Experimental study and numerical analysis on bearing characteristics of large diameter ultra long bored piles with post grouting on the tip and side

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Abstract. To research the bearing characteristics of post grouting large diameter ultra long piles under post grouting on the tip and side, the load test of three test piles of a super high rise project was carried out, and the numerical analysis method was used to research the load transfer law of post-grouting large diameter ultra long bored piles. Based on this, the differences and advantages of the post-grouting on the tip and side pile versus the non grouting pile and the pile end grouting pile are analyzed. The analytical results show as follows: post grouting on the tip and side will significantly change the performance and distribution of side friction of the piles, and improve mechanical properties of soil and pile-soil interface around piles. The ultimate bearing capacity of the post grouting on the tip and side pile foundation has increased 100% and 52% more than the non grouting and pile end grouting pile foundations. The side friction of post-grouting on the tip and side pile plays a significant difference from the non grouting piles.

1. Introduction.
With the development of high-rise buildings, large diameter ultra long piles are often used to bear the load of superstructure. However, the quality of large diameter ultra long bored piles can be affected by the muddy skin effect, the stress relaxation of soil around pile, the sediment at the pile tip, and the soil disturbance at the pile tip. But these problems can be effectively solved by the application of post-grouting technology. Bustamante\(^1\) and Sherwood D E\(^2\) conducted comparative tests of grouting and non-grouting test piles. It was concluded that grouting can improve the bearing capacity of the pile and reduce the settlement of the pile, and post-grouting can be used to recover the problem of bearing capacity reduction caused by soil stress release and disturbance. CHENG Ye\(^3\) researched the effect of post-grouting at the pile tip on the bearing capacity of large diameter ultra long piles, and concluded that the post grouting technology at the pile tip can effectively improve the bearing capacity of the pile foundation and side friction above the cross section of the pile bottom. HU Chunlin\(^4\) obtained the increase coefficient of ultimate bearing capacity and the ultimate resistance of pile foundation by post-grouting technology through the static load test results of 186 test piles. Based on the law, a formula for calculating the ultimate bearing capacity of grouted pile is proposed. HUANG Shenggen\(^5\) researched the influence of post-grouting technology on the ultimate bearing capacity of
large diameter ultra long piles by numerical analysis methods, the results show that the post-grouting technology can improve side friction of the pile and the deformation modulus of the soil at the end of the pile and the soil around the pile.

Most of the pile foundation projects use pile end grouting or pile side grouting. Due to the complexity of the process, the post-grouting on the tip and side pile is rarely used, and few studies have been related to it. So there are few researches on the bearing behavior of large diameter and ultra long piles under post-grouting on the tip and side. Therefore, the research on this problem is an urgent problem to be solved in engineering and academia at present.

2. Test Overview.
A super high-rise project covers an area of about 27,000 m², the main building occupies an area of about 3900 m², and the height is about 428m. The basement has 4 floors, of which the floor of the main building is buried at a depth of about 25m, and the floor area of the underground garage is about 21m deep. The upper structure of the project uses a core barrel and the lower part uses a pile raft foundation. The test site is located on the terraced landform of the Grade II terrace in the coastal area, and is filled with artificial soil, the terrain is generally flat. The physical and mechanical properties of the foundation soil are shown in Table 1, and the soil layer and test pile section are shown in Fig. 1.

### Table 1. Physical and mechanical properties of foundation soil.

| Soil layer   | $\gamma$ (kN/m³) | $c$ (kPa) | $\phi$ (°) | $E_{1-2}$ (MPa) | $f_{ak}$ (kPa) |
|--------------|------------------|-----------|------------|----------------|----------------|
| ① Plain fill | 20.1             | 10*       | 10*        | 10.13          | —              |
| ② Medium sand | 19.9             | 12.5      | 32.3       | 9.54           | 200            |
| ③ Clay       | 18.3             | 44.2      | 8.1        | 6.42           | 180            |
| ④ Coarse sand | 20.5             | 5*        | 30.3       | 10.65          | 300            |
| ④-1 Silty clay | 18.8             | 38.3      | 5.0        | 4.70           | 200            |
| ⑤ Silty sand | 19.9             | 10*       | 28.2       | 14.95          | 300            |
| ⑥ Clay       | 18.1             | 36.1      | 9.7        | 7.59           | 320            |
| ⑥-1 Medium sand | 17.6             | 8*        | 30.0       | 15*           | 350            |
| ⑦ Silty clay | 19.3             | 70.1      | 26.0       | 10.62          | 380            |
| ⑧ Medium Dense | 20.6             | 8*        | 30.0       | 29.91          | 450            |

*Note: The “*” is an empirical value.*
The test consists of three test piles, the length of the pile is 110m, and the pile diameter is 1m. The characteristic value of the vertical bearing capacity of the single pile is approximately 19000 kN, and the maximum test load to be adopted is 45600 kN. Double sleeve method is adopted to isolate pile side friction of foundation pit section. The double sleeve length is 25m, that is the effective length of the pile is 85m. The post-grouting method adopts the post-grouting on the tip and side. Table 2 is the parameters of the test pile.

Table 2. Basic parameters of test piles.

| Pile number | Pile diameter (mm) | Effective length (m) | Post-grouting technology | vertical bearing capacity characteristic value (kN) | Preliminary evaluation of vertical ultimate bearing capacity of single pile (kN) | Concrete grade |
|-------------|--------------------|----------------------|--------------------------|-----------------------------------------------|--------------------------------------------------------------------------------|----------------|
| SA-1/2/3    | 1000               | 85                   | post-grouting on the tip and side | 19000                                         | 38000                                                                          | C50            |
3. Analysis of test results.

3.1. The Q-s curve of the test pile.

The Q-s curves of the three test piles are shown in Fig. 2. The Q-s curve of the whole pile is directly read by the on-site instrument, including the compression of the pile at the double sleeve, and the Q-s curve of the effective length of the pile is based on the force analysis of the actual pile foundation and the compression of the pile at the double sleeve is deducted at each load level.

![Q-s curve](image)

It can be seen from Fig. 2 that the Q-s curve of the test piles is slowly changing and there is no obvious inflection point, and the curve gradually becomes steeper as the load increases. In the 0 to 22800 kN loading section, the pile top settlement is less than 10 mm and the Q-s curve is almost linear. When the load was increased to 36480kN, the curve entered the elasto-plastic deformation stage, and the settlement increased more significantly under this stage of loading. The ultimate bearing capacity can be determined according to the amount of settlement, take \( s = 0.05 D \) [6] corresponding pile load, the ultimate bearing capacity of the pile is about 40000kN.

3.2. Pile side friction distribution.

![Shear stress vs. depth](image)
The pile side frictional distribution of the test pile is shown in Fig. 3. The results of the post-grouting on the tip and side are not exactly the same as the conventional pile foundation. Because the pile load does not transmit to the pile end under the initial load, and there is no compression deformation at the bottom of the pile, the side friction of the pile will be increased with the increase of the upper load, and the softening phenomenon will occur because the pile compression makes the displacement between the pile and soil reach the maximum relative displacement. So the normal distribution of pile side friction along the pile will undergo a transformation from "lantern type" \([9]\) to "R type" in the conventional pile foundation test. But the post-grouting on the tip and side can change the distribution and exertion of pile side friction. Due to the large injection of cement slurry at the end of the pile, a large number of cement slurry is returned to the soft clay in the pile side, so the slurry is filled with the soft soil layer at the interface of the pile and soil. The mechanical properties of pile-soil interface can be obviously changed by the compaction and permeability of slurry to the surrounding soil.

4. Numerical analysis of the post-grouting on the tip and side.

4.1. Numerical analysis model.

The size of the finite element model takes into account the boundary effect, the horizontal distance of the soil is 1 times the length of the pile and the vertical distance is 2.5 times the pile length. In connection with the actual grouting situation, the height of the slurry is 15m and the depth of the pile tip is 2m. The accuracy of the numerical analysis will be affected by the value of the calculation model parameters. In this paper, the parameters in the model are calculated by the geotechnical test and a large number of measured data. Referring to previous\([7]\) experience, the elastic modulus is 2~5 times of compression modulus. The mechanical parameters of grouting and solid are difficult to be determined by borehole drilling, so it can be determined by laboratory cemented soil test. According to the strength test of five kinds of cement reinforced soil in literature\([10]\) and considering the complexity in field grouting, the elastic modulus of clay grouting and solid is 200MPa, and the elastic modulus of silty clay and solid modulus of elasticity is 400MPa. The parameters are shown in Table 3.

| Model material | Elastic modulus (MPa) | \(\gamma\) (kN/m\(^3\)) | \(\nu\) | \(c\) (kPa) | \(\phi\) (°) |
|----------------|----------------------|----------------|------|-------|------|
| Pile           | 3.45\times10^4       | 25             | 0.2  | —     | —    |
| Sleeve section | 30                   | 19.6           | 0.3  | 25    | 30   |
| Clay           | 38                   | 18.1           | 0.29 | 36.1  | 9.7  |
| Silty clay     | 53                   | 19.3           | 0.3  | 70.1  | 26.0 |
Cement-reinforced clay  & 200 & 21 & 0.25 & 75 & 36 \\
Cement-reinforced silty clay  & 400 & 21 & 0.24 & 75 & 36 \\

*Note: the shear stiffness modulus of pile-soil interface is set to 0 to simulate the isolation effect of double sleeve section in the former 25m pile segment.

4.2. Model verification.
The SA-1 is calculated by numerical analysis method, and the results are compared with the measured data to verify the reliability of the model.

Table 4. Comparison of the lateral friction between the numerical analysis and the test pile.

| Type    | Measured results(kPa) | Simulation results(kPa) |
|---------|------------------------|-------------------------|
| Load/kN | 25-35m | 35-67m | 67-88m | 88-110m | 25-35m | 35-67m | 67-88m | 88-110m |
| 4560    | / | / | / | / | 31.07 | 17.52 | 14.34 | 12.16 |
| 9120    | 39.78 | 26.39 | 33.30 | 39.46 | 43.26 | 35.21 | 30.38 | 31.05 |
| 13680   | 36.50 | 48.24 | 46.18 | 61.86 | 58.37 | 46.85 | 43.46 | 59.33 |
| 18240   | 36.88 | 68.09 | 69.21 | 74.02 | 72.28 | 60.43 | 61.03 | 72.56 |
| 22800   | 40.86 | 82.99 | 91.77 | 94.72 | 76.85 | 80.41 | 83.43 | 90.77 |
| 27360   | 53.85 | 92.19 | 113.69 | 117.44 | 82.43 | 89.35 | 98.84 | 110.36 |
| 31920   | 56.23 | 110.29 | 137.61 | 136.22 | 85.66 | 101.31 | 126.87 | 139.30 |
| 36480   | 63.51 | 129.15 | 144.75 | 166.65 | 88.35 | 116.74 | 140.58 | 160.69 |
| 41040   | 69.20 | 134.89 | 152.87 | 200.93 | 90.86 | 129.27 | 150.14 | 197.11 |
| 45600   | 26.76 | 167.76 | 162.51 | 232.79 | 91.12 | 146.52 | 159.32 | 221.73 |

Fig.4 (a) is the contrast diagram of the $Q$-$s$ curves. It can be seen from the diagram that the two curves have a high degree of anastomosis in the linear change stage, and there are some small differences between the settlement changes with the increase of load. Fig. 4 (b) is the comparison chart of pile side friction. The dotted line shows the measured result, and the solid line represents the simulation result. The results of numerical analysis agree well with the measured results. The difference between the simulated and field test piles is mainly due to the difference between the parameters selected in the simulation and the actual geological condition of the pile test site, and the lifting effect of the pile end grouting can not be fully considered in the numerical simulation, thus causing a certain error between the simulated results and the measured values. But the scope of the
overall error does not affect the analysis of pile bearing characteristics, which also proves the
rationality of parameter selection.

4.3. Analysis of grouting condition.

In order to research the ultimate bearing capacity of pile foundation of the post-grouting on the tip and
side, non-grouting and pile end grouting. The models are analyzed on the basis of the test pile model
to research the ultimate bearing capacity of pile foundation of non-grouting and pile end grouting. The
grouting and solid properties are set as the attributes of the corresponding pile foundation to simulate
the non-grouting condition, and the other parameters are consistent with the test pile model. The
simulation results are shown in Fig.5.

![Fig.5 Comparison of the results of without grouting, pile-end grouting and association grouting.](image)

Table 5. Pile tip resistance and end resistance ratio of a variety of grouting under maximum load.

| Grouting type                      | Maximum load /kN | Pile tip resistance /kN | End resistance ratio % |
|------------------------------------|------------------|-------------------------|------------------------|
| Non grouting                       | 24000            | 2304                    | 9.6                    |
| Pile end grouting                  | 30000            | 1590                    | 5.3                    |
| post-grouting on the tip and side  | 45600            | 638                     | 1.4                    |

It can be seen from table 5 that in the case of pile end grouting, when the pile load was loaded to
30000 kN, the end resistance ratio was 5.3%. In the case of post-grouting on the tip and side, when the
pile load of 45600kN is applied, the end resistance ratio is not more than 2%. The post-grouting on the
tip and side pile effectively improves the mechanical properties of pile-soil interface, and improves the
ratio of pile side friction to pile load.

4.4. Comparison of friction between conventional (non-grouting) and post-grouting on the tip and side
piles.

Fig.6 shows that in the process of loading the conventional non-grouting pile foundation, the
25m–35m section of the pile is first exerted before the fourth stage load, and the side friction gradually
decreases along the pile. With the increase of load level, the side friction of the 25m~35m section of the pile increases slowly, while the side friction of the silty clay layer at the 35m~67m pile is more than that of the clay layer 25m~35m, and increases gradually. Finally, the side friction of the pile in the clay layer is about 70kPa, while the maximum side friction in the middle silty clay section is about 90kPa. Fig.7 shows that under the primary load level, the upper side pile friction value of post-grouting on the tip and side pile foundation is greater than the lower part of pile. With the increase of load level, the improvement effect of grouting and grouting pressure in the lower part of the pile is better than that in the upper part of the pile, and the side friction of the lower part of the pile is better. Under the ultimate load, the side friction of the clay reinforcement is about 90kPa, and the side friction at the end of the pile is about 230kPa.

![Fig.6 Distribution of lateral friction of non grouting pile.](image)

![Fig.7 Distribution of lateral friction of piles under post-grouting on the tip and side.](image)

![Fig.8 Comparison of pile side friction between non-grouting and post-grouting on the tip and side.](image)

As shown in Fig.8, under the less pile load, there is little difference between the side friction of the non-grouting and the post-grouting on the tip and side pile foundation in the clay layer, while the side
friction of the post-grouting on the tip and side pile in the silty clay layer of the lower part of the pile is larger than that of the non grouting. Under the large pile load, the side friction of the non grouting pile is played along the long length of the pile, and the overall distribution of the side friction is greater in the side of the upper part of the pile than in the lower part of the pile. Under the post-grouting on the tip and side, the side friction increases with the increase of load.

5. Conclusion.
Based on the post grouting large diameter ultra long pile test and numerical analysis, the bearing capacity is analyzed. On the basis of verifying the reliability of the model, the large diameter ultra long piles with non grouting, pile end grouting and post-grouting on the tip and side are simulated respectively, and the following conclusions are drawn.

(1) By analyzing the Q-s curves of the three test piles, it is found that the Q-s curve is slowly deformed for the post-grouting large-diameter long piles, and there is no obvious steep drop point. Therefore, the judgment of the ultimate bearing capacity of large-diameter ultra-long piles should be considered comprehensively according to the principle of settlement control and the specification requirements.

(2) Post-grouting changed the performance and distribution of pile side friction. Under the action of load, the side frictional is exerted along the pile. With the increase of the load at the pile, the side friction increases and there is no obvious softening phenomenon. In addition, the post-grouting improved the strength of the soil around the pile near the pile tip and the mechanical properties of the pile-soil interface, and its side friction was always greater than that at the upper part of the pile.

(3) The ultimate bearing capacity of post-grouting on the tip and side pile foundation is increased by 100% and 52% compared to that of non-grouting and pile end grouting. There are great differences in the distribution of side friction between the conventional grouting pile foundation and the post-grouting on the tip and side pile foundation.

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