Pile Load Test of Post-grouting Bored Pile at Beijing Capital International Airport

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Abstract. Bottom slime and shaft mudcake are two principal deteriorative factors affecting the mobilization of bearing capacity of slurry bored piles. As an effective later improvement technology, post-grouting can significantly improve bored pile bearing capacity. Based on static load test results of Beijing capital international airport project, vertical bearing properties of post-grouted bored pile have been studied. The analyses reveal that: with pile-toe and pile-shaft post-grouting, the interface between pile and surrounding soil was strengthened and the relative sliding displacement in between was reduced, end resistance of pile was enhanced and could be mobilized at earlier stage with smaller sliding displacement. As a result, the performance of bored pile was improved with increased bearing capacity and reduced settlement.

1. Introduction

Post-grouting bored pile technology refers to that, after the pile is completed, the grouting pipe embedded in the pile body is injected with cement slurry under certain pressure. Through the infiltration, compaction, splitting and cementation of cement slurry, the bottom slime, the shaft mucake and the soil around the pile are strengthened to improve the bearing capacity of the cast-in-place pile and change the load-settlement characteristics of the pile\(^1\). Three post-grouting technologies, the pile-end grouting, the pile-surrounding grouting and the pile-end and pile-surrounding association grouting, have been developed and have been widely used in engineering\(^2-3\). The vertical bearing capacity of different types of piles is analyzed through the pile load test in terminal 3 of Beijing capital international airport.

2. Pile load test

2.1 Project introduction

Beijing Capital International Airport Terminal 3 is about 3 kilometers long in North and south, 1 kilometer wide in East and west, with a total building area of 960,000 m\(^2\). It is the core project of the capital airport expansion project. According to the form of building structure, load distribution and engineering geological conditions, more than 18,000 bored piles with mud wall protection are used in the project. Compression piles are the main piles, and a few pull-out piles are added. It was the largest application of post-grouting pile technology to improve the quality of piles and the bearing capacity of piles.
2.2 Site geology
The engineering site stratum is mainly composed of new and recent artificial fill and Quaternary alluvial and diluvial materials. In the exploration depth of 100 m, besides artificial filling, silty clay, clay, sandy silt, silty fine sand and medium-coarse sand in Quaternary sediments mainly form multiple sedimentary rhythms in vertical direction.

2.3 Pile test design and test results
A total of 66 post-grouting piles and 6 non-grouting piles were subjected to destructive static load tests in 14 regions with thicker clay layers. According to the load distribution and design requirements of the building, test piles with different diameter and length were arranged in different areas. According to different pile types and grouting effect, the position of bearing stratum at pile tip was selected as ⑨ fine medium sand layer, ⑩ fine medium sand layer and ⑪ fine sand layer.

The combined grouting at the end and side of the pile was carried out. The grouting amount at the end of the pile was 1000 kg. Different grouting methods were adopted at the side of the pile according to the different length of the pile. A side grouting method was set up for the pile whose length was less than 30 m. The grouting amount was 600 kg, and two side grouting methods were set for the pile whose length is more than 30 m, and the grouting amount was 400 kg for each side grouting method. There was only one side grouting for uplift pile, and the grouting volume was 400 kg. The actual grouting effect was shown in Figure 1. The functions of cementing mud skin and splitting reinforcement are clearly visible.

![Figure 1. Reinforcement effect of post-grouting](image)

The single cyclic slow maintenance load method was used to carry out the vertical compression and tension static load test of single pile. The internal force test of pile body was carried out with the embedded steel bar stress meter on the steel cage, to obtain the distribution of pile lateral friction resistance and pile end resistance. According to the test results and considering the dispersion and other factors, the vertical ultimate bearing capacity of each pile type is shown in Table 1, and the load settlement curve of some test piles is shown in Figure 2.

![Figure 2. Curve of Q-S of test piles](image)

NC-TP2 is type 4, SD-TP2 and SD-TP5 are type 5, SD-TP3 is type 11, NE-TP4 and NE-TP 5 are type 17.
3. Analysis of bearing capacity

3.1 Load settlement characteristics

The most obvious improvement of the bearing capacity of the post-grouting pile is that the bearing capacity is greatly improved and the settlement amount is greatly reduced, which is the most fundamental reason for the popularization and application of this method. As shown in Table 1, the vertical ultimate compressive bearing capacity of pile type 4, 3, and 7 was increased by 120%, 144%, and 97%, respectively, for pile type 17, 18, and 19 corresponding to the pile end side. Therefore, as long as the grouting parameters are reasonably determined and the construction process is strictly controlled, the effect of the post-grouting technology to improve the bearing capacity of the bored pile is very significant for the fine sand layer, the middle sand layer and the fine sand layer.

The load-deformation curves of the grouting piles after the combination of the un-grouted piles NE-TP4, NE-TP 5 and the pile end piles had obvious regularity, as shown in Figure 3. The former had a large amount of deformation, the curve had obvious inflection points, and there was a steep descending section, which had reached the ultimate bearing capacity and exhibits shearing shear failure; the deformation characteristics of the latter were changed by grouting, and the load settlement curve was compared with the former. The curvature was small and the gradient is gradual. Under larger load, the settlement was obviously smaller than that of the un-grouted pile, so the cast-in-place pile has higher bearing capacity after grouting. In summary, the post-grouting pile can achieve higher bearing capacity with smaller diameter and shorter pile length, and has higher economic value.

3.2 Play and synergy of pile end and pile side resistance

The vertical compressive load of the bored pile is shared by the pile end resistance and the pile side frictional resistance. The size and function of the piles essentially determine the bearing characteristics of the cast-in-place pile. The post-grouting technology optimizes the coordination effect between the two by improving the lateral frictional resistance and the pile end resistance, respectively, to achieve the effect of improving the bearing performance of the bored pile.

After grouting, the reinforcement of the weak side of the pile side form the “expansion effect” [4], and the compressive modulus of the soil on the pile side increase, which all improve the ultimate frictional resistance of the pile side. The pile end grouting solidifies the loose sediment at the bottom of the pile, and the high-strength cement soil at the bottom of the pile is integrated with the pile body to achieve the “expansion effect”, and the total end resistance is significantly increased. The post-grouting osmosis consolidation and splitting reinforcement effect strengthens the soil layer in the

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Table 1. Ultimate bearing capacity of test piles

| type | mechanical type | bearing layer | pile diameter (mm) | effective pile length (m) | whether the grouting vertical ultimate bearing capacity (kN) |
|------|-----------------|---------------|--------------------|---------------------------|----------------------------------------------------------|
| 1    | pressure ⑨      | 800           | 24                 | yes                       | 11200                                                    |
| 2    | pressure ⑨      | 1000          | 24                 | yes                       | 12000                                                    |
| 3    | pressure ⑨      | 800           | 25                 | yes                       | 10000                                                    |
| 4    | pressure ⑨      | 1000          | 25                 | yes                       | 12000                                                    |
| 5    | pressure ⑨      | 1000          | 26                 | yes                       | 13000                                                    |
| 6    | pressure ⑨      | 800           | 27.5               | yes                       | 10000                                                    |
| 7    | pressure ⑨      | 1000          | 27.5               | yes                       | 13800                                                    |
| 8    | pressure ⑨      | 800           | 28                 | yes                       | 12300                                                    |
| 9    | pressure ⑨      | 800           | 30                 | yes                       | 12200                                                    |
| 10   | pressure ⑨      | 1000          | 30                 | yes                       | 14300                                                    |
| 11   | pressure ⑨      | 1000          | 32.5               | yes                       | 15000                                                    |
| 12   | pressure ⑨      | 1200          | 32.5               | yes                       | 17900                                                    |
| 13   | pressure ⑨      | 1000          | 37                 | yes                       | 17700                                                    |
| 14   | pressure ⑨      | 1000          | 42.5               | yes                       | 20000                                                    |
| 15   | pressure ⑨      | 1200          | 47.5               | yes                       | 23500                                                    |
| 16   | pull            | 800           | 24.5               | yes                       | 5800                                                     |
| 17   | pressure ⑨      | 1000          | 25                 | no                        | 5500                                                     |
| 18   | pressure ⑨      | 800           | 25                 | no                        | 4100                                                     |
| 19   | pressure ⑨      | 1000          | 27.5               | no                        | 7000                                                     |
sliding surface of the pile bottom, which increases the cohesion and internal friction angle of the soil, and will also increase the bearing capacity of the pile end. Taking the pile in table 3 as an example, after grouting, the side friction resistance of the pile can be increased by 68.7%, and the pile end resistance can be increased by 300%.

Table 2. Bearing properties of test piles

| No.   | maximum load /kN | maximum settlement /mm | when reaching the ultimate bearing capacity |
|-------|------------------|-------------------------|--------------------------------------------|
|       |                  |                         | ultimate bearing capacity /kN | side friction /kN | pile end resistance /kN |
| NE-TP5 | 11000            | 79                      | 8000                                      | 7350              | 900               |
| SD-TP5 | 16000            | 20                      | 16000                                     | 12400             | 3600              |

In the pile load test, the test pile with the fine sand layer as the pile end bearing layer, whether it was post-grouting pile or non-grouting pile, under the ultimate load, all piles were mainly loaded with side resistance. All piles were end bearing friction pile, as shown in Tables 2 and 3. The proportion of the load at the end of the post-grouting pile was greater than the non-grouting pile. The proportion of the load at the end of the pile was increased, so the proportion of the load on the side of the pile was relatively reduced.

Table 3. The ratio between pile end resistance and skin friction of different type piles under the ultimate load

| Type | load sharing ratio of post-grouting pile /% | load sharing ratio of non-grouting pile /% |
|------|-------------------------------------------|-------------------------------------------|
|      | pile slid       | pile end       | pile slid       | pile end       |
| 5    | 77             | 23             | 84             | 16             |
| 11   | 83             | 17             | 87             | 13             |
| 12   | 80             | 20             | 85             | 15             |
| 15   | 81             | 19             | 88             | 12             |

Due to the sediment in the bored pile end, a large displacement of the pile top is required to exert the pile end resistance. After grouting, the pile end resistance of the post-grouting pile is obviously larger than that of the non-grouting pile at the same displacement. The grouting pile can exert a large end resistance only by a small displacement of the pile top, as shown in Table 3. The pile end resistance plays an early role, and the difference between the pile side frictional resistance and the pile top displacement requirement is reduced. The pile end resistance and the pile side frictional resistance increase at the same time. Thereby, the bearing performance of the pile can be more coordinated.

4. Conclusion

(1) Post-grouting technology can improve the bearing capacity of bored piles, reduce settlement, reduce pile diameter, shorten pile length, reduce pile number, save investment and shorten construction period. The wide application of this technology has good economic benefits.

(2) The compressive piles with the fine sand layer and the middle sand layer as the bearing layer are all end-bearing friction piles. After grouting, the pile-soil interaction is improved, and the pile end resistance and the pile side friction resistance are greatly improved. When the function is exerted, the difference in the requirements of pile top displacement is reduced.

References

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