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Experimental research and engineering application of rigid pile composite foundation with moderately weathered mudstone pile end

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Abstract: In view of the controversial issue of 'whether end bearing piles can be used in rigid pile composite foundation' in engineering field, this paper discusses the bearing and deformation characteristics of the end bearing rigid pile composite foundation through the field experiment and the engineering application of the rigid pile composite foundation with the pile end of moderately weathered mudstone. It is considered that soft rock or extremely soft rock, such as moderately weathered rock or strongly weathered rock, can be used as the pile end bearing layer of rigid pile composite foundation to form end bearing rigid pile composite foundation. By adjusting the thickness of the cushion layer, the pile-soil load sharing of the end bearing rigid pile composite foundation can be effectively coordinated; the composite foundation of end bearing rigid pile should improve the strength grade of pile material to avoid the damage of pile material. The end bearing rigid pile composite foundation has a large increase in bearing capacity and strong deformation control ability, which is suitable for foundation treatment of high-rise buildings.

Keywords: rigid pile, composite foundation, end bearing, moderately weathered mudstone, field experiment, engineering application

1. Introduction

Rigid pile composite foundation has the advantages of high bearing capacity, strong resistance to deformation, low-carbon green feature and low cost, which is widely used in high-rise building foundation treatment [1]. In the area where the buried depth of the rock layer is suitable, there are different understandings in the engineering field. One view is that [2]: the pile in the rigid pile composite foundation should adopt the friction pile, that is, the pile end should not fall on the rock layer, and the end bearing pile is almost no settlement, and the settlement of the soil between the piles may be separated from the foundation, resulting in the excessive load sharing of the pile. It is unsafe, so the composite foundation requires that the pile end should fall in the soil layer at a certain distance above the rock layer,

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or choose the rock-socketed pile foundation scheme with high carbon emission, long construction period and high cost ; another view is that [3]: the pile end falls in the rock layer, and by setting the appropriate thickness of the cushion, the whole life cycle plays a role in coordinating the pile and soil to bear the upper load, so that the end bearing effect of the rock layer can be fully utilized to obtain higher bearing capacity and smaller settlement.

In view of the above academic disputes, some scholars [4,5] have carried out special research by using model test and numerical analysis. They think that the thickness of the cushion has a significant regulating effect on the pile-soil load distribution of the rigid pile composite foundation with rock at the end of the pile. The cushion with reasonable thickness is considered to give full play to the bearing capacity of soil between piles. In this paper, through the field experiment and the engineering application, the bearing capacity and deformation characteristics of the end bearing rigid pile composite foundation are further discussed, which provides reference for theoretical research and engineering application.

2. Field experiment research

2.1. Geotechnical engineering characteristics of site

The field experiment was located in an industrial building project in Qujing City, Yunnan Province. The stratum conditions of the site from top to bottom were as follows : Layer ① of cultivated soil; Layer ② of silty clay; Layer ③ of silty clay containing organic matter; Layer ④ of silty clay; Layer ⑤ of strongly weathered siltstone mudstone; Layer ⑥ of moderately weathered siltstone mudstone. The typical geological section of the site is shown in Figure 1, and the recommended values of geotechnical physical and mechanical indexes are shown in Table 1.

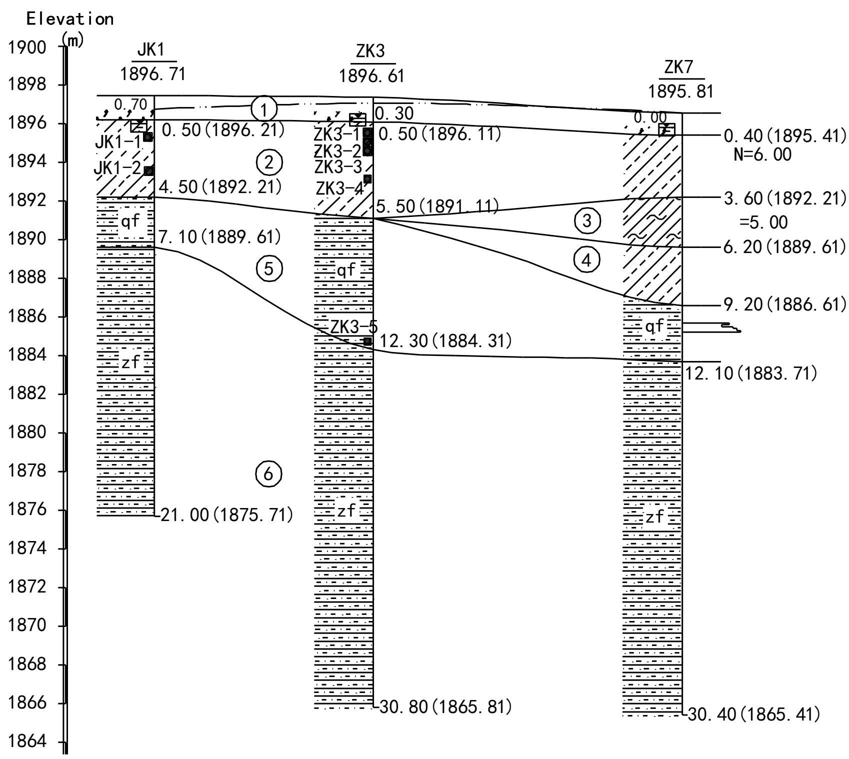


Figure 1. Engineering geologic profile.

Table 1. Statistical table of main physical and mechanical indexes of each soil layer.

Soil layer	Natural water content ω (%)	Natural density ρ_0 (g/cm^3)	Natural void ratio e	Degree of saturation Sr (%)	Liquidity index I_L	Modulus of compression Es (MPa)	Cohesion of quick direct shear test C (kPa)	Internal friction angle of quick direct shear test φ (°)	Suggested characteristic value of bearing capacity of natural foundation (kPa）
Cultivated soil ①	/	1.7*	/	/	/	/	15*	8*	/
Silty clay ②	24.5	1.97	0.728	91.5	0.45	5.99	32.30	9.59	150
Silty clay containing organic matter ③	47.8	1.73	1.312	93.9	0.71	3.59	19.52	4.79	110
Silty clay ④	20.0	2.05	0.604	90.1	0.44	5.77	34.25	10.34	160
Strongly weathered siltstone mudstone ⑤	15.9	2.12	0.489	88.6	0.297	6.70	39.12	12.64	230
Moderately weathered siltstone mudstone ⑥	/	2.57	Characteristic value of bearing capacity of rock foundation fa is 2.10 MPa. The rock classification is relatively complete. frk =10.05 MPa				90*	30*	2000

With * is the empirical value. The shear strength of Moderately weathered rock is the shear strength of structural plane.

2.2. Field experiment

In order to study the bearing and deformation behavior of end bearing rigid pile composite foundation, the compressive static load test of end bearing rigid pile single pile and the load test of composite foundation were designed. The test design parameters and contents are shown in Table 2 and Table 3. The concrete grade of rigid pile body was C25. The pile end passed through the strongly weathered silty mudstone of the layer ⑤ into the weathered silty mudstone of the layer ⑥ of the bearing strata. The construction adopted the technology of down-the-hole hammer pilot hole and long spiral compound drilling center pressure grouting to form piles.

After the pile head and the soil between piles were smoothed, a groove was dug at the top of the pile. Then the debris in the groove were cleared and an appropriate amount of cement mortar was filled in. The pressure box induction surface was placed upward into the groove, pressed to be flush with the top of the pile and leveled with a leveling instrument. The groove was excavated at the specified position of the soil between piles, and an appropriate amount of fine sand is paved in the groove. The pressure box was placed into the groove with its sensing surface facing up, adjusted so that its surface was level with the ground surface, and then leveled accordingly. The cushion was made of medium sand, which was compacted to the specified thickness in two layers with the same strength and times. The layout of pressure box is shown in Figure 2.

After the layout of the pressure box and the cushion were completed, the load plate was hoisted or cast in place, which should be guaranteed to have sufficient rigidity. Then, the counterforce device of the reacting equipment was built, and the loading and measuring equipment such as jack and displacement meter were arranged. The test was carried out by the slow maintenance load method [6].

Table 2. Field experiment design parameters of rigid composite foundation

Pile diameter(mm)	Pile length (m)	Pile spacing (m)	Bearing capacity of single pile (kPa)	Bearing eigenvalue of foundation soil (kPa)	Composite foundation bearing capacity characteristic value (kPa)
500	9.4	1.8	800	180	360

Table 3. Field experiment content.

Test number	Test object	Load plate parameters	Cushion thickness (mm)
0#	Rigid single pile	/	/
1-1#	Rigid pile composite foundation	1.8m × 1.8m, cast-in-site	200
1-2#	Rigid pile composite foundation	1.8m × 1.8m, cast-in-site	300

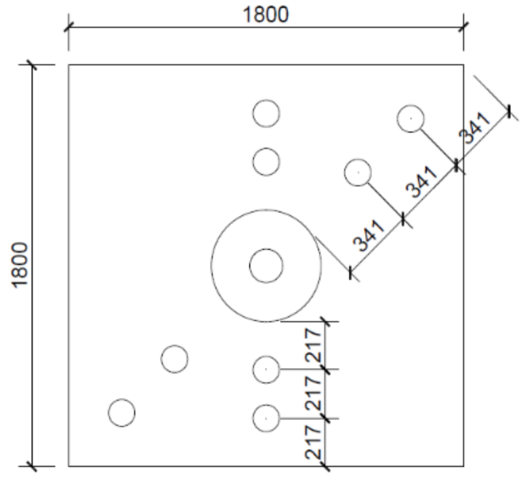
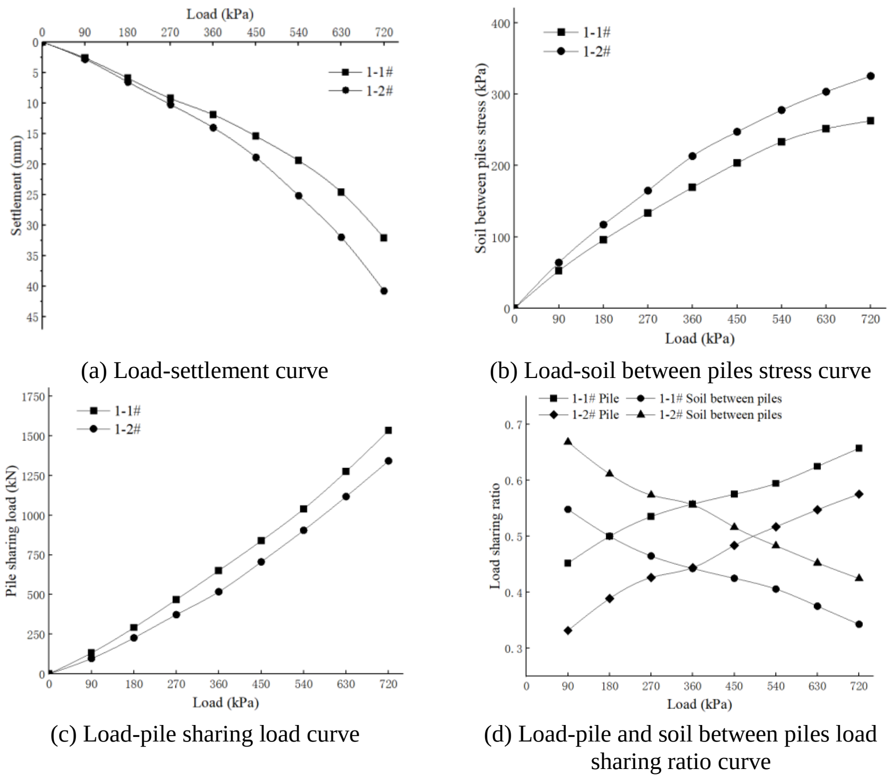


Figure 2. Field experiment pressure box layout diagram.

2.3. Experiment results analysis

The characteristic value of natural foundation bearing capacity of the base bearing layer in this test area is about 180 kPa. The settlement deformation and stress condition of the test 1-1 # ~ 1-2 # are shown in Figure 3.



(a) Load-settlement curve (b) Load-soil between piles stress curve

(c) Load-pile sharing load curve (d) Load-pile and soil between piles load sharing ratio curve

Figure 3. The settlement deformation and stress condition of the test.

It can be seen from the Load-settlement curve that the test 1-1 # and 1-2 # meet the characteristic value requirements of the bearing capacity of the composite foundation, which is 360 kPa. It can be seen from the curve of Figure 3. (a) that under the same load level, the settlement of test 1-2 # is greater than that of test 1-1 #. The reason is that because the thickness of 1-2 # cushion is thicker than that of 1-1 #, the soil between piles shares more load (Figure 3. (b)), and the pile shares less load, resulting in a slightly larger overall settlement of 1-2 # test. Figure 3. (d) shows that the load sharing ratio of piles increases with the increase of load level, while the load sharing ratio of soil between piles decreases with the increase of load level. This is because when the load level is small, the stress area of soil between piles is larger, so it bears more loads. With the increase of load level, the soil between piles produces compression deformation. Because the bearing layer of pile end is medium weathered mudstone, the penetration deformation under pile end is limited, and the deformation of pile is mainly the upper penetration deformation caused by the penetration of pile top into cushion. The load is transferred from soil between piles to piles, and the load sharing ratio of piles increases gradually. When the load reaches the characteristic value of the bearing capacity of the composite foundation, the load sharing ratio of the test 1-1 # pile and the soil between the piles is 0.58 and 0.42 respectively, while the load sharing ratio of the test 1-2 # pile and the soil between the piles is 0.42 and 0.58 respectively. Compared with test 1-1 #, although the settlement of test 1-2 # is slightly larger, the load sharing ratio between pile and soil between piles is appropriate, the bearing capacity of soil between piles is better played, and the pile is safer.

According to the test results, when the rigid pile composite foundation takes the moderately weathered mudstone as the pile end bearing layer, it can meet the requirements of the bearing capacity of the composite foundation, and does not cause the pile to bear too much load sharing ratio, and the rigid pile body is relatively safe. Through the test of 1-1 # and 1-2 #, it can be seen that different cushion thickness will make the pile soil produce different load sharing ratio. Therefore, for the end bearing rigid pile composite foundation, the cushion can be appropriately adjusted according to the demand to coordinate the load sharing between the pile and the soil, so that the bearing capacity of the soil between the piles can also be well played.

3. Engineering application

3.1. Project overview

Building Characteristics. A high-rise residential building in Chengdu had 28 floors above ground and 3 floors underground. The building was of frame shear wall structure and had a raft foundation. The natural foundation did not meet the bearing capacity and deformation requirements of the superstructure. The bearing capacity of the superstructure should not have been less than 540 kPa. The maximum settlement could not exceed 50mm, and the foundation tilt should not have been greater than 2.5 ‰. The building had the characteristics of many layers and a large load, which imposed high requirements on the bearing capacity and deformation of the foundation after reinforcement. The difficulty of foundation treatment was greater than that of general high-rise buildings.

Geotechnical engineering properties. The strata in the project site were composed of miscellaneous fill and plain fill layer ①, clay layer ②, cobble-bearing clay layer ③, cobble layer ④ and mudstone layer ⑤. The typical geological section of the site is shown in Figure 4, and the recommended values of geotechnical physical and mechanical indexes are shown in Table 4.

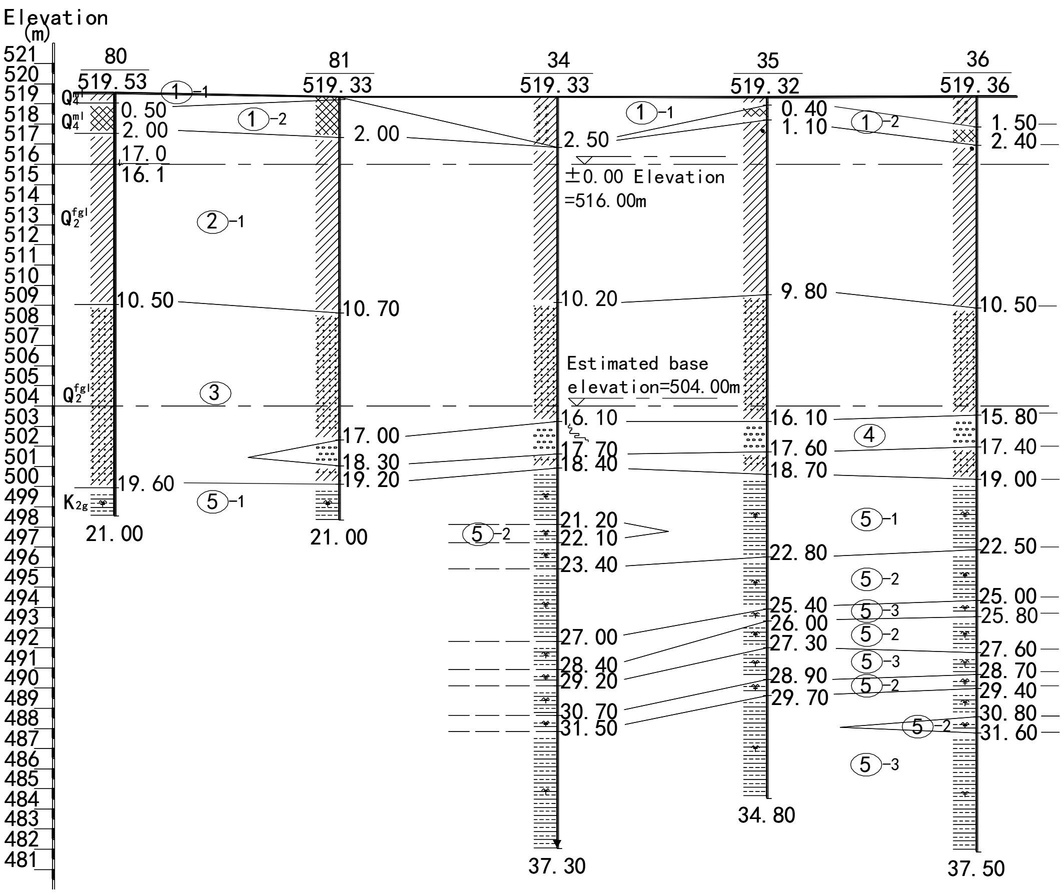


Figure 4. Typical geological profile of site.

Table 4. Suggested value table of rock and soil physical and mechanical indexes.

Soil layer \ Indexes	Natural unity weight γ (kN/m^3)	Standard value of uniaxial compressive strength f_{rk} (MPa)		Characteristic value of foundation bearing capacity f_{ak} (kPa)	Compression modulus E_s (MPa)
		Natural	Saturated		
Miscellaneous fill ①$_1$	18.5	/	/	/	/
Plain fill ①$_2$	18.5	/	/	70	3.0
Compacted fill ①3	18.5	/	/	140	5.5
Clay ②$_1$	19.0	/	/	230	13.0
Clay ②$_2$	19.0	/	/	190	7.0
Cobble-bearing clay ③	20.5			290	12.0
Cobble ④	21.0			320	25.0
Fully weathered mudstone ⑤$_1$	20.0	/	/	180	8.0
Strongly weathered mudstone ⑤$_2$	21.0	1.0	/	250	13.0
Moderately weathered mudstone ⑤$_3$	23.0	3.5	1.9	800	/

It can be seen from the survey report that the bearing layer of the base of the building is the cobble-containing clay layer ③, and the characteristic value of the bearing capacity is 290 kPa. The layer is evenly distributed, the bearing capacity is high, and the layer is stable. The cobble layer, fully weathered mudstone, strongly weathered mudstone layer and moderately weathered mudstone layer are under it. The standard value of saturated uniaxial compressive strength of moderately weathered mudstone layer is 1.9 MPa, which belongs to extremely soft rock. It has good physical and mechanical properties, large thickness, stable layer and high bearing capacity of foundation. It is an ideal pile-end bearing layer. The stratum of the whole site is relatively uniform and the bearing capacity is relatively high, which is conducive to controlling the deformation of the high-rise building foundation, especially the inclination of the building.

3.2. Design and construction of rigid pile composite foundation

Scheme design of rigid pile composite foundation. According to the characteristics of the building and the conditions of the site, the rigid pile composite foundation was determined by comprehensive analysis. The pile body passed through the fully weathered mudstone layer ⑤1 and the strongly weathered mudstone layer ⑤2. The moderately weathered mudstone layer ⑤3 was the bearing layer of pile end, and the depth of pile end entering the layer ⑤3 was 1.0 ~ 1.5 m. The characteristic value of bearing capacity of single pile was 800 kN. According to the range of 150mm-300mm in Reference [7], the thickness of the cushion was appropriately thickened to 200mm, and the material is gravel with a particle size of less than 3cm. Cushion material is gravel with particle size less than 3cm. The design parameters of rigid pile composite foundation are shown in Table 5.

Though calculation, the characteristic value of bearing capacity of composite foundation is 602 kPa, and the maximum settlement of building is 29.23 mm, which meets the design requirements of bearing capacity and settlement of superstructure. Because the main building is adjacent to the underground garage with independent foundation, the bearing capacity of the composite foundation is not modified in depth.

Table 5. Design parameters of rigid pile composite foundation.

Effective pile length (m)	Pile end into 5 3 layer depth (m)	Pile diameter (m)	Pile spacing (m)	Strength grade of pile concrete	Number of piles	Thickness of the cushion (mm)
12	1.0 ~ 1.5	0.4	1.5	C25	470	200

Construction of rigid pile composite foundation. The rigid pile construction adopted the long spiral drill center pressure grouting pile-forming technology. Due to the short length of the pile, it was necessary to ensure that the pile end entered a certain depth of the moderately weathered mudstone layer ⑤$_3$. It was strictly prohibited to lift the drill first and then fill the material to ensure that there was no empty soil at the end of the pile. In the construction, combined with the survey report, the soil condition discharged from the drill pipe was observed. During the drilling process, it was easier to drill in the fully weathered mudstone layer ⑤$_1$. But when entering the strongly weathered mudstone layer ⑤$_2$, especially the moderately weathered mudstone layer ⑤$_3$, the drilling opportunities were obviously characterized by shaking and slower footage. According to these characteristics, the depth of the pile tip into the moderately weathered mudstone layer ⑤$_3$ could be judged in the construction.

3.3. The effect and evaluation of foundation treatment

After the completion of rigid pile construction, the detection unit carried out static load test of single pile composite foundation for each building, and carried out low strain dynamic test on pile integrity. Figure 5 is the static load test curve of single pile composite foundation. The test results show that the bearing capacity of the composite foundation met the design requirements, the quality of the pile body was complete, and there were no class III and class IV piles which could influence the normal operation.

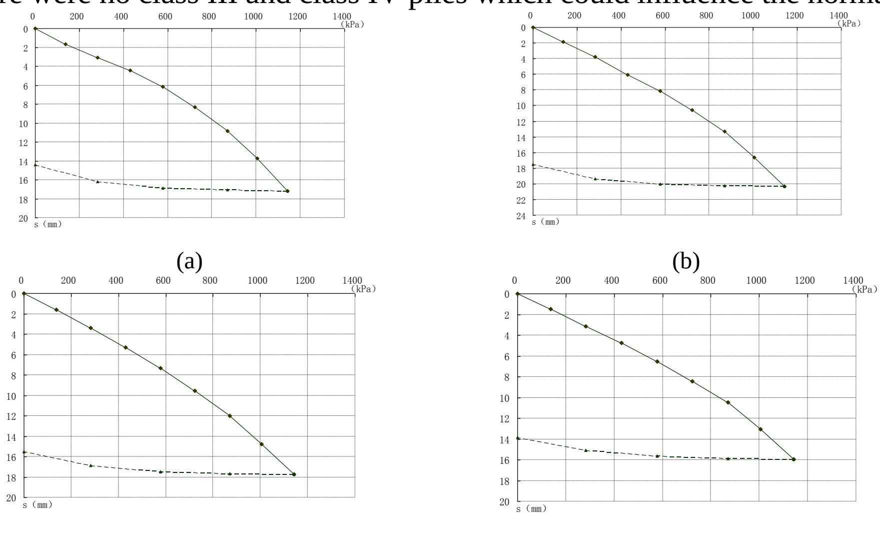


Figure 5. Load-settlement curve of single pile composite foundation.

In the process of structural construction and after the main body was sealed, the settlement of the building was observed. The settlement curve is shown in Figure 6. During the 550-day continuous observation period, the measured cumulative maximum value of settlement was 12.7 mm, and the average cumulative value was 10.1 mm. The settlement rate of the last two observation cycles was 0.01 mm / day. According to the engineering experience in Chengdu area, the settlement rate of the last 100 days was less than 0.02 mm / day as the standard for the building to enter the stable stage. The building had entered the stable stage of settlement, and the final settlement met the design requirements.

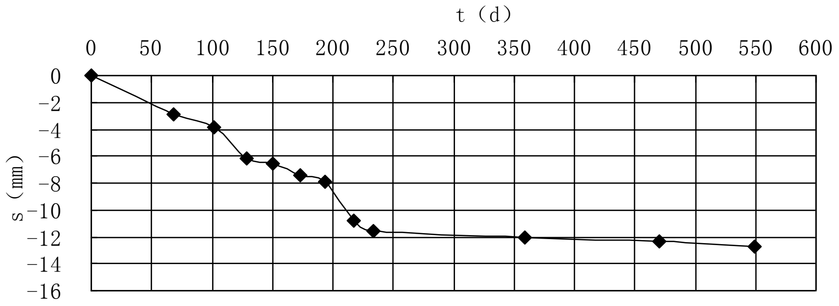


Figure 6. Building settlement-time curve.

It can also be seen from Figure 5. and Figure 6. that the deformation of the composite foundation is less than 20 mm under the double load of the composite foundation load test, and the final settlement of the building is not more than 15 mm, which is far less than the design requirement of the upper structure of 50 mm. In this project, the moderately weathered mudstone was used as the bearing layer of the pile end, and the end-bearing rigid pile composite foundation scheme was adopted. By improving the concrete strength grade of the pile body and setting the cushion with appropriate thickness, the bearing capacity of the pile could be ensured to be safe and fully utilized. While satisfying the high bearing capacity of the foundation, because the bearing layer of the pile end is moderately weathered mudstone, it was very beneficial to control the settlement, so that the resistance to deformation of the end-bearing rigid pile composite foundation was also greatly improved. Therefore, for high-rise buildings with high bearing capacity and strict deformation control, the end-bearing rigid pile composite foundation has better applicability.

Conclusion

Through the field experiment and engineering application case of rigid pile composite foundation with moderately weathered mudstone at the pile end, the following conclusions are drawn:

(1) Soft rock or extremely soft rock, such as moderately weathered rock or strongly weathered rock, can be used as the pile end bearing layer of rigid pile composite foundation to form end bearing rigid pile composite foundation.

(2) For the end-bearing rigid pile composite foundation, by properly adjusting the thickness of the cushion, the pile-soil load sharing can be effectively coordinated, and the bearing capacity of the soil between the piles can be better played. It also ensures the pile-soil interaction and constitutes the composite foundation.

(3) For the end-bearing rigid pile composite foundation, the strength grade of the pile material should be appropriately improved to avoid the damage of the pile material.

(4) The engineering application results show that the end-bearing rigid pile composite foundation has a large increase in bearing capacity and strong deformation control ability, which is suitable for high-rise building foundation treatment.

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Conflicts of interests

The authors declare no conflict of interest.

Authors' contribution

Conceptualization, Yinkai Song, Jianxing Tong and Qiufeng Tang; formal analysis, Yinkai Song and Jianxing Tong; data curation, Jianxing Tong and Qiufeng Tang; writing—original draft preparation, Yinkai Song; writing—review and editing, Jianxing Tong. All authors have read and agreed to the published version of the manuscript.

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