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Research Article

Model Test and Numerical Simulation of the Mudcake Thickness Effect on the Bearing Capacity of Vertically Loaded Single Piles

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Mudcake is an important factor affecting the bearing capacity of vertically loaded single piles. The model test and numerical calculation were used to analyse the stress and displacement characteristics of vertically loaded single piles under the conditions of different mudcake thickness and loading capacity. The effect of mudcake thickness on bearing capacity has been analyzed systematically, and its mechanism and changing laws were revealed. Eventually, the concept of the mudcake thickness effect was proposed, which must be considered fully during the construction of mud protection bored piles. The research results have important scientific value and guiding significance for understanding of the influence of pile side mudcake on the bearing capacity of vertically loaded single piles.

1. Introduction

Mudcake is an important factor that affects the normal performance of vertically loaded single pile [1–3]. It is generally accepted that the existence of mudcake weakens pile side resistance and leads to the decrease in the bearing capacity of a single pile. It is of great scientific value and practical significance to correctly understand the influence of mudcake thickness on the bearing capacity of a single pile.

The effect of mudcake on the bearing capacity of a vertically loaded single pile has received wide attention. Hosoi [4] found by experiment that the friction resistance between concrete and mudcake soil was significantly lower than that between concrete and the same type of mudcake-free soil and proposed that if the mudcake on the side of a mud protection bored pile could not be completely removed, the influence of mudcake on the friction resistance of the pile should be fully considered. Majana et al. [5] carried out a laboratory model test to study the influence of mudcake thickness on the load transfer law of cast-in-place pile in saturated sandy soil and believed that attenuation of pile side resistance was mainly due to excessive mudcake thickness. Based on a bridge reconstruction project, Wu [6] expounded the mechanism of the influence of mudcake thickness on the bearing capacity of a single pile by an on-site test. Hu et.al. [7] studied the mudcake thickness influence on the bearing capacity of a single pile by the method of numerical calculation and model test on the special condition of red bed mudstone, put forward the concept of single pile bearing capacity correction coefficient, and modified the single pile bearing capacity calculation formula in the Technical Specification for the Building Pile Foundation (JGJ 94-2008); however, the pile length and pile diameter which also are influence factors have not been considered adequately in their research. Chen et al. [8] discussed the influence of mudcake on pile-soil rough contact surface mechanical characteristics including the relationship of shear stress and displacement and peak shear strength and peak friction angle by the model test. It was exposed that the shear stress and shear displacement relationship curves showed characteristics of softening under the condition of no mudcake and hardening under the condition of mudcake. The thickness of mudcake was an important factor for the attenuation of shear strength of the contact surface. Chen et al. [9] discussed the changing laws of displacement of the pile top, lateral resistance, and tip resistance of vertically loaded single piles with mudcake by the model test, and pointed out

that the cement as mud additive could effectively improve the bearing capacity of the single pile and reduced the mudcake influence on pile side friction.

In conclusion, many scholars and engineers have carried out multiple studies on pile side mudcake. However, the comprehensive influence of mudcake thickness on the bearing capacity of a vertically loaded single pile is still insufficient. In view of this, the model test and numerical calculation were used in this paper to analyze stress and displacement characteristics of vertically loaded single piles under the conditions of different mudcake thickness and load. The effect of mudcake thickness on the bearing capacity of a vertically loaded single pile has been analyzed systematically, and its mechanism and changing laws were revealed. Eventually, the concept of the mudcake thickness effect was proposed, which must be considered fully during the construction of mud protection bored piles.

2. Model Test

2.1. Test Overview

2.1.1. Test Device. The model test of the bearing performance of a vertically loaded single pile was conducted in the Anhui Province Key Laboratory of Building Structure and Underground Engineering. The model test was carried out in a self-made test box which was composed of two cylindrical steel drums welded by semicylindrical high-strength steel plates. The steel drums are 1.8 m in height and 1.2 m in diameter, which not only eliminate the influence of test boundary conditions but also ensure the test stiffness conditions. The test device is mainly composed of a loading device (jack), reaction device (reaction frame), and measuring device (dial indicator and strain gauge) (Figure 1).

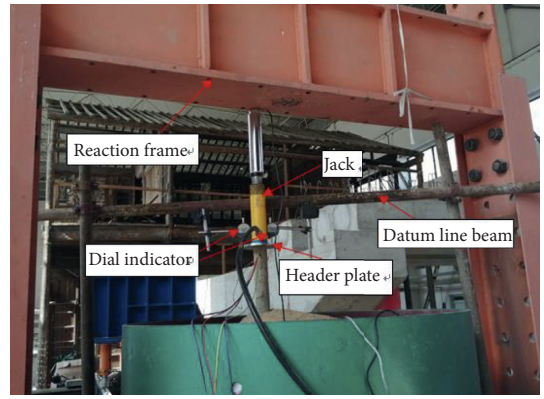


Figure 1: Model test apparatus.

2.1.2. Test Materials

(1) Test Sand. The sand used for the test was taken from the project site of an industrial park in Hefei, which is located in the middle of the Jianghuai Hills. The selected sand is relatively pure medium sand, and its particle grading analysis curve is as shown in Figure 2.

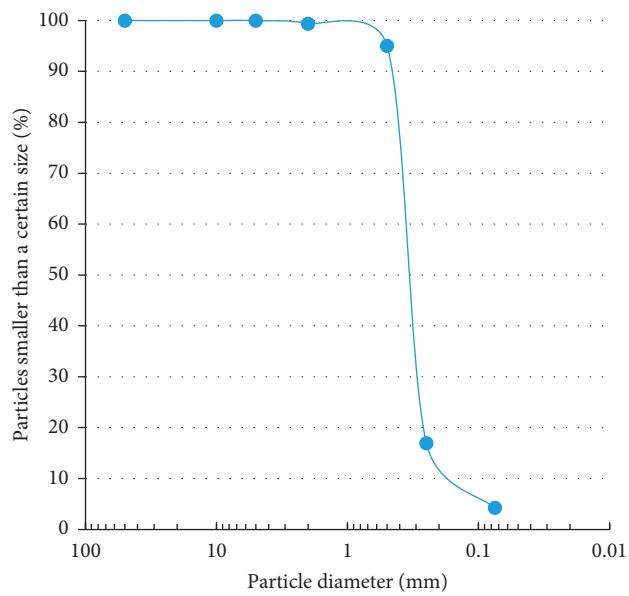


Figure 2: Grading curve of sand particles for test.

In the model test, sand was filled in layers and compacted manually. In order to evenly fill the foundation soil in each layer, the thickness of compaction was controlled. Each layer was filled to 10 cm and compacted to 8 cm. Samples for geotechnical tests were taken by cutting ring from the top surface and the levels of −30 cm, −60 cm, −90 cm, and −120 cm of the sand for testing. Physical and mechanical parameters of sand are shown in Table 1.

(2) Model Pile. Based on the reduced-scale of the model test and the similar percentage of the material stiffness of the pile material, the hollow Perspex tube with a diameter of 50 mm and an inner wall thickness of 5 mm was selected for the model pile in this test. The length of the model pile is 1.2 m, and the elastic modulus is 3.48 GPa. In order to facilitate loading, the actual length of the model pile used in the test is 1.4 m. During the test, the model pile exceeded the upper surface of the test soil by 0.2 m. Strain gauges were pasted inside both the pile top and pile bottom, and axial forces of the pile top and pile bottom were measured during the test. Model piles are shown in Figure 3.

(3) Mudcake Thickness Control. The mudcake used in this test was the mud collected at a project site in Hefei, and the mudcake density is 1.5 g/cm^3. The method of quality control was used to control the thickness of mudcake, and the manufacturing process of a single pile with mudcake was as follows: (1) the quality and external area of the model pile were weighed and calculated without mudcake; (2) the predetermined quality of piles was calculated with mudcake; (3) the surface of test piles was covered evenly with mud. After several hours each time, when the mud was solidified and could be touched gently, the test pile was covered with another layer of mud evenly. The total mass of the pile with mudcake was weighed after each layer of mud was brushed until the predetermined mass was reached; and (4) it was covered with a layer of plastic wrap when the mudcake was dry and placed in the shade for curing (Figure 4).

Table 1: Physical and mechanical parameters of sand used in the test.

Unit weight (kN/m^3)	Compression modulus (MPa)	Internal friction angle (°)	Cohesion (kPa)
18.2	40	33	0

Figure 3: Model piles.

Figure 4: Mudcake thickness control.

2.1.3. Test Process. In the model test of the bearing capacity of a vertically loaded single pile, the mudcake thickness of the pile was selected as 0 mm, 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm, respectively. The load was applied by means of a hand-operated separate hydraulic jack. The output oil pressure was measured by using an oil pressure meter installed on the oil road and controlled according to the load-oil pressure curve calibrated on a pressure machine. During the test, the internal force of the pile top and bottom was measured in real time by using the strain gauge affixed to the pile top and bottom (Figure 5).

The load started from 0.5 kN and increased by 0.5 kN step by step. Loading was stopped when the pile displacement increased sharply. The vertical displacement of the pile top was measured at 5 min, 10 min, 15 min, 30 min, 45 min, and 60 min, respectively, after each load level, and when the settlement of each level was less than 0.1 mm, within 30 min, the next load level began [10–12].

2.2. Test Results

2.2.1. Stress Characteristics of the Vertically Loaded Single Pile. Based on the measured data of strain gauges at the top and bottom of the pile in the model test, curves of load and pile tip resistance changing with time can be obtained under the conditions of different mudcake thickness (Figure 6).

It can be seen that the maximum stable bearing capacity of the pile without mudcake is about 5800 N, and the pile tip resistance is within the range of 7%–10% of the load, showing significant bearing characteristics of the end bearing friction pile. The existence of pile side mudcake reduces the bearing capacity of the single pile significantly. When the thickness of mudcake is 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm, the

maximum stable bearing capacity of the single pile is 4000 N, 5400 N, 4200 N, and 3800 N, respectively.

The vertical load of the single pile is borne by pile side resistance and pile tip resistance. Pile side resistance can be regarded as the difference between load and pile tip resistance. In this paper, the difference between the arithmetic mean value of the two measured values of load in the model test and that of the two measured values of the tip resistance was the value of single pile side resistance, and Figure 7 shows the measured values of the load and the side resistance change with time under the conditions of different mudcake thickness.

It can be seen that the existence of mudcake on the side of the pile reduces the overall side resistance of the vertically loaded single pile significantly. When the mudcake thickness is 0.0 m, 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm, the percentage of the side resistance is 90%–93%, 60%–80%, 75%–82%, 45%–55%, and 78%–82% of the load, respectively. The existence of mudcake on the pile side changes the direct combination between the pile and the soil mass, affects the interaction between the pile and the soil mass on the pile side, and then, causes the reduction of the pile side friction.

Figure 5: Stress acquisition instrument.

2.2.2. Displacement Characteristics of the Vertically Loaded Single Pile. Based on the model test, Q-S curves of pile top load and pile top vertical displacement with different mudcake thickness (k) can be obtained (Figure 8). It can be seen that the Q-S curves of the single pile drop slowly. Q-S curves of the pile with mudcake deviate from the curve of pile without mudcake at the beginning of loading. With the increase in mudcake thickness, the Q-S curve of the mudskin pile becomes steeper and steeper.

The bearing capacity of a vertically loaded single pile is closely related to the vertical displacement of the pile top, which is an important index of the bearing capacity of a single pile. With the increasing requirements of engineering structures on foundation deformation and differential deformation, the method of determining the bearing capacity of the vertically loaded single pile based on the vertical displacement control standard of the pile top is gradually favored by the majority of experts, scholars, and engineers [13–15]. The vertical displacement control standard of the pile top is 2.5 mm (0.05 d, d is the pile diameter, the same as below), 3.0 mm (0.06 d), and 3.5 mm (0.07 d), respectively. Under the abovementioned standard, the bearing capacity of a single pile with different mudcake thickness and the percentage of bearing capacity of a single pile with mudcake accounting for that without mudcake were obtained (Table 2 and Figure 9).

With the increase of mudcake thickness, the bearing capacity of the vertically loaded single pile decreases slowly at first, then decreases suddenly, and finally, tends to be stable. The larger the displacement control standard is, the more remarkable the change gets. When the control standard is 2.5 mm, 3.0 mm, and 3.5 mm, respectively, the bearing capacity of the single pile with mudcake of 0.5 mm accounts for about 96%, 98%, and 98%, respectively, of that of single pile without mudcake.When the thickness of mudcake is 1.0 mm, the bearing capacity of the single pile with mudcake accounts for about 76%, 81%, and 85%, respectively. When the thickness of mudcake reaches or exceeds 1.5 mm, the bearing capacity of the single pile with mudcake is within the range of 62%–65%, 67%–71%, and 72%–75%, respectively.

For a single pile with different thickness of mudcake, when the mudcake thickness is thin, the interaction between piles and soil is controlled mainly by the interface between the pile and the soil surrounding the pile, and the mudcake only acts as a lubricant. With the increase in the thickness of mudcake, single pile bearing capacity shows a trend of slow decline. With continuous increase of the thickness of mudcake, the binding effect of the soil around the mudcake on mudcake is becoming weaker and weaker and it is easier for the slip to happen between the pile and mudcake. The interaction between piles and soil is controlled by the interface between the pile and the mudcake, and at this stage, single pile bearing capacity rapidly decreases with the increase of the thickness of mudcake. When the mudcake thickness exceeds a certain value, the interaction between the pile and the soil mainly depends on the strength of the mudcake itself. At this stage, the bearing capacity of a single pile tends to be stable with the increase of the mudcake thickness.

3. Numerical Calculation

3.1. Calculation Model and Parameters. Midas/GTS software is widely used in the pile performance calculation because it is suitable for large deformation calculation and contact processing and provides complete three-dimensional dynamic analysis and a variety of constitutive models [16–19].

The pile side soil and mudcake were considered as ideal elastic-plastic material, and the pile was considered as linear elastic material in the calculation. The Mohr–Coulomb failure

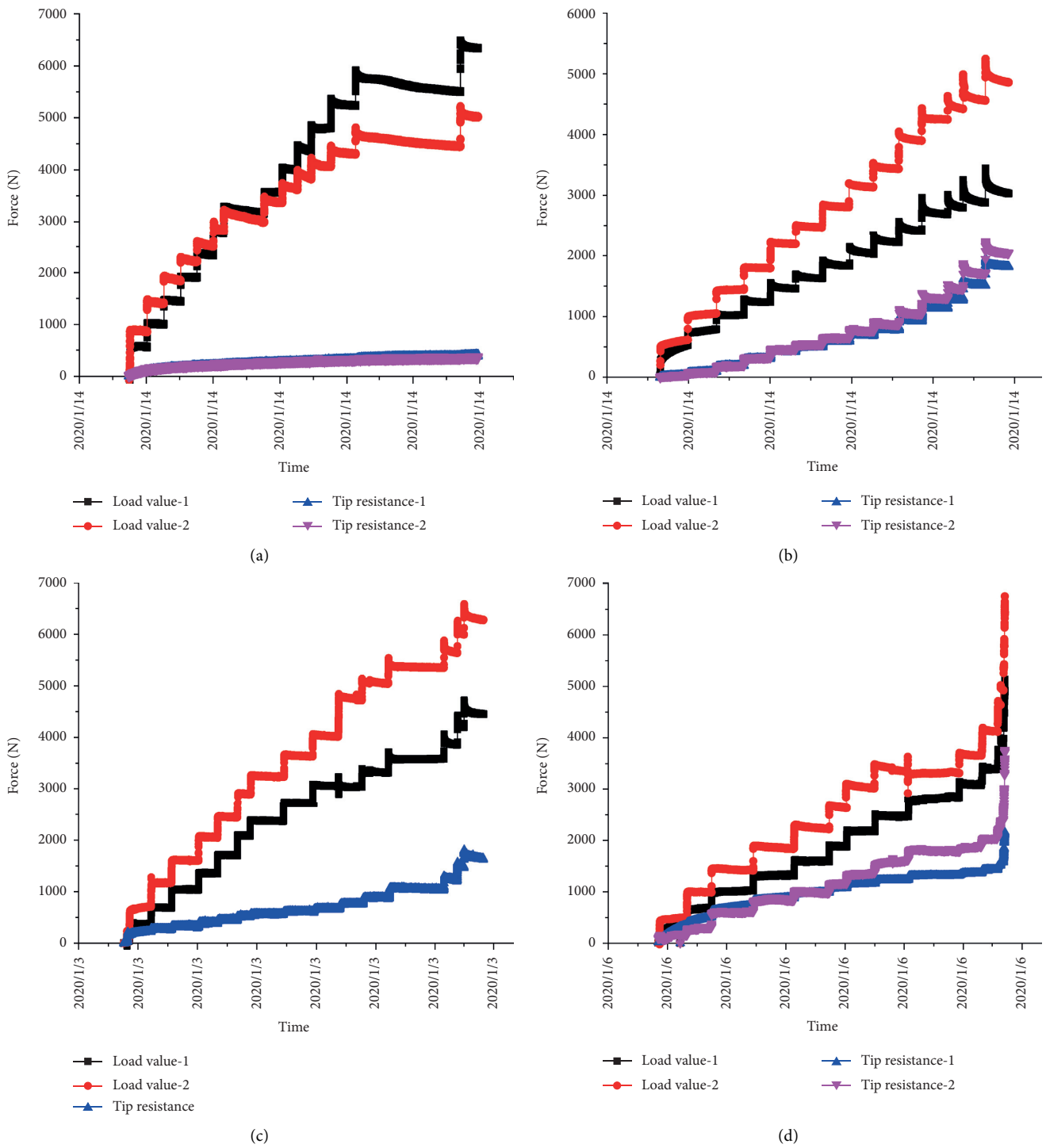
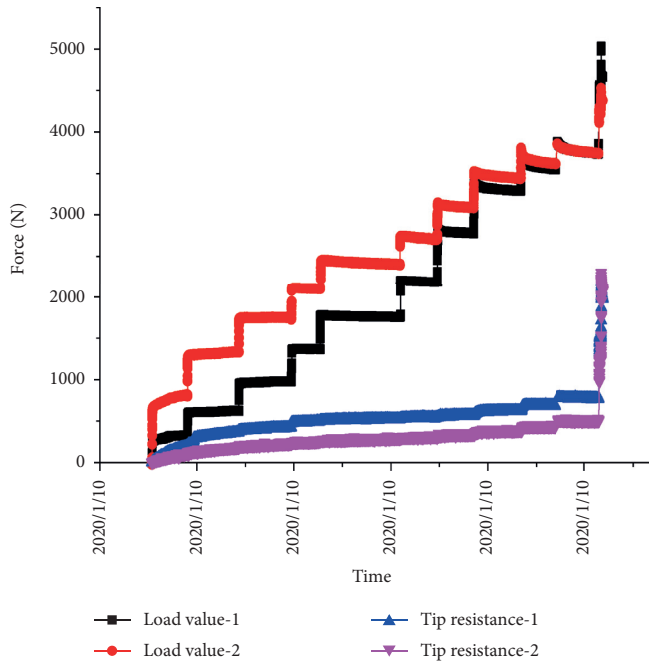
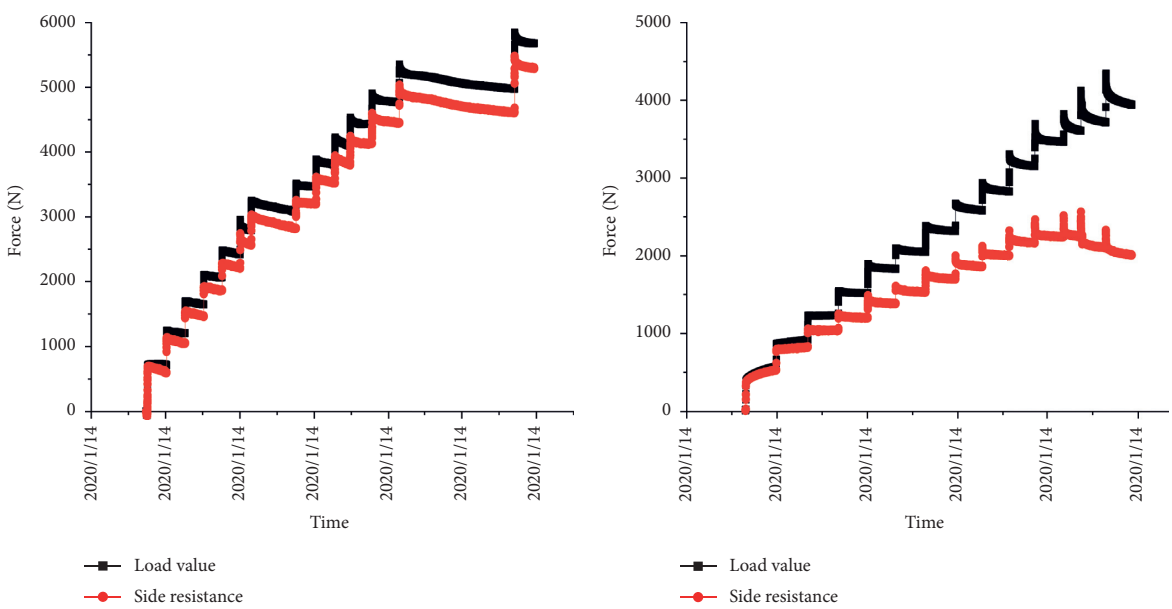


Figure 6: Continued.



(e)

Figure 6: Change of load and tip resistance of the vertically loaded single pile with time. (a) 0 mm. (b) 0.5 mm. (c) 1.0 mm. (d) 1.5 mm. (e) 2.0 mm.



(a) (b)

Figure 7: Continued.

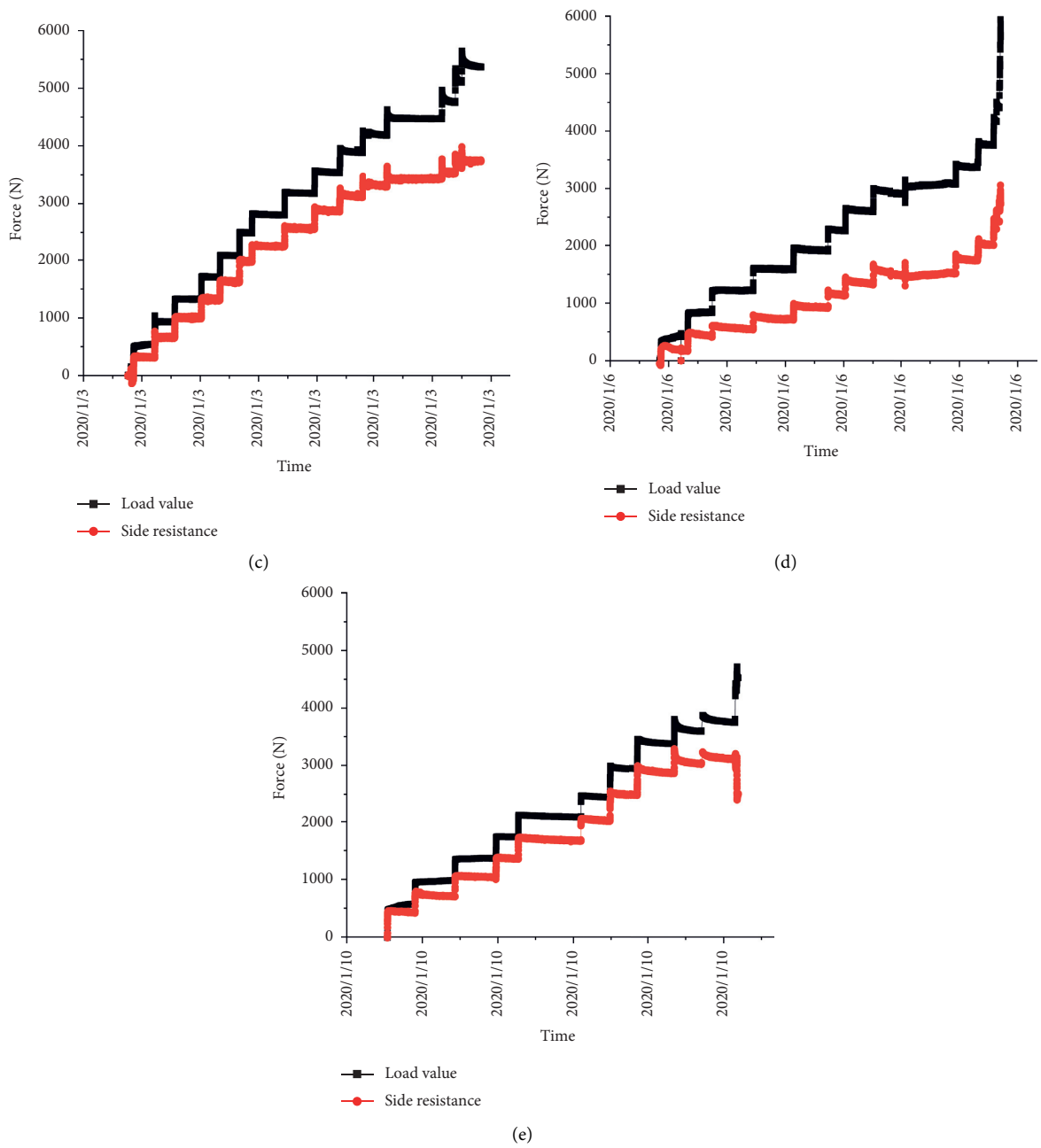


Figure 7: Change of load and side resistance of the vertically loaded single pile with time. (a) 0 mm. (b) 0.5 mm. (c) 1.0 mm. (d) 1.5 mm. (e) 2.0 mm.

criterion was used. The contact between the pile and soil and the changes of the material parameters of the mudcake with different thickness were not considered. The diameter and length of the pile were 2.5 mm and 60m, respectively, and the calculation model was 50 m × 50 m × 90 m (Figure 10). According to the actual data of the project site, the numerical calculation parameters are as shown in Table 3.

3.2. Calculation Process and Analysis of Results

3.2.1. Calculation Process. The mudcake thickness of 0 mm, 10 mm, 20 mm, 30 mm, and 50 mm were calculated to study the effect of mudcake on the bearing capacity of the vertically loaded single pile. Uniformly distributed load in vertical direction was applied on the pile top. The load was applied step by step with an increase of 3000 kN starting from 5000 kN. When the vertical load on the pile top reached 32000 kN finally, the tip resistance and displacement of the pile shaft were calculated (Figure 11).

3.2.2. Bearing Capacity of the Single Pile. After the pile tip resistance was calculated (Figure 11(a)), side resistance can be obtained by taking the difference between the load of the single pile and the pile tip resistance. Table 4 and Figure 12

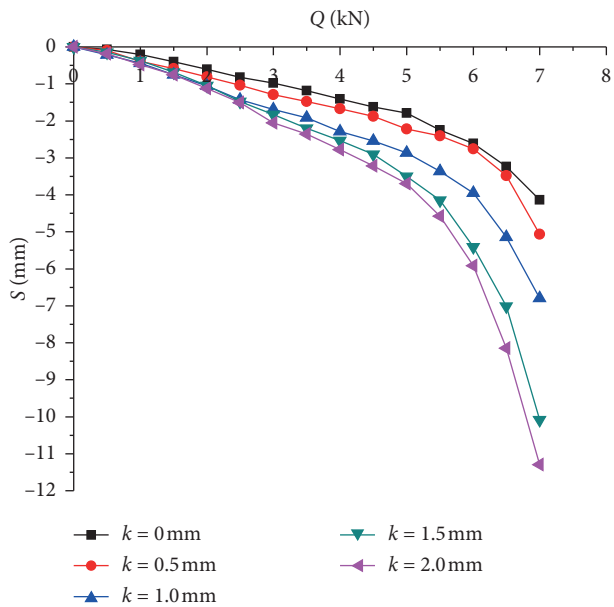


Figure 8: Load-settlement curves of pile with different mudcake thickness.

Table 2: Bearing capacity of the single pile with mudcake and its percentage accounting for that without mudcake.

Mudcake thickness (mm)		0	0.5	1.0	1.5	2.0
2.5 mm	Bearing capacity (kN)	5.85	5.63	4.42	3.95	3.63
	Percentage (%)	100	96	76	67	62
3.0 mm	Bearing capacity (kN)	6.31	6.17	5.13	4.48	4.25
	Percentage (%)	100	98	81	71	67
3.5 mm	Bearing capacity (kN)	6.64	6.51	5.62	5.02	4.79
	Percentage (%)	100	98	85	75	72

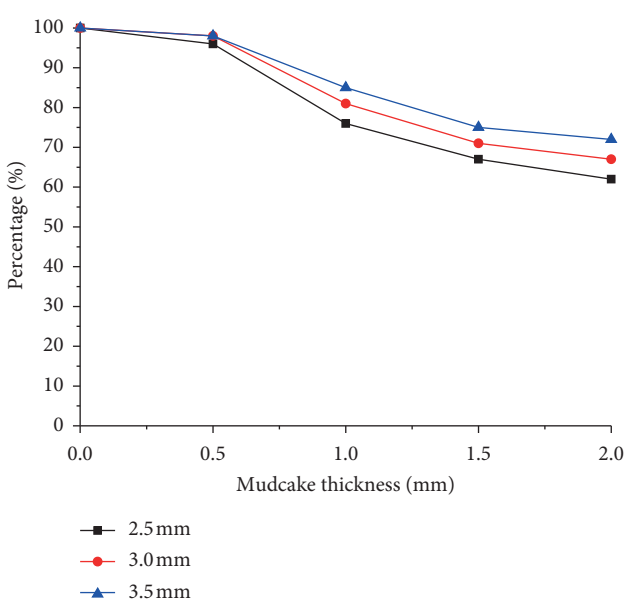


Figure 9: The percentages of single pile bearing capacity with mudcake accounting for that without mudcake

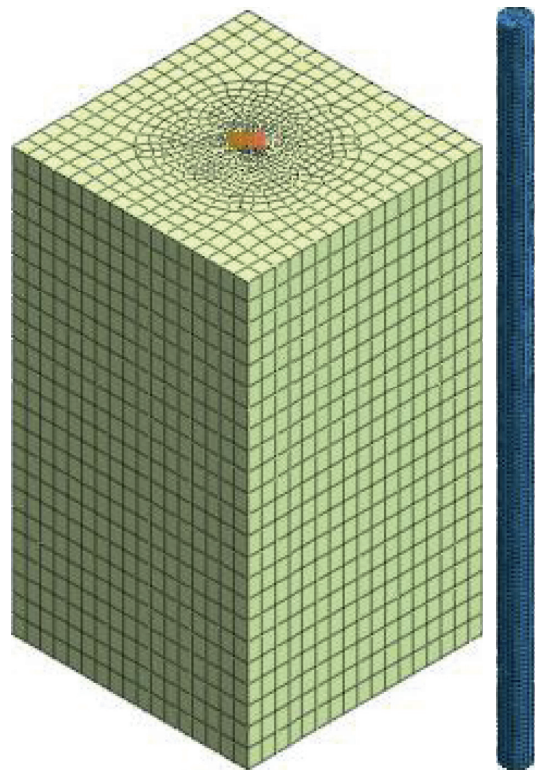


Figure 10: Calculation model and meshing.

show the side resistance and its percentage accounting for loading capacity under vertical loads.

It can be seen that, with the increase of mudcake thickness, the pile side resistance decreases first and, then, tends to be stable. When vertical loads of 2000 kN and 32000 kN were applied to the pile top, pile side resistance accounts for 92%–94% of the load, indicating that the bearing capacity of the single pile is mainly borne by pile side resistance. Under the pile top load of 50000 kN and 62000 kN, when the mudcake thickness is 10 mm, pile side resistance accounts for about 90% and 88% of the load, respectively. After the thickness of mudcake reaches 20 mm, the percentage of pile side resistance is within the range of 86%–88%. It shows that the existence of mudcake affects the normal development of side resistance of the single pile.

3.2.3. Displacement of the Vertically Loaded Single Pile. According to the results of displacement(Figure 11(b)), the numerical calculation results of the Q-S curve of the vertical load of the single pile and the vertical displacement of the pile top are as shown in Figure 13.

The bearing capacity of the single pile was determined according to the vertical displacement control standard of the pile top. When the control standard is 1%d, 2%d, and 3% d, respectively, the bearing capacity of the single pile with different mudcake thickness and its percentage accounting for that without mudcake are as shown in Table 5 and Figure 14.

It can be seen that, with the increase of mudcake thickness, the bearing capacity of the vertically loaded single

Table 3: Numerical calculation parameters.

Material	Unit weight (kN/m^3)	Elasticity modulus (kPa)	Poisson ratio	Internal friction angle (°)	Cohesion (kPa)
Pile shaft	27.0	2.9×10^7	0.25	-	-
Pile side soil	20.5	3.7×10^4	0.30	30	0
Mudcake	15.0	5.0×10^3	0.45	10	10

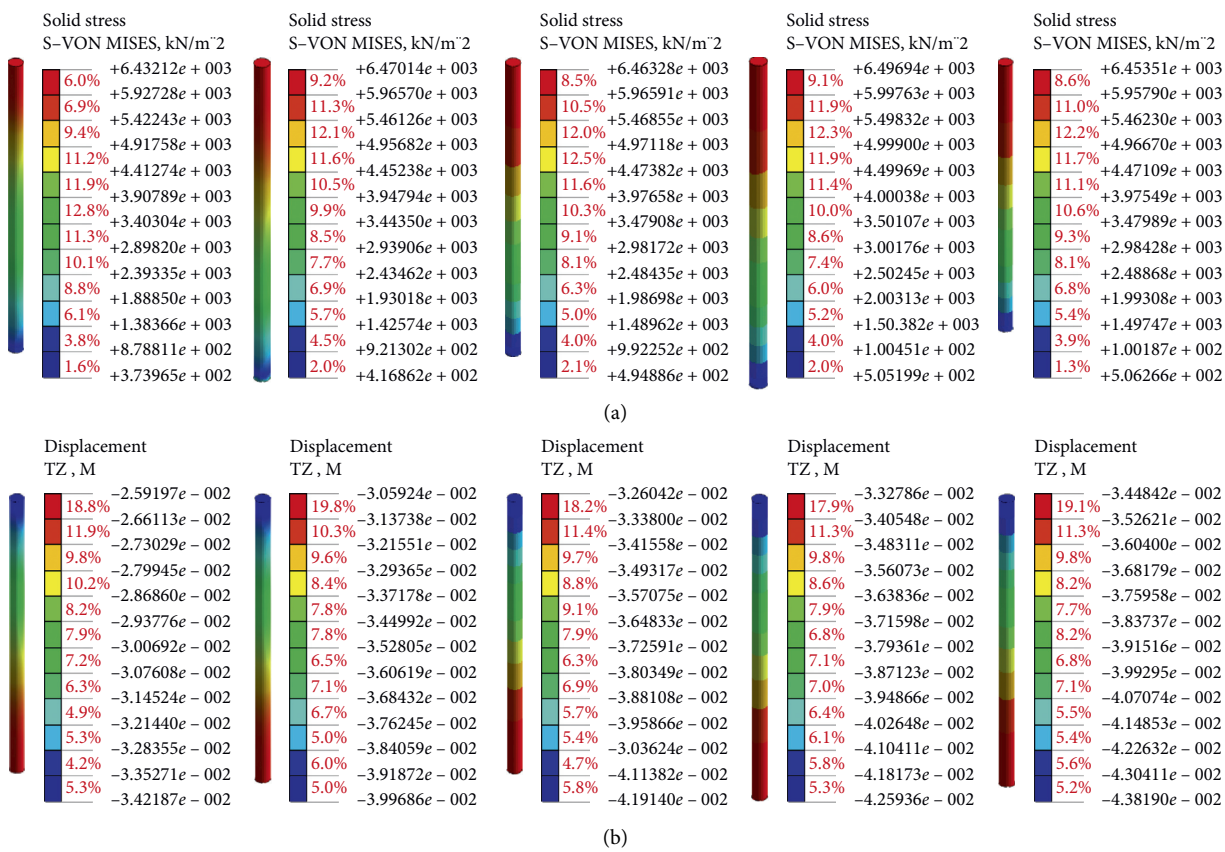


Figure 11: Stress and displacement with different mudcake thickness. (a) Stress. (b) Displacement (right-to-left : 0 mm, 10 mm, 20 mm, 30 mm, and 50 mm).

Table 4: Pile side resistance and its percentage accounting for loading capacity with different mudcake thickness.

Loading (kN)		Thickness (mm)				
		0	10	20	30	50
20000	Side resistance (kN)	18785	18587	18411	18407	18424
	Percentage (%)	93.93	92.93	92.05	92.03	92.12
32000	Side resistance (kN)	30168	29957	29575	29525	29519
	Percentage (%)	94.27	93.62	92.42	92.26	92.25
50000	Side resistance (kN)	46309	45128	44056	43977	44171
	Percentage (%)	94.62	90.26	88.11	87.95	88.34
62000	Side resistance(kN)	58754	54730	53311	53267	53592
	Percentage (%)	94.76	88.27	85.99	85.91	86.44

pile decreases rapidly at first and, then, tends to be stable. The larger the vertical displacement control standard of the pile top is, the smaller the bearing capacity is when it tends to be stable. When the control standard is 1% d, 2% d, and 3% d, respectively, the bearing capacity of the single pile with 10 mm mudcake thickness accounts for about 96%, 85%, and 78% of the corresponding bearing capacity of the pile without mudcake. When the thickness of mudcake exceeds 20 mm, the bearing capacity of the single pile with mudcake is within the range of 88.5%–91.5%, 71.1%–72.7%, and 66.3%–66.2%, respectively.

4. Mudcake Thickness Effect on the Bearing Capacity of the Vertically Loaded Single Pile

Mudcake is a layer of sticky clay between the pile and the soil on the side of the pile. The pile side mudcake is the product of a series of complex physical and chemical interactions of mud for wall protection, pile shaft, and pile side soil, and its engineering properties are often inferior to the pile side soil [1]. The existence of pile side mudcake prevents the direct combination between the pile and the pile side soil, affects the interaction between the pile and pile side soil, causes the increase of the vertical displacement of the pile, reduces the side friction resistance of the pile, and then, affects the normal performance of the bearing capacity of vertically

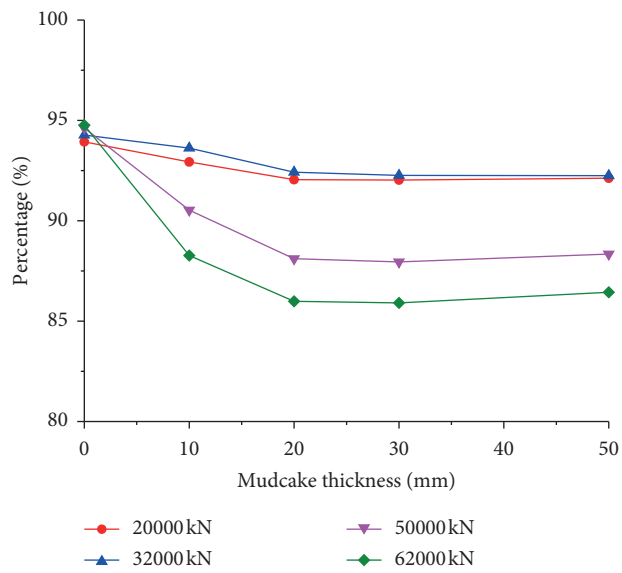


Figure 12: Variation of percentages of side resistance accounting for load with mudcake thickness.

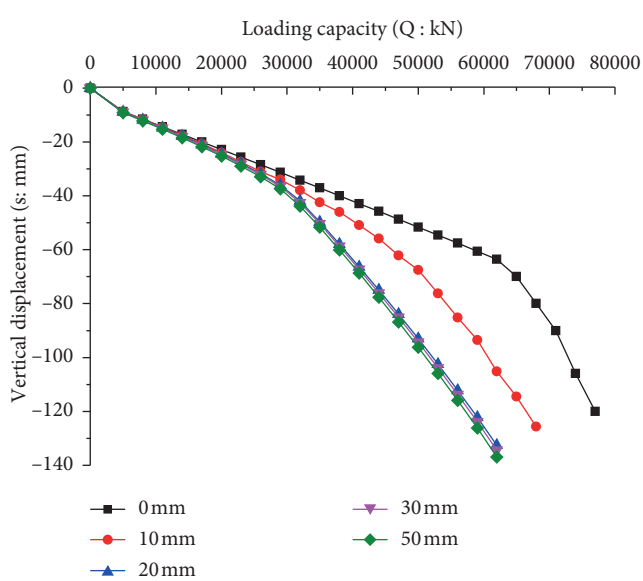


Figure 13: Q-S curve of the single vertically loaded pile.

Table 5: Bearing capacity of the single pile with different mudcake thickness and its percentage accounting for that without mudcake

Mudcake thickness (mm)		0	10	20	30	50
1% d	Bearing capacity (kN)	22324	21486	20432	20226	19758
	Percentage (%)	100.00%	96.25%	91.52%	90.60%	88.51%
2% d	Bearing capacity (kN)	48298	40921	35110	34839	34365
	Percentage (%)	100.00%	84.73%	72.69%	72.13%	71.15%
3% d	Bearing capacity (kN)	66500	52018	44000	43644	42753
	Percentage (%)	100.00%	78.22%	66.17%	65.63%	64.29%

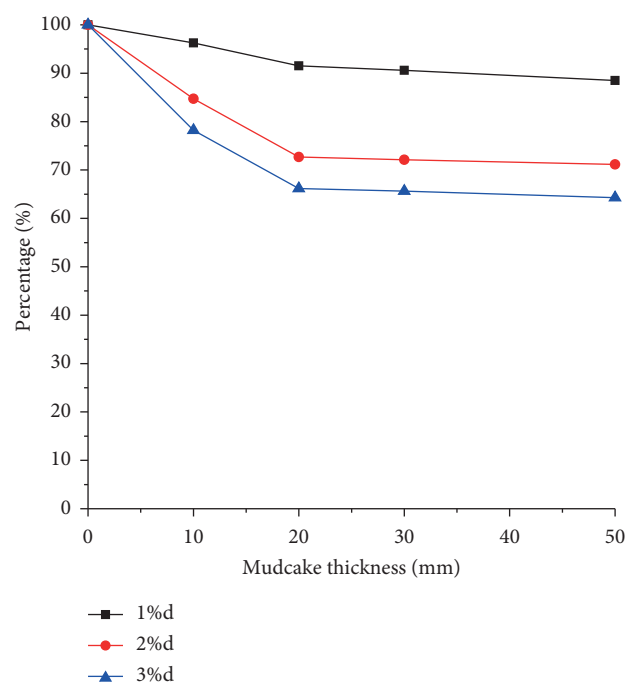


Figure 14: The percentage of single pile bearing capacity with mudcake accounting for that without mudcake

loaded single piles. Effect refers to a specific scientific phenomenon under specific environmental conditions, which is produced by some specific motivation or reason. In this paper, the specific scientific phenomenon that the vertical load bearing performance of the single pile is affected by the existence of mudcake of different thickness between the pile and the pile side soil is defined as the mudcake thickness effect on the bearing performance of the vertically loaded single pile.

The mudcake thickness effect on the bearing capacity of the vertically loaded single pile often causes the reduction of the actual bearing capacity of the single pile, which poses a hazard to engineering construction. During the construction of mud protection bored piles, the mudcake thickness effect on the bearing capacity of the vertically loaded single pile should be fully considered. If necessary, technical measures such as improving mud properties and high-pressure grouting can be adopted to reduce the pile side mudcake thickness.

5. Conclusions

(1) The change laws of the mudcake thickness effect on the bearing capacity of the vertically loaded single pile were obtained. With the increase of the mudcake thickness, the side resistance, vertical displacement, and bearing capacity of the vertically loaded single pile decrease gradually, firstly, and then, increase suddenly and become stable eventually.

(2) The concept of the mudcake thickness effect on the bearing capacity of the vertically loaded single pile was put forward, and it was pointed out that the thickness effect of the mudcake on the bearing capacity of the vertically loaded single pile should be fully considered during the construction of mud protection bored piles.

(3) The mechanism of the mudcake thickness effect on the bearing capacity of the vertically loaded single pile was revealed. Because pile side mudcake blocks the direct connection between the pile and the pile side soil, the interaction between pile and pile side soil is affected. As a result, the vertical displacement of the pile increases, pile side friction decreases, and the normal performance of vertically loaded bearing capacity of the single pile is affected greatly.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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