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Experimental Study on the Bearing Behaviour of Super-Long Post-Gouting Cast-in-Place Pile in Deep Soft Soil

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Abstract. The post-grouting technology is widely employed in cast-in-place pile, but also a lack of awareness of the effect of post-grouting on super long cast-in-place pile in deep soft soil. To discover the mechanical mechanism of post-grouting cast-in-place pile in deep soft soil, O-cell pile testing before and after post grouting are carried out on two piles instrumented with steel-string transducer, and the frictional resistance and tip resistance are obtained. The following conclusion can be reached: 1) Side grouting and end-side association grouting can significantly increase the axial bearing capacity and the axial displacement decreases significantly at the same load. 2) The unit side resistance of pile is increased by using post-grouting and the effect on coarse-grained soil is better than that on fine-grained soil. 3) The load transfer law of overlength cast-in-place pile will not be changed by post-grouting, and the load-settlement curve will be slow descending. In order to increase the pile bearing capacity and reduce settlement simultaneously, side grouting can be the recommendation for super-long cast-in-place pile in deep soft soil.

Keywords. Post-grouting, O-cell pile testing, cast-in-place pile, axial bearing capacity, load transfer law

1. Introduction

As an important form of bridge foundation, cast-in-place piles are widely applied as its advantages of in high bearing capacity and widely applicable[1]. The technology of constructing cast-in-place pile in deep soft soil with geological drilling rig slurry retaining wall technology is briefly adopted and it's often associated with soil disturbance and the mud in the end and side of piles. The exertion of pile shaft resistance and base resistance will be affected and the pile tip settlement will also increase [2-3]. The technology of grouting can overcome the shortcomings and improve the bearing performance of piles. Therefore, it has been introduced into the specification and has been applied rapidly in the construction work[4-8]. Lots of relevant studies on the influence of post-grouting technology on the pile bearing capacity have been published. These studies are mainly involved shorter and mid-length piles. The

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vertical bearing capacity of super long cast-in-pile after post-grouting in deep soft soil have hardly touched. Therefore, two piles instrumented with steel-string transducer before and after post grouting are selected to carry out O-cell pile testing. The test results are used for analyzing the effect of grouting on the pile bearing capacity. And load-bearing capacity and load deformation of super-long pile are experimented. The conclusions are helpful to design and construction of super long cast-in-pile in deep soft soil.

2. Geology and Test Program

This project located at the eastern coastal areas with typical deep soft soil. According to the geological exploration, engineering geologic condition at Bridge site area is complicated. The upper part of test site is silt and silty soft soil, and the middle and lower part mainly consists of clay and silty clay. The silty sand is discontinuously distributed and mostly missing, and the layer bottom reveals slope deposit mixed soil and moderately weathered bedrock.

Super long cast-in-place pile with concrete strength of C40 is used in this project and two piles are designed to be tested by O-Cell test. These piles named S2-1 and S2-2 with diameters of 1200mm are instrumented with steel-string transducer. The soil parameters of the test piles are summarized in table 1 and the basic information of test pile is shown in table 2. O-cell load test is performed on pile S2-1 before and after post-grouting and pile S2-2 only has been tested after grouting.

Table 1. Soil layer distribution and physical and mechanical parameter

Type of soil	Top Elevation/m	Water content (%)	Density ρ(g/cm^3)	Void ratio	Direct shear test	
					Internal friction angle φ_q(°)	Cohesion c_q (kPa)
①$_1$clay	3.28	41.7	1.80	1.159	9.1	18.5
②$_{12}$mud	-1.64	67.8	1.57	1.970	2.9	7.1
②$_2$mud	-11.36	63.5	1.59	1.840	3.3	8.2
③$_2$clay	-21.49	42.5	1.74	1.256	7.8	16.6
④$_1$Silty clay	-37.44	31.9	1.90	0.913	12.5	26.0
⑤$_1$Silty clay	-49.18	34.7	1.85	0.996	10.5	20.5
⑥$_1$Silty clay	-51.46	32.8	1.86	0.957	10.8	20.7
⑨$_2$Gravel with clay	-51.80	--	--	--	--	--
⑩$_1$Completely weathered ashstone	-57.70	30.8	1.85	0.930	14.1	22.6

Table 2. Overview of the test piles

Pile ID	Diameter /mm	Pile Top Elevation/m	Pile Toe Elevation/m	Pile Length/m	Bearing stratum	Test method
S2-1	1200	3.28	-56.72	60.00	Gravel with clay	Load test before and after grouting
S2-2	1200	3.28	-56.72	60.00	Gravel with clay	Load test after grouting

According to the provisions of Code for Static Loading Test of Foundation Pile-self-balanced Method (JT/T738-2009), the load cell is installed at the balance point position. The position is calculated based on the soil parameter and formulas recommended by Code for Technical Specifications for Building Pile Foundation (JGJ 94-2008). The skin resistance of upper pile is calculated refer to the standard uplift bearing capacity of single pile (T_{uk}) and the standard compressive bearing capacity (Q_{uk}) of lower pile refers to the Technical Specifications for Building Pile Foundation (JGJ 94-2008). Steel-string transducers are respectively located at the interface of soil layers. There are 9 sections of pile installed with transducers and each section has two. Before the O-cell load test, cross hole ultrasonic testing and low strain pile integrity test are executed to ensure pile shaft integrity.

Open grouting with the sequence of combined side and tip grouting is adopted. Pile side grouting is prior to pile end grouting. The interval between pile side grouting and tip grouting shall not be less than 2h. Grouting pressure, grouting amount and flow rate are all automatic recorded by automatic control system, details seen in table 3.

Table 3. Grouting parameters of friction piles

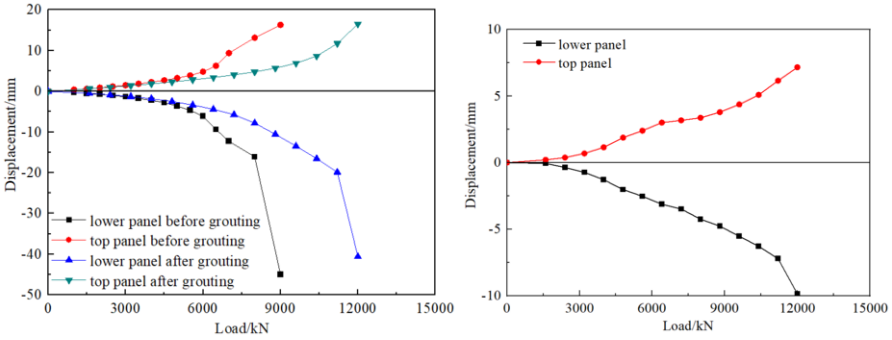
No.	Position	ID	Elevation/ m	S2-1		S2-2	
				Cement content/t	Termination pressure /MPa	Cement content/t	Termination pressure /MPa
1	Pile shaft	SZ-1	-12.72	0.963	2.19	0.967	1.66
2		SZ-2	-24.72	0.976	1.00	0.967	2.58
3		SZ-3	-32.72	0.966	2.30	0.973	1.93
4		SZ-4	-40.72	0.982	0.97	0.964	1.50
5		SZ-5	-48.72	1.002	3.40	0.975	2.30
6	Pile end	Pile end	-56.72	3.689	1.66	4.632	2.59

3. Test Results and Discussion

3.1. Load-Displacement Characteristics

The test results of the two test piles are shown in figure 1, where the displacement is positive in the upward direction and negative in the downward direction. From the load-settlement curve (Q-s curve) as shown in figure 1, the displacement of top panel of pile S2-1 is not large under various load, but the displacement of the lower panel reaches the high value under the maximum load, and the cumulative maximum displacement is more than 40mm which indicates that pile have been damaged. According to different load levels, the displacement of top and lower panels of S2-2 pile does not much increase, and no damage occurs during the loading process. Test is ended when it reaches the maximum loading capacity of the equipment. The Q-s curves of pile S2-1 before reaching failure are chosen to analyse. Among them, the maximum load of pile S2-1 before grouting is 8000kN, the maximum load of S2-1 pile after grouting is 11200kN, and the maximum load of S2-2 pile after grouting is 12000kN. It can be seen from the Q-s curve in figure 1 that the side resistance of the upper pile is not fully mobilized. By comparing the Q-s curves of S2-1 pile before and after grouting, the change of Q-s curve after grouting is significantly slower than that before grouting, and the displacement under the same load is significantly smaller. According to the three times of test results of O-cell load tests on two cast-in-place piles, post-grouting

can obviously increase the ultimate bearing capacity of the cast-in-place piles and reduce the settlement.



(a) Pile S2-1 (b) Pile S2-2

Figure 1. Q-s curves of the tested piles

According to the provisions in Appendix B of Code for Static Loading Test of Foundation Pile-self-balanced Method (JT/T738-2009), the Q-s curve of test piles measured by O-cell load test is equivalent to an equivalent curve of pile top loading by conventional static load test. The equivalent conversion curve of these two piles are shown in figure 2.

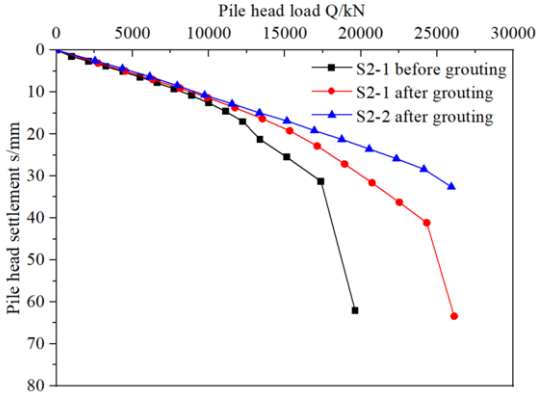


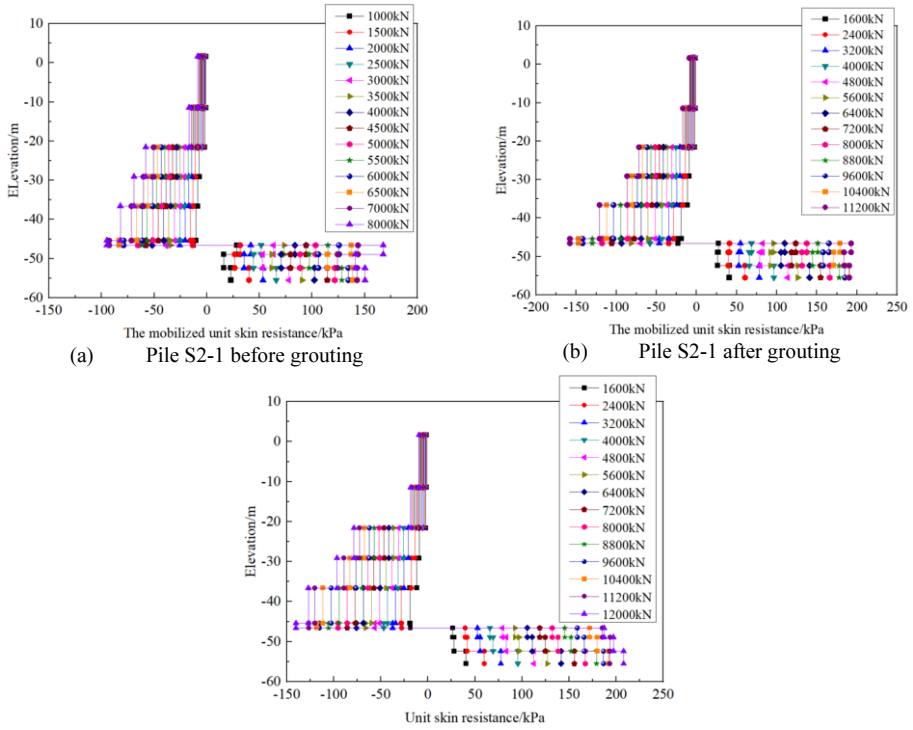
Figure 2. Equivalent pile top load - displacement curve

For the pile S2-1 without grouting, the corresponding maximum load of the equivalent curve is 17,378.8kN and the settlement of pile top is 31.28mm. The maximum equivalent curve load of S2-1 pile after grouting is 24328.8kN and the settlement of pile top is 41.15mm. The maximum equivalent curve load of S2-2 pile after grouting is 25941.3kN, and the settlement is 32.57mm.

3.2. Pile Shaft Resistance

Under the multi-staged loading, the axial force of the test pile can be obtained through the test data of the steel bar meter embedded in the pile. And the skin resistance can be calculated through the measured axial force. The distribution of skin resistance in each

soil layer around the pile is shown in figure 3, where the skin resistance is positive in the upward direction and negative in the downward.



(a) Pile S2-1 before grouting (b) Pile S2-1 after grouting

(c) Pile S2-2 after grouting

Figure 3. The distribution of mobilized skin resistance of test pile

The measured skin resistance of each soil layer is summarized as shown in Table 4. According to the test results of pile S2-1 before and after grouting, the unit skin resistance of each soil layer has an obvious improvement, but different soil layers of the same pile and different piles in the same soil layer have certain differences in the improvement amplitude. The effect of post-grouting on skin resistance of pile in soft soil mud is not obvious.

Table 4. Improving effect of pile skin resistance after grouting

Section	Type of soil	The mobilized skin resistance (kPa)			Improve（%）	
		①	②	③		
		S2-1 before grouting	S2-1 After grouting	S2-2 After grouting	②/①	③/①
G1-G2	②$_1$mud	-8.5	-8.8	-9.6	3.5%	12.9%
G2-G3	②$_2$mud	-16.8	-17.0	-18.3	1.2%	8.9%
G3-G4	③$_2$clay	-58.0	-71.8	-78.7	23.8%	35.7%
G4-G5	③$_2$ clay	-69.2	-86.6	-96.6	25.1%	39.6%
G5-G6	④$_1$silty clay	-82.1	-120.8	-127.0	47.1%	54.7%
G6-G7	⑤$_1$ silty clay	151	193.7	184.5	28.3%	22.2%
G7-G8	⑥$_1$ silty clay	141.3	183.9	197.1	30.1%	39.5%
G8-G9	⑨$_2$gravel with clay	150.4	190.4	208.0	26.6%	38.3%

3.3. Pile End Resistance

The buried position of load cell of test pile S2-1 and S2-2 is -46.60m and the distance to the pile toe is 10.12m. The height of the deepest steel rebar meter of the lowest layer is -55.52m and the distance to the pile toe is 1.2m. To simplify the analysis, the pile axial force measured by the deepest steel bar is approximately taken as the pile tip resistance, as shown in figure 4. The pile tip resistance of test pile S2-1 and S2-2 increases with the increase of load. Because the load cell is far away from the pile toe, the skin resistance of the lower pile shaft is mobilized prior to the pile tip resistance, and the percentage of pile tip resistance increases with the increase of load. It can be estimated that the increase effect on the end resistance is 50%~68% from experiments. According to the displacement of the pile shaft below load cell, pile tip settlement under the same load after grouting also decreases obviously.

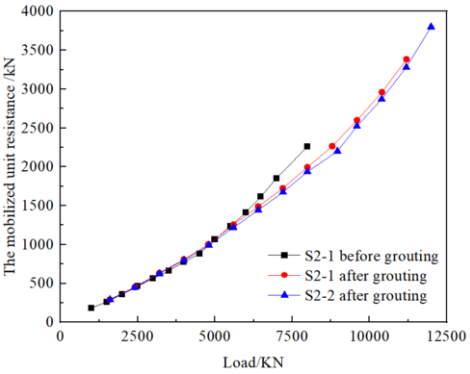


Figure 4. Q-s curves of pile tip

4. Conclusion and Recommendation

The issue about eliminating the influence on the bearing behaviour caused by the mud in the end and side of piles can be solved by applying the post-grouting technology. But the mechanism of post-grouting on the super long cast-in-place pile in the deep soft soil can not be understood adequately due to lack of field load test. In light of this, this paper provides experimental research and analyses the load-settlement characteristics of pile before and after grouting. The research results can guide the design and construction of super long cast-in-place pile in the deep soft soil. The following conclusions can be drawn:

The axial bearing capacity of super-long cast-in-place piles can significantly improve by the end-side association grouting. Under the same load, the settlement of the post grout pile decreases obviously.

Side grouting can significantly improve the pile skin resistance, but different in the development of soil layers. The increase amplitude of coarse-grained soil is greater than that of fine-grained soil, and the pile side post-grouting can be most used to improve the skin resistance of test pile in coarse-grained soil.

For this project, pile-end post-grouting can increase the pile end resistance by about 50%~68%, but the influence depth is limited. Pile-end post-grouting can be mainly used to improve the characteristics of the pile end sediment layer and the soil layer nearby.

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