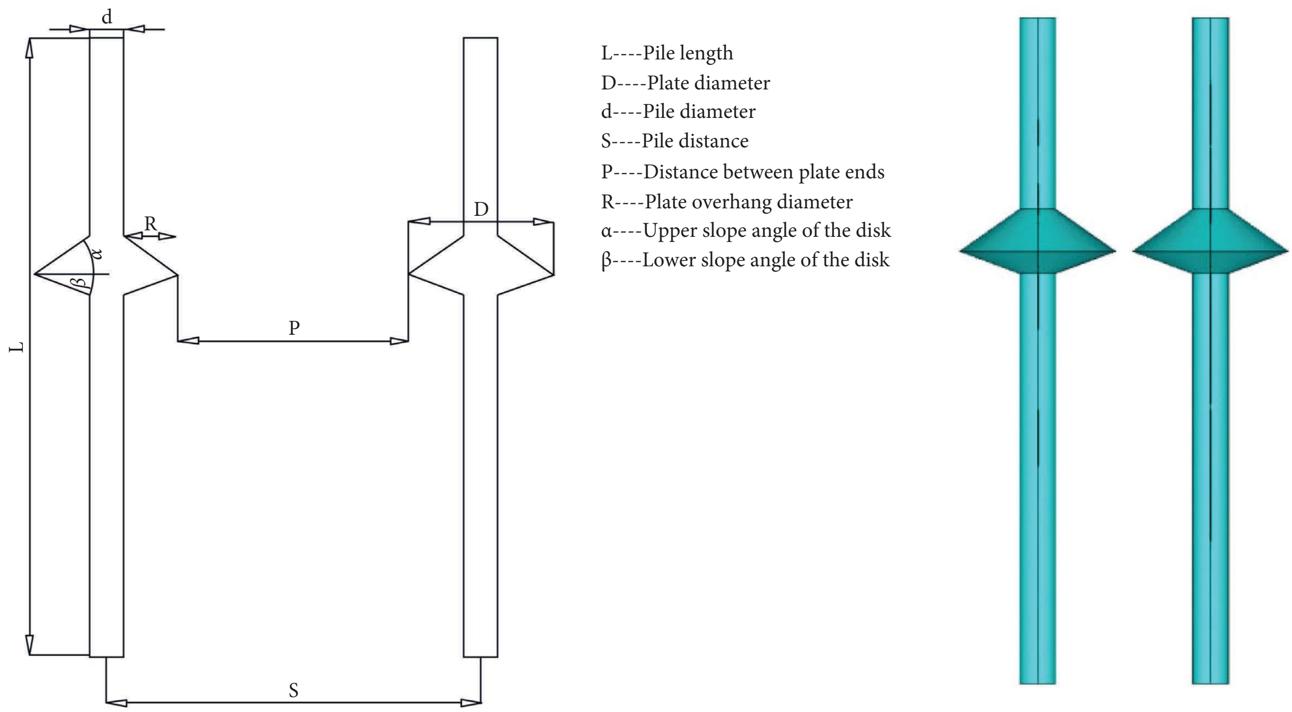


Figure 1: Schematic of the double pile model.

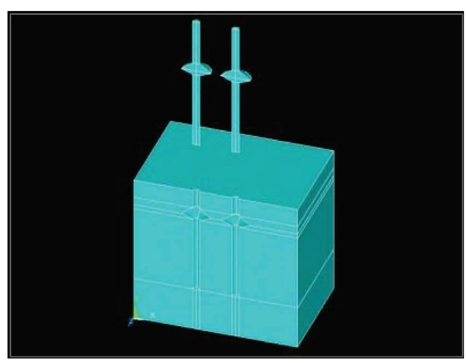


Figure 2: Establishing the pile-soil model.

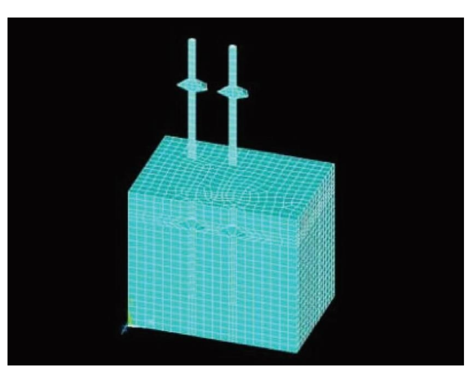


Figure 3: Effect of mesh division.

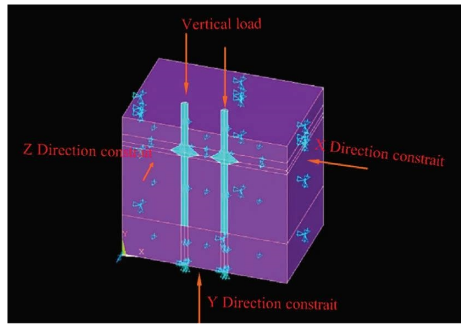


Figure 4: Constraint situation and load application position.

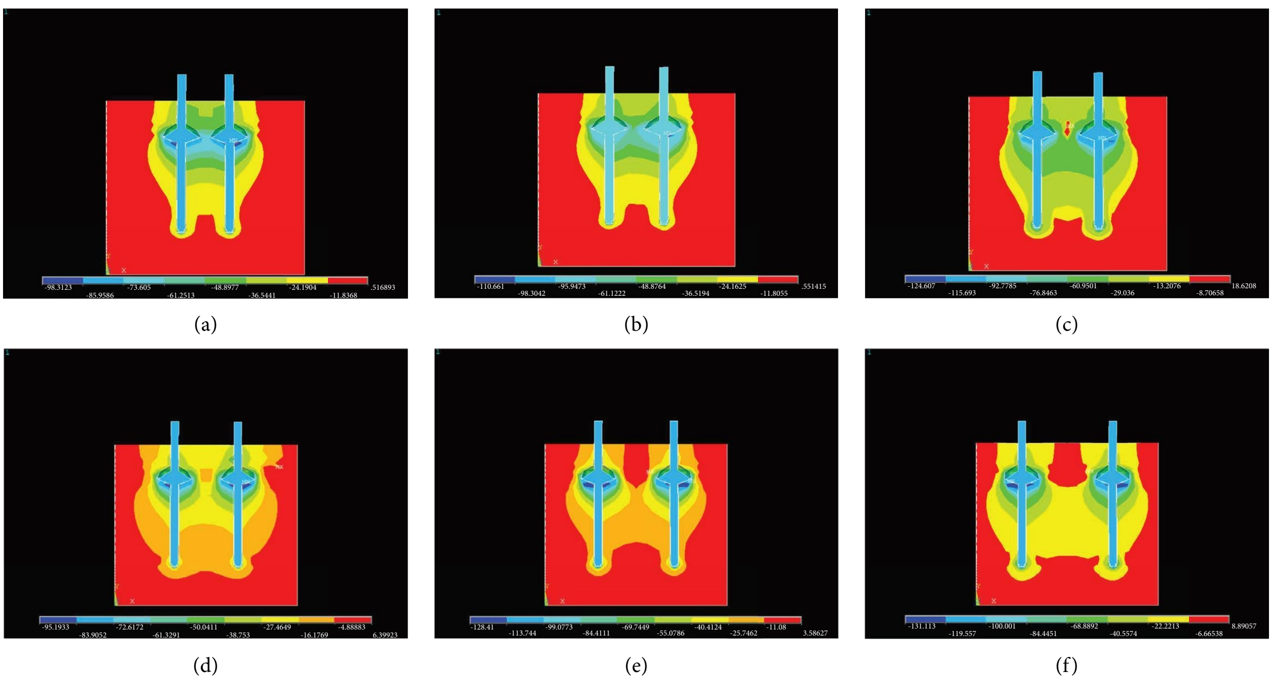


Figure 5: Displacement distributions of each group of model piles under extreme load. (a) MS1. (b) MS2. (c) MS3. (d) MS4. (e) MS5. (f) MS6.

3. Displacement Results Analysis

3.1. Comparison Analysis of Displacement Distributions of Each Group of Model Piles. In the ANSYS simulation analysis, the displacement distribution diagram of each group of the double-pile is extracted when it reaches the ultimate compressive bearing capacity (Figure 5). The displacement distribution diagram of the MD model pile is extracted when it reaches the ultimate compressive bearing capacity (Figure 6).

Figure 5 shows that when the CEP double pile model is subjected to ultimate load, the overall trend of the displacement distributions of each group of model piles is basically similar; that is, the CEP double pile model produces different degrees of slip misalignment of the soil below the bearing disc under vertical pressure, and the extent of damage to the soil around the pile is mainly concentrated in the soil close to the soil below the bearing disc (green area in the figure). In Figures 5(a)–5(c), the pile spacing is small, the displacement influence range generated by the double-pile model has a certain overlapping part (green area), and the joint action of the double piles leads to a larger displacement of the soil between the piles downward. Figure 5(d) illustrates that when the pile spacing is 4226 mm, the disk end spacing is 2.5 times the disk overhang diameter, the area with larger displacement below the bearing disk of each single pile no longer overlaps, and the overall displacement produced by the soil between piles becomes smaller. Thus, at this pile spacing, the double-pile effect is weakened, and the CEP double pile compressive bearing capacity is improved. In Figures 5(e) and 5(f), when the pile spacing increases to a certain degree, the displacement produced by the two bearing discs that exert effects on the soil body between the piles is smaller and only overlaps at the periphery, whereas

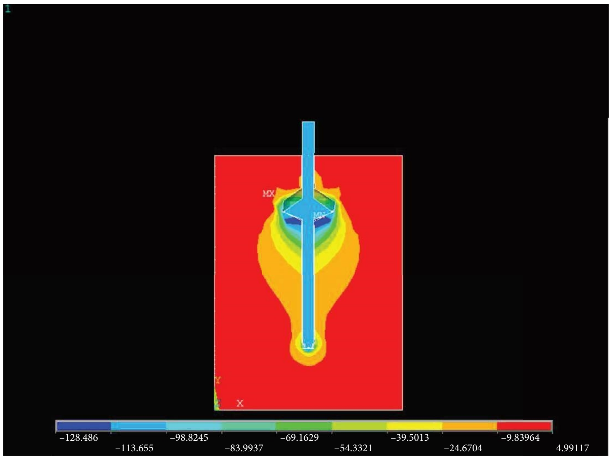


Figure 6: MD displacement distribution map.

the soil body below the bearing disc produces larger displacement, and the double-pile effect is weakened further. From Figure 6, we found that when the CEP monopile is subjected to ultimate load, the pile-soil separation occurs on the disk, the bearing disk plays the main role, and the larger displacement area occurs in the soil below the bearing disk. The CEP double pile increases with pile spacing. Each single pile is closer to the CEP single pile under pressure, the double-pile effect gradually weakens, and the range of soil body between piles interacting with each other continuously declines, thereby reducing the overall displacement generated by the soil body between piles and improving the compressive bearing capacity gradually.

3.2. Load-Displacement Curve Analysis. The vertical pressure is loaded step-by-step, the pile top displacement data under each level of load are extracted and collated, and the load-displacement curve is drawn, as shown in Figure 7(a).

(1) Figure 7(a) shows that the development trend of each curve is similar, the displacement of the top pile, and the slope of the curve increase continuously with load; that is, the amount of change in displacement gradually rises due to the extrusion of the bearing disc and the soil under the disc under the action of the vertical pressure of the CEP double-pile, which causes the soil to slip. Furthermore, the compressive bearing capacity of the soil gradually decreases, which is not enough to resist the vertical pressure, resulting in the change of displacement rate being accelerated.

(2) At the early stage of loading, when the vertical pressure is 200–1000 kN, the six curves are almost in the overlapping state; that is, the displacement changes are the same. At this time, the soil around the pile is not damaged, and the pile spacing has less influence on the bearing performance of the CEP double pile. When the vertical pressure exceeds 1000 kN, the displacement variation gradually decreases with the increase in pile spacing. For example, when the vertical pressure ranges from 1000 to 4000 kN, the displacement variations of MS1–MS6 pile are 94.31, 87.42, 83.74, 81.57, 77.58, and 76.55 mm. The displacement variation of MS5 and MS6 groups with the largest pile spacing almost overlap. This phenomenon is due to the fact that when the vertical pressure increases continuously, the overlapping range of pile-soil interaction decreases, the double-pile effect weakens, and the compressive bearing capacity of the double-pile foundation increases, which makes the displacement variation of the CEP double piles with larger pile spacing smaller.

(3) As can be seen from Figure 7, when the vertical pressure is greater than 1000 kN and the CEP double piles are subjected to the same vertical pressure, the displacement of the pile top gradually decreases with the increase in pile spacing. For example, when the vertical pressure is 4000 kN, the displacements of MS1–MS6 pile top are 106.51, 97.96, 91.42, 88.87, 85.27, and 84.12 mm. The difference among MS1, MS2, MS3, and MS4 pile top displacement is large, whereas the difference between MS5 and MS6 pile top displacement is small, indicating that when the pile spacing increases, the double pile effect is weakened, the compressive bearing capacity of CEP double pile is gradually improved, and the pile top displacement is gradually reduced. When the spacing of the CEP double pile disc end is greater than 2.5 times the disc overhang diameter, the double pile effect on the compressive bearing capacity of CEP double pile is small. Therefore, in the actual process, to reduce the influence of the double pile effect on the compressive bearing capacity of CEP double pile, we must try to ensure that the spacing between the disc ends of CEP double pile is greater than 2.5 times the disc overhang diameter.

To further investigate the similarities and differences between CEP double piles and CEP monopile, the test data of the MD monopile model were compared with MS2, MS4, and MS6 double pile models, and the load-displacement curves are drawn in Figure 7(b).

Figure 7(b) depicts that when the vertical pressure ranges from 200 to 1000 kN, the change in the displacement of the monopile model is small, and the curves of the three sets of double pile models are gentle and almost coincide, indicating that the CEP double piles do not have mutual influence at this time, and the compressive bearing capacity of monopile and double piles is not different. When the vertical pressure exceeds 1000 kN, the displacement of the top of the CEP monopile increases sharply with the load. After this point, the curve trend, which is called the inflection point of the MD monopile load-displacement curve, occurs obviously, and the inflection point also appears when the vertical pressure for both double piles is 2000 kN. The gentle decline of the original curve displacement transformed into a sharp decline. Finally, each curve reached the last data point; that is, the MD monopile, MS2, MS4, and MS6 double piles' ultimate compressive bearing capacity are

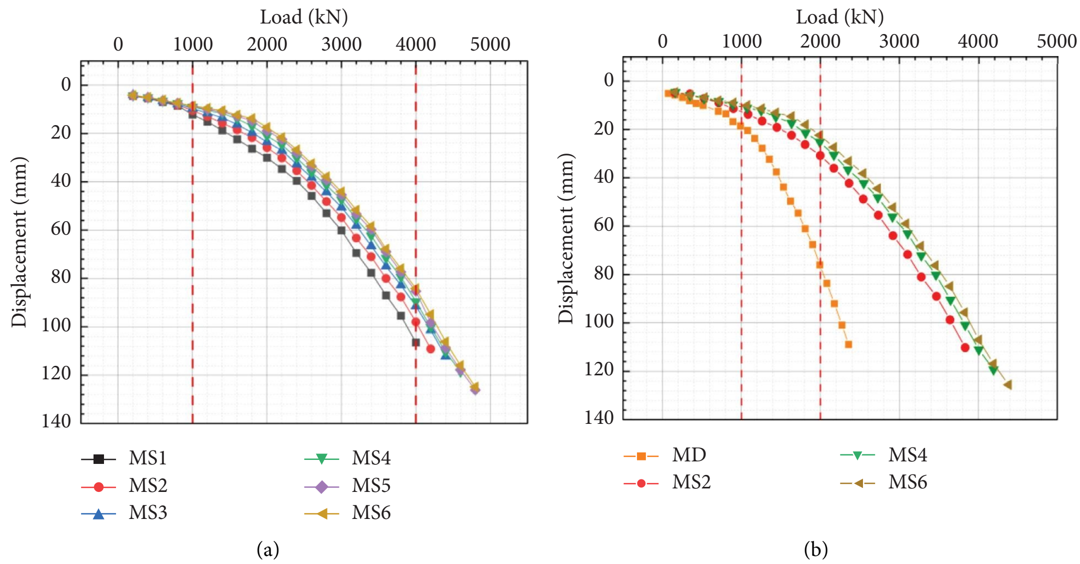
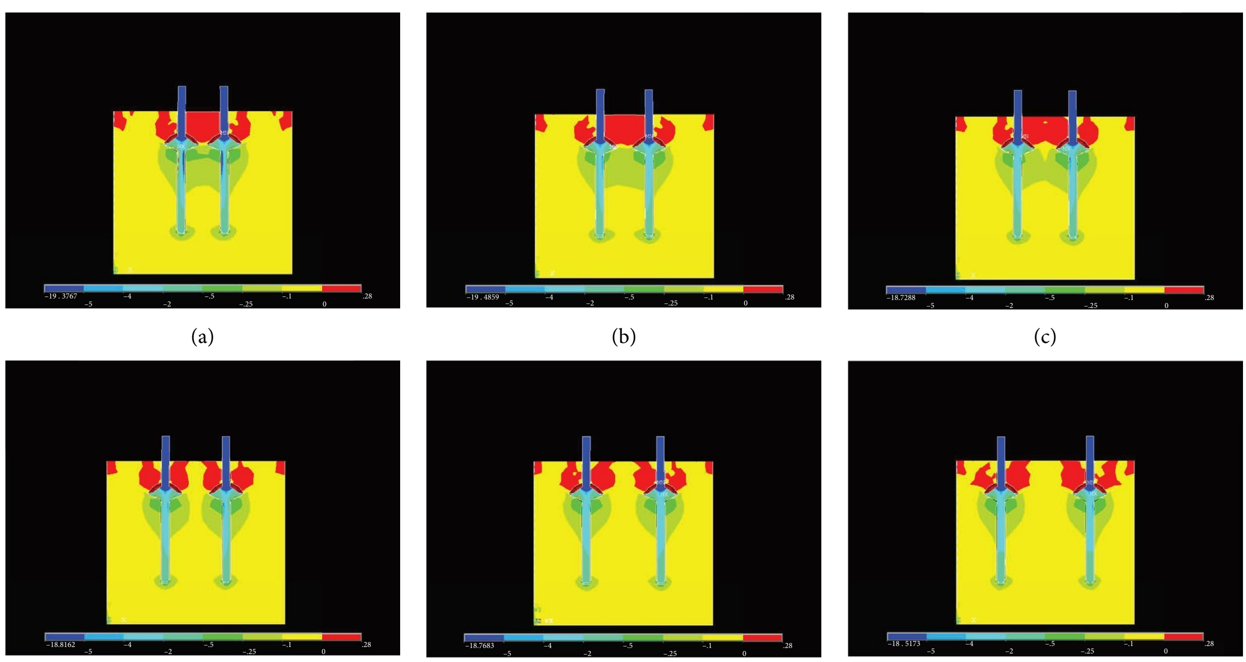


Figure 7: (a) Load-displacement curve. (b) Comparison of the CEP double pile and single pile load-displacement curves.



(a) (b) (c)

(d) (e) (f)

Figure 8: Y-directional stress cloud of each model pile and soil body (unit: MPa). (a) MS1. (b) MS2. (c) MS3. (d) MS4. (e) MS5. (f) MS6.

2600, 4200, 4600, and 4800 kN, respectively. The three groups of double-pile ultimate compressive bearing capacity are 1.62, 1.77, and 1.85 times of the monopile, from which we can learn that the ultimate compressive load bearing capacity of CEP double piles increases with the pile spacing, and the larger the pile spacing of the double piles is, the closer the ultimate compressive load bearing capacity is to 2 times of that of the single piles. However, the ultimate compressive load bearing capacity of MS6 CEP double piles did not reach twice that of single piles because of the influence of double piles on each other. Therefore, when studying the compressive load bearing capacity of CEP double piles, the influence of pile spacing and double-pile effect should be fully considered.

4. Stress Cloud Analysis

To understand the effect of pile spacing on the stress of CEP double piles, the model pile and soil Y-directional stress clouds of six groups of different pile spacings at this time were extracted (Figure 8) and compared with the stress distribution of the CEP monopile, the MD model pile, and soil Y-directional stress clouds (Figure 9).

Figure 8 shows that when the vertical pressure is the same, the Y-directional stress distribution trend of the dual piles with different pile spacings is the same, the stress above the bearing disc is higher, and the stress below the bearing disc is lower. The comparison with Figure 9 shows that the stress distribution of the dual piles is similar to that of the single piles, which means that the stress distribution of the dual piles is not affected by the pile spacing at this time. Furthermore, the bearing disc plays an important role in bearing the vertical pressure. First of all, under the action of the vertical pressure of the double-pile, the Y-directional stress distribution of the soil at the pile end of each model pile is almost the same. The separation of the bearing disc and the soil on the disc occurs, and the Y-directional stress of the soil on the disc tends to be 0. The Y-directional stress distribution of the soil above the bearing disc and the soil at the pile end of the double-pile is the same as that of the single pile, whereas the Y-directional stress area of the soil under the disc (green area) is larger. The overlapping phenomenon of the soil in the Y-stress area in the MS1 group, which is due to the small pile spacing that resulted in a larger soil interaction between the double piles and a larger double pile effect, is obvious; whereas, from the MS4 group to MS6 group, the soil in the Y-stress area is separated with the increase in pile spacing, and the soil interaction between the double piles gradually decreases. The Y-directional stress distribution of the soil under the bearing plate is similar to that of the single pile. Thus, with the increase in pile spacing, the stress influence of the bearing plate on the soil between the piles and the double-pile effect is weakened and the compressive bearing capacity is gradually improved.

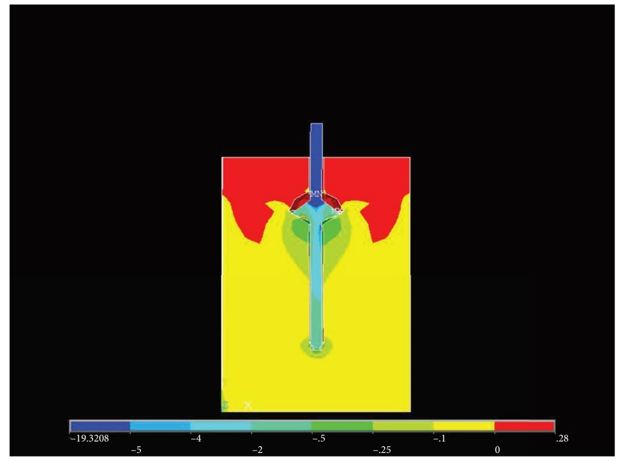


Figure 9: MD model pile and soil stress cloud.

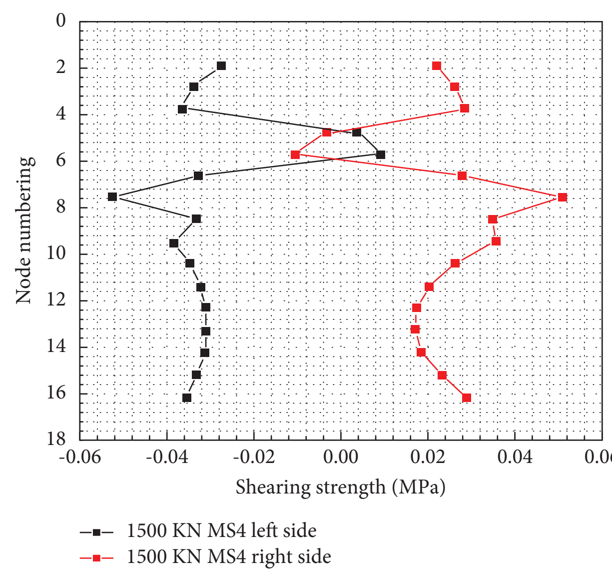


Figure 10: XY direction shear stress curves of the soil on the left and right sides of MS4 pile.

5. Shear Stress Curve Analysis

To analyze the change in the shear stress of the soil on the left and right sides of the pile, the MS4 model pile under 1500 kN vertical pressure is used as an example to start the study. Then, the shear stress of each node was extracted. Finally, the XY directional shear stress curves of the soil on the left and right sides of the model pile were plotted (Figure 10) to compare the difference between the XY directional shear stress of the soil on the left and right sides of the CEP double pile and the CEP single pile. The points were taken for the MD single pile model under the same circumstances, and the MD in the XY direction shear stress curve of the model pile is shown in Figure 11.

Figure 10 shows that under the action of 1500 kN vertical pressure, the XY directional shear stress curves of the soil on the left and right sides of the MS4 model pile are approximately symmetrically distributed, and the XY directional shear stresses of the soil distributed in the pile body away from the bearing disk position are not very different. However, the XY directional shear stresses of the soil at the bearing disk position change abruptly, and the XY directional shear stresses of the soil under the bearing disk are larger than the XY directional shear stresses of the soil on the bearing disk. This phenomenon is due to the pile body under vertical pressure. The bearing disc and the soil on the disc are separated, and only the pile side frictional force comes into play while the soil under the bearing disc is extruded, and the slip phenomenon occurs.

The comparison of Figures 10 and 11 shows that the XY-directional shear stress curves of the soil on the left and right sides of the CEP double pile and CEP single pile are almost the same, but the XY-directional shear stress curves of the soil on the left and right sides of the CEP single pile show a symmetrical pattern with the same shear stress value. Meanwhile, the XY-directional shear stress of the soil on the right side of the CEP double pile is slightly smaller compared with that of the soil on the left side, the maximum shear stress value in the XY direction of the left soil is 0.053 MPa, and the maximum shear stress value in the XY direction of the right soil is 0.048 MPa. The reason is that the soil on the right side of the left pile of MS4 group is damaged by the

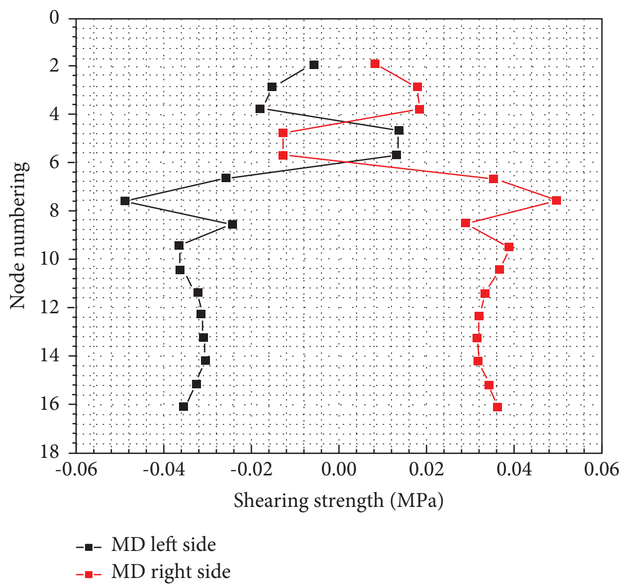


Figure 11: *XY* direction shear stress curves of the soil on the left and right sides of the MD pile.

interaction of the double piles, thereby causing the shear stress on the right side of the bearing plate to decline. Different from the single pile, the double-pile effect has a certain effect on the change in *XY*-directional shear stress of the soil on the left and right sides of the CEP double pile.

6. Conclusions

The finite element simulation analysis of the CEP double piles model with different pile spacings under vertical pressure leads to the following conclusions:

(1) Due to the increasing pile spacing of the CEP double pile model, the displacement and stress influence range of the soil between piles decrease. Each monopile gradually approaches the CEP monopile compressive condition and the compressive bearing capacity increases continuously.

(2) When the pile spacing keeps increasing, the change in the displacement of the CEP double pile model decreases continuously and the pile top displacement also decreases with the increase in pile spacing under the same load. This phenomenon indicates that when the pile spacing increases, the double-pile effect weakens, and the compressive bearing capacity is improved. Furthermore, when the CEP double pile disc end spacing is greater than 2.5 times the disc overhang diameter, the double-pile effect has less influence on the CEP double pile compressive bearing capacity. Therefore, to reduce the influence of double-pile effect on the compressive bearing capacity of CEP double-pile in the actual project, we must try to ensure that the spacing of CEP double pile disc end is greater than 2.5 times the disc overhang diameter.

(3) From the *XY* direction shear stress curves of the soil on the left and right sides of the pile, it can be seen that the *XY* direction shear stress curves of the soil on the left and right sides of the single pile show a symmetrical pattern and the same shear stress values. Meanwhile, the *XY* direction shear stress of the soil on the right side of the double-pile is slightly smaller than that of the soil on the left side. The pile spacing has some influence on the *XY* direction shear stress of the soil on the left and right sides of the pile, and the influence on the soil on the right side is greater.

(4) The ultimate compressive bearing capacity of the CEP double pile model increases with pile spacing. Hence, the larger the pile spacing of the double-pile is, the closer the ultimate compressive bearing capacity is 2 times of the single pile. However, the ultimate compressive bearing capacity of the CEP double pile with 4.5 times of disk end spacing is not 2 times of the single pile because of the mutual influence of double pile. Therefore, when studying the compressive load capacity of the CEP double-pile, the effect of pile spacing and the double-pile effect should be considered fully.

(5) This simulation study on CEP double pile mainly analyzes the influence of pile spacing on the bearing performance of CEP double pile, compared with the previous study on pile bearing performance, it can be learned that within a specific range, CEP double pile bearing capacity is not twice the relationship of CEP monopile bearing capacity, CEP double pile interaction leads to the bearing capacity discount, which is due to when CEP double pile is subjected to vertical pressure, through the pile body to the bearing disc. When the pile spacing is small, the soil below the bearing disc is extruded, the soil above the bearing disc is cracked, the soil between the piles interacts with each other, the CEP double pile not only bears the external load but also bears the action of the soil on the pile body, with the increase of the pile spacing, the soil interaction between the piles is weakened, the compressive bearing performance is improved, through this study. For this, the study lays the foundation for the research of CEP double pile bearing performance.

7. Outlook

(1) In this study, the influence of pile spacing on the compressive bearing capacity of CEP double piles under the action of vertical pressure has been studied in depth through ANSYS finite element simulation. However, in actual engineering, many other factors affect the compressive bearing capacity and damage state of the CEP pile, such as the number of bearing discs, bearing disc angle, and bearing disc position. The next step is to consider the influence of various

factors on the bearing capacity of the CEP group pile and improve the CEP pile research theory.

(2) The ANSYS finite element simulation soil model is selected from powder clay. Since CEP double pile can be applied to many kinds of soil layers, the soil properties also have a specific influence on the compressive bearing capacity of CEP double pile. The next step must study many geological conditions to provide a reliable theoretical basis.

Data Availability

The data used to support the findings of this study are available from the corresponding authors upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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