Experimental study on bearing behaviour of different uplift piles

ZHENG Ai-rong*, ZHU GE Ai-jun

CCCC Tianjin Port Engineering Institute Ltd., Key Laboratory of Geotechnical Engineering, Ministry of Communications, PRC, Key Laboratory of Geotechnical Engineering of Tianjin, Tianjin, 300222, China, CCCC First Harbor Engineering Company Ltd., Tianjin, 300461, China

*Corresponding author’s e-mail: airong717@163.com

Abstract. Based on pile load test results of uplift bored piles for a deep-embedded underground transformer substation, the uplift behaviour of enlarged toe pile and shaft post-grouting bored piles have been studied. The loading transfer characteristics and uplift capacity improvement mechanism for the two different type uplift piles have been investigated. The research shows that post-grouting can significantly improve bored pile uplift bearing capacity. After pile shaft grouting, the interface condition between pile and soil is improved, the friction resistance of pile side is increased obviously, and the uplift bearing capacity is improved. For long uplift pile, the uplift resistance of shaft grouting bored pile is better than that of enlarged toe pile.

1. Introduction

The uplift piles are widely used in large basement anti-floating, high-rise building uplifting, suspension bridge and cable-stayed bridge anchor pile foundation. The main mechanism of the uplift pile is to resist the axial pulling force by the friction between the pile body and the soil. There are many types of uplift piles, and the enlarged toe pile is a common type [1-3].

Since the first application of wellbore cement grouting in the Alibaba Puri mine in England in 1864, grouting technology has been widely used in foundation reinforcement and treatment of unfavorable geological phenomena, and formed post-grouting pile technology. The penetration, compaction, splitting and cementation of cement slurry can strengthen the soil around the pile and improve the bearing capacity of the bored pile [4, 5].

Based on the uplift pile test of the 500kV substation project, the uplift bearing capacity of the enlarged toe pile and the post-grouting pile is compared.

2. Pile load test

2.1. Project introduction

The 500kV substation is a circular building with a main structure diameter of more than 130 meters. The buried depth of the floor is 33.4m under the natural elevation of the ground. The top surface of the structure is a ground greening plaza, which is an underground structure. The construction of such large-scale deep-buried underground buildings in coastal areas, the anti-floating scheme is a key issue to be considered in the basic design. Based on the engineering geological conditions and construction
experience of the area, after several discussions, it was decided to use two types of uplift piles, such as enlarged toe piles and equal-section side grouting piles, for test piles.

2.2. Site geology
The site is a typical coastal soft soil layer. The upper layer is 30m deep and is composed of silt soil and clay in the state of fluid plasticity and soft plastic. The lower layer is distributed with clay, silt and sand layer, and the stratum is distributed within the effective pile length. There are: ① sandy silt layer: grass yellow and gray, saturated, slightly dense to medium dense, layer thickness 4.5m-8.2m; ② powder sand layer: gray, saturated, medium dense to dense, layer thickness 6.2m-11.6m; ③ silty clay layer: gray, very wet, soft plastic to plastic, layer thickness 12.9m-16.5m; ④ silty clay and silt interbed: gray, very wet, plastic, slightly dense, layer thickness 7.4m-15.5m; ⑤ silty clay and silt interbed: gray, very wet, plastic, slightly dense to medium dense, layer thickness 2.2m-6.7m; ⑥ middle sand layer: gray, saturated, medium dense to dense, layer thickness 8.0m-9.7m. Stabilize groundwater depth by 0.5m-1.0m.

2.3. Pile test design
The anti-extraction test pile consisted of 12 bored piles, including 3 bottom-expanded piles, pile number T1-T3, 3 pile-side grouting piles, pile number T4-T6, and 6 bottom anchor piles. The buried depth of the pile end was 82.5m, and the bearing layer was ⑥ middle sand layer.

The elevation of the pile top of the engineering pile of this project was -33.5m. In order to simulate the actual situation of the engineering pile and determine the bearing capacity of the actual engineering pile single pile accurately, the six bored piles in the pull-out test area were constructed by double casing method, so that the bored piles from the ground to -33.5m Part of the pile body was separated from the soil.

Four grouting points were arranged at intervals of 15m, 10m, 10m and 10m under the top of the post-grouting piles, and the amount of cement pressed into each grouting point was 400kg. The enlarged toe piles had an enlarged head height of 2m and a maximum diameter of 1.5m. Rebar stress meters were embedded in the pile body corresponding to the boundary of each soil layer (the depths were 0.5m, 33.5m, 37.5m, 46.0m, 60.0m, 73.0m and 77.0m) to measure the axial force of each section of the pile body and the frictional resistance of the pile side.

2.4. Test results
Since the test piles were also used as engineering piles, the maximum load of the test was 8000kN. At the last stage of loading, there were no obvious damage phenomena. The ultimate bearing capacity of the test piles are shown in Table 1. The load-displacement curves of the uplift piles are shown in Figure 1.

![Figure 1. Curves of load-displacement of T1-T6](image-url)
The uplift bearing capacity of the piles is more than that of the post-grouting piles. Therefore, the uplift bearing capacity of the piles under different loads is greater than 8000 kN. The test results show that the stability of uplift piles of different pile types is better than that of the enlarged toe piles.

It can be seen from Figure 1 that the load-displacement curves of uplift piles with different pile types belong to slow deformation, and there is no obvious starting point of steep rise. Under the maximum loading, the deformation of the pile top did not exceed 100 mm. Therefore, it can be judged that the ultimate bearing capacity of both pile types is greater than 8000 kN.

The discreteness of the test data of two types of piles is different. The load-deformation curves of the three side-grouting piles are in good agreement during the whole pile testing process, while the load-deformation data of belled piles are more discrete. The difference of discreteness of test data reflects the difference of quality stability of piles. The test results show that the stability of uplift bearing capacity of grouting piles is better than that of belled piles. The reason for this difference is related to the construction technology. The process of expanded bottom pile is more than that of grouting pile, which results in more factors affecting the quality of piles and increases the instability of bearing behavior. Side grouting can improve the quality of piles and the friction resistance of piles, thus improving the uplift resistance of piles.

3.2. Pile axial force and load transfer law

By calculating the distribution of frictional resistance around piles under different load levels, the law of load transfer can be understood. Tables 2 and 3 give the statistical values of the axial forces of two kinds of uplift piles under different loads.

| Table 1. Ultimate bearing capacity of test piles |
|-----------------------------------------------|
| No.   | type                  | pile diameter (mm) | pile length (m) | effective pile length (m) | vertical ultimate bearing capacity (kN) |
|-------|-----------------------|--------------------|-----------------|---------------------------|----------------------------------------|
| T1-T3 | enlarged toe pile     | 800                | 82.5            | 48.6                      | 8000                                   |
| T4-T6 | side grouting pile    | 800                | 82.5            | 48.6                      | 8000                                   |

3. Comparisons of uplift performance between enlarged toe pile and side grouting pile

3.1. Load and displacement analysis

As shown in Figure 1, the pile top deformation of the side grouting piles is smaller than that of the enlarged toe piles. Under the maximum loading, the top deformation of the two types of piles differs by more than 40%. Therefore, the uplift bearing capacity of the post-grouting piles is better than that of the enlarged toe piles.

The process of expanded bottom pile is more than that of grouting pile, which results in more factors affecting the quality of piles and increases the instability of bearing behavior. Side grouting can improve the quality of piles and the friction resistance of piles, thus improving the uplift resistance of piles.
Table 4 Pile-haft friction force of different type piles under the vertical load of 8000kN

| number | soil layer                        | depth (m)  | enlarged toe pile | grouting pile |
|--------|----------------------------------|------------|-------------------|---------------|
|        |                                  |            | friction force    | load          | friction force | load          |
|        |                                  |            | (kPa)             | (kN)          | (kPa)         | (kN)          |
| ⑦₁    | sandy silt                       | 33.5~37.5  | 59                | 4000          | 60            | 4000          |
| ⑦₂    | silt                             | 37.5~46.0  | 68                | 5500          | 78            | 6500          |
| ⑧₁    | silty clay                       | 46.0~60.0  | 41                | 6000          | 51            | 8000          |
| ⑧₂    | silty clay and silt interbed     | 60.0~73.0  | 51                | 8000          | 52            | 8000          |
| ⑧₃    | silty clay and silt interbed     | 73.0~77.0  | 64                | 8000          | 39            | 8000          |

Note: The load data in the table refers to the corresponding vertical load value of the pile top when the lateral frictional resistance of the soil layer reaches the value in the left column.

By calculating the frictional resistance of different soil layers under different loading levels, it can be found that with the increase of load, the frictional resistance of each soil layer gradually develops and the load gradually transfers to the pile toe. When the load reaches a certain value or the displacement of pile top reaches a certain value, the lateral friction of soil reaches the limit. Table 4 shows the frictional resistance of each soil layer on the side of two types of piles when the load is 8000kN. From Table 4, it can be seen that under the maximum loading condition of this test, friction of ⑦₁, ⑦₂ and ⑧₁ soil layers of enlarged toe piles reaches the limit, while friction of ⑦₁ and ⑦₂ soil layers of grouting piles reaches the limit, while the other soil layers still have the potential of uplift resistance. Comparing ⑦₂ and ⑧₁ soil layer friction, it can be found that the friction of grouting pile is larger than that of enlarged pile, and the increase range was between 15% and 25%. From Table 2, it can be seen that when the pile top load is 4000kN, that is, when the lateral friction of ⑦₁ layer soil is fully exerted, the displacement of the pile top of the grouting pile is much smaller than that of the enlarged toe pile, which shows that the effect of post grouting on improving soil performance is remarkable. ⑧₂ and ⑧₃ soil layers did not reach the ultimate lateral friction.

4. Conclusion
(1) Grouting piles are suitable for sand-rich formations. In the sand layer, the pile side grouting can achieve better results, which can significantly improve the uplift bearing capacity of the pile foundation and effectively control the displacement of the pile top.
(2) Because of the improvement of the side friction of pile by post grouting technology and the technical problems of enlarged bottom pile itself, the side grouting uplift pile has better applicability than enlarged toe pile for the long uplift pile.

References
[1] ZHOU Rong-feng, WANG Zhen-xin. (2006) Construction technology of pedestal pile 35m long for the southern square of Shanghai railway south station. Building Construction, 28(2):84-86.
[2] Charles H. (1988) Uplift load-displacement behaviors of spread foundation. Journal of Geotechnical Engineering, ASCE, 114(2): 189-215.
[3] CHEN Xu-wei, GE wei. (2005) Test analysis on the uplift resistance of bored cast-in-place pile with enlarged bottom and its application. Architecture Technology, 36(3):225-227.
[4] ZHENG Ai-rong. (2008) Post-grouting bored pile technology. China Harbour Engineering,(6): 46-49.
[5] ZHANG You-pa, WU Shun-chuan, FANG Zu-lie. (2002) Property analysis of rock and soil masses properties after cement-grouting. Journal of University of Science and Technology Beijing, 35(3): 77-81.