Research on Bearing Capacity of Post-grouting Super-long Bored Pile

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Abstract: The bearing capacity of the post-grouting super-long bored pile, calculated by the standard enhancement coefficient, is 66% larger than that of the measured. The FEM analysis shows that when the grouting radius at the pile end is 1.5 \(d\) and the permeating height of the cement slurry is 4.05 m from the pile end, the end resistance enhancement coefficient is 1.17, and the pile side average friction resistance enhancement coefficient is 1.31 within 12 m above the pile end. The calculated bearing capacity is close to the measured bearing capacity of the post-grouting pile by those enhancement coefficients. The calculation shows that: a) in the case of no grouting, the pile end reaction force is about 5.78% of the pile top load; b) in the case of grouting, when the grouting diffusion radius at the pile end is 1.5 \(d\) and the permeating height from the pile end is 4.05 m, the post-grouting pile end reaction force is about 6.78% of the pile top load; and c) after grouting, the load transmitted to the pile end cannot be significantly increased; d) using the reinforcement coefficient suggested by the Standard, the calculated bearing capacity is larger than the measured.

1. Introduction
The post-grouting technology of bored piles has been studied by many scholars at home and abroad, and some useful consensus has been obtained in improving the bearing capacity and reducing the settlement of piles\(^1\)-\(^4\). It is found that the increase of bearing capacity is related to the diameter and length of the pile.

Much research has been done on the bearing capacity of medium and long grouting piles. After the post-grouting at the pile end, the results of the field test bearing capacity by Zhang Kaipu\(^2\) is nearly twice higher than the theoretical calculation \((l/d=48, \ l \ is \ the \ pile \ length, \ d \ is \ the \ pile \ diameter, \ the \ same \ below)\). The standard value of ultimate bearing capacity of single pile measured by Qu Huiping\(^3\) is 160-180% higher than the design value \((l/d=32)\). Zhou Bo\(^4\) found that the ultimate bearing capacity of pile group foundation increased by 38.9% compared with that of pile group foundation with non-grouting reinforcement, when the pile group foundation was treated by post-grouting from 2 \(d\) below the pile end to 5 \(d\) above the pile end \((l/d=15.6)\).

Zheng A. R.\(^5\) carried out a destructive static load test \((l/d=25-31)\) on 66 grouting piles and 6 non-grouting piles. The test showed that the ultimate bearing capacity of grouting pile is increased by more than 97% compared with that of non-grouting pile. Van Loc Nguyen et al.\(^6\) found that the
bearing capacity of the large diameter post-grouting pile \((d=1.5 \text{ m}, l=63 \text{ m}, l/d=42)\) is about 20\% higher than that of the non-grouting pile. Zhang Chunfeng et al.\cite{7} did researches on the bearing capacity of post-grouting super-long pile \((l/d=90)\). Under the maximum load, the end resistance of non-grouting pile and post-grouting pile only accounts for 5.0\% and 10.5\% of the top load respectively, post-grouting has no obvious effect on end resistance.

In summary, in the case of post-grouting at the pile end, the increase of bearing capacity of super-long pile \((l/d \geq 90)\) is less than that of medium-long pile \((40 \leq l/d < 90)\). The increase in the bearing capacity of the large-diameter pile is not as large as that of the small-diameter pile.

According to the data, it is found that there are few comparative analysis data on the static load tests of the post-grouting super-long piles and the non-grouting super-long piles in the same site, and the case in this paper will make up for this deficiency. The several tests of super-long piles in this paper showed that the measured value of the bearing capacity of post-grouting pile is much smaller than the value calculated by the Standard\cite{8}. In order to find the causes, the bearing capacity and deformation behaviour of post-grouting super-long piles are analyzed by using finite element calculation software. The obtained results can be used as reference for similar projects.

2. Engineering background
The engineering pile is a super-long bored pile, whose diameter is 900 mm and length is about 89.1 m \((l/d=99)\). The concrete strength of the pile is C50, and the bearing layer of the pile end is silty clay mixed with round gravel. In order to reduce the influence of bottom sediment on pile bearing capacity, the post-grouting at the pile end is adopted.

The test piles are numbered as SZ4, SZ5, SZ6, SZ7, SZ8 and SZ9. They are divided into two groups according to whether they are post-grouting or not. And the grouting comparison test is performed. SZ4, SZ5 and SZ6 are post-grouting piles, which are used to determine the bearing capacity of grouting pile, while SZ7, SZ8 and SZ9 are non-grouting piles, which are used to compare and test the bearing capacity improvement of post-grouting. The physical and mechanical properties of the test pile site are shown in Table 1.

| Soil layer number | Name of soil layer | Thickness \(^a\)/m | Weight \(/(kN/m^3)\) | Void ratio | Liquid index | Ultimate lateral resistance/kPa | Ultimate end resistance /kPa |
|------------------|------------------|-----------------|-----------------|-------------|--------------|-------------------------------|-----------------------------|
| ② Clay           | 1.90             | 18.21           | 0.981           | 0.51        | 26           |                               |                             |
| ③ Silt clay      | 7.73             | 16.80           | 1.375           | 1.34        | 12           |                               |                             |
| ③ Silt           | 20.00            | 16.07           | 1.645           | 1.30        | 9            |                               |                             |
| ④ Clay           | 1.98             | 16.81           | 1.348           | 0.84        | 18           |                               |                             |
| ④ Clay           | 18.60            | 17.15           | 1.244           | 0.74        | 24           |                               |                             |
| ⑤ Silty clay     | 12.92            | 18.15           | 0.976           | 0.55        | 40           |                               |                             |
| ⑥ Silty clay     | 7.00             | 18.10           | 0.963           | 0.71        | 46           | 1000                          |                             |
| ⑦ Silty clay     | 20.00            | 18.16           | 0.983           | 0.48        | 50           | 2000                          |                             |

\(^a\)Thickness is the average thickness of the soil layer.

3. Standard value of ultimate bearing capacity of single pile calculated by Standard
According to the empirical formula in the Standard\cite{8}, the standard value of ultimate bearing capacity of non-grouting single pile is calculated by Formula (1).

\[
Q_{uk} = Q_{sk} + Q_{pk} = \mu \sum \psi_{sl} q_{sl} l_i + \psi_{p} q_{pk} A_p
\]  

(1)

The relevant parameters in Table 1 are substituted into formula (1), and it can be calculated that the standard value of ultimate bearing capacity of non-grouting pile is 8380 kN.

The standard value of ultimate bearing capacity of grouting single pile is calculated by Formula (2).
\[ Q_{uk} = Q_{sk} + Q_{gsk} + Q_{gpk} = u \sum q_{sjk} l_j + u \sum \beta_{si} q_{sik} l_{gi} + \beta_p q_{pk} A_p \]  

(2)

\[ u \] ---- Perimeter of pile  
\[ l_j \] ---- Thickness of \( j \) layer soil which is not reinforced by post-grouting at pile end  
\[ l_{gi} \] ---- Thickness of layer soil which is reinforced by post-grouting at pile end. For grouting only at the pile end, the vertical reinforcement section is within 12 m above pile end  
\[ q_{sjk}, q_{sik}, q_{pk} \] ---- They are respectively the initial ultimate standard values of the side resistance of the \( i \) layer soil which is reinforced by post-grouting at pile end, the initial ultimate standard values of the side resistance of the \( j \) layer soil which is not reinforced by post-grouting at pile end, and the initial ultimate standard end resistance values  
\[ \beta_{si}, \beta_p \] ---- Respectively, the lateral resistance and end resistance enhancement coefficient of the post-grouting pile at the end  

According to Table 5.3.10 in the Standard\(^8\) and \( \beta_s = 1.6, \beta_p = 2.3 \) in the 7th layer of soil, substitute the relevant parameters in Table 1 into formula (2), and it can be calculated the standard value of ultimate bearing capacity of the post-grouting pile is 12632 kN. Therefore, it can be concluded that the standard value of the ultimate bearing capacity of grouting pile at the pile end is 50.7% higher than that of non-grouting pile.

4. \( Q-s \) curve of static load test  
The \( Q-s \) curves (load-settlement curves) of three grouting piles and three non-grouting piles are shown in Figure 1.

It can be seen from Figure 1 that \( Q-s \) curves of three groups of grouting piles (SZ4, SZ5, SZ6) agree well, and those of three groups of non-grouting piles (SZ7, SZ8, SZ9) agree well also, the test data can be credible.

The \( Q-s \) curves of all the piles have a turning point, which indicates that the ultimate load of the piles has been reached. The standard value of ultimate bearing capacity of the non-grouting piles is 7600 kN, while that of the grouting piles is 8800 kN.

It is shown that the standard value of ultimate bearing capacity of the post-grouting pile is 15.8% higher than that of the non-grouting pile.

5. Numerical analysis of single pile static load test  
In order to quantitatively analyze the bearing capacity of the post-grouting pile and the non-grouting pile, and reveal the load transfer law of the super-long pile, the simulation of the static load test is carried out by the Plaxis 2D finite element software.
The axisymmetric model is used in the modeling analysis. The radius of the model is 50 m and the depth is 120 m. The elastic model is adopted for the pile, with a length of 90 m and a diameter of 0.9 m. Mohr-Coulomb model is used for soil, and the soil is classified into four soil layers by similar parameters. After classification, soil layers and the calculated soil parameters are shown in Table 2. The parameters of the silty clay mixed with round gravel with grouting are obtained based on the experience of grouting reinforcement, which is also shown in Table 2.

| Parameter                      | Soil layer                      | Weight/(kN/m³) | Cohesion /kPa | Internal friction angle/° | Compression modulus/MPa | Poisson's ratio |
|-------------------------------|--------------------------------|----------------|---------------|---------------------------|-------------------------|----------------|
| Silt clay                     | 16.3                           | 12             | 10            | 2                         | 0.35                    |                |
| Clay                          | 17.0                           | 22             | 12            | 3.5                       | 0.3                     |                |
| Silty clay                    | 18.0                           | 36             | 17            | 4                         | 0.25                    |                |
| Silty clay mixed with round gravel | 19.0                         | 32.9           | 17.6          | 7.9                       | 0.2                     |                |
| Grouting soil                 | 20.0                           | 100            | 38            | 30                        | 0.2                     |                |

5.1 Effect of grouting diffusion range on bearing capacity

In order to analyze the influence of diffusion range of the post-grouting on the bearing capacity, different diffusion radii are calculated. It is assumed that the cement slurry can spread effectively under the ideal condition and form a certain range of reinforced soil around pile end. Figure 2 shows Q-s curves of different grouting diffusion radius at the pile end by calculated. Table 3 shows the influence of the diffusion range at the pile end on the bearing capacity and deformation.

Figure 2. Q-s curves of different grouting diffusion radius at the pile end by calculated

As shown in Figure 2 and Table 3, with the increase of cement slurry diffusion radius, the bearing capacity is increasing, and the deformation of corresponding loading grade is also decreasing. When the diffusion radius is 0.9 m (1.0 d), the increase coefficient of bearing capacity is 1.12, which is larger than that of the non-grouting. When the grouting diffusion radius is 1.35 m (1.5 d), the increase coefficient of bearing capacity is 1.18. Further increasing grouting radius, the increase of bearing capacity is not obvious, neither is the ability of controlling settlement.
| Pile end reaction ratio\(%\) | 5.78 | 6.58 | 6.78 | 6.91 | 7.22 |
|---------------------------|------|------|------|------|------|
| \(\beta_p\)\(^c\) | 1    | 1.14 | 1.17 | 1.2  | 1.25 |

\(a\) Bearing capacity enhancement coefficient = bearing capacity of grouting pile / bearing capacity of non-grouting pile.

\(b\) Pile end reaction force ratio = pile end force / pile top force.

\(c\) The end resistance enhancement coefficient \(\beta_p = \) grouting pile end resistance / non-grouting pile end resistance, and the pile end resistance refers to the corresponding value of the last point on each \(Q\)-s curve in Fig. 2.

With the increase of the diffusion radius, the pile end reaction force ratio increases. Under the condition of non-grouting, the reaction force at pile end accounts for 5.78% of the load at the pile top. While the diffusion radius of grouting at the pile end is 2.25 m (2.5 \(d\)), the reaction force at the pile end accounts for 7.22% of the load at the pile top. It can be concluded that, for the super-long bored pile, the proportion of load transfer from the pile top to the pile end does not change greatly with the grouting and non-grouting at the pile end.

It can be observed from Table 3 that when the diffusion radius is 0.9 m (1.0 \(d\)), the end resistance enhancement coefficient is 1.14, which is larger than that of non-grouting pile. When the diffusion radius of the grouting at the pile end is 1.35 m (1.5 \(d\)), the coefficient increase of the end resistance is 1.17. Further increasing the grouting radius, the increase of end resistance is not obvious. Even if the grouting radius reached 2.5 \(d\), the increase in end resistance does not exceed 30%.

5.2 Effect of post-grouting height on bearing capacity

After grouting at the pile end, the cement slurry will penetrate upward and occupy the position along the pile side. The Standard\(^{[8]}\) suggests that when grouting at the pile end, the enhancement range of the lateral frictional resistance is about 12 m above the pile end.

In order to study the influence of the cement slurry permeating height on the bearing capacity, different permeating heights are calculated. Figure 3 shows the \(Q\)-s curves of different permeating heights by simulation. And Table 4 is the influence of the grouting height on the bearing capacity and deformation.

![Figure 3. \(Q\)-s curves of different permeating heights by calculated](image)

| Grouting height /m | 0    | 1.35 | 4.05 | 6.75 | 9.45 | 12.15 |
|-------------------|------|------|------|------|------|-------|
| Bearing capacity/kN | 8155 | 9658 | 9842 | 10013| 10109| 10080 |
| Settlement of pile top /mm | 24.9 | 23.0 | 23.2 | 23.1 | 22.9 | 21.8 |
| Bearing capacity Enhancement coefficient | 1.00 | 1.18 | 1.21 | 1.23 | 1.24 | 1.24 |
| \(\beta_s^{b}\) | 1    | 1.12 | 1.31 | 1.43 | 1.52 | 1.66 |

\(a\) The calculation condition is the diffusion radius of 1.35 m.
The friction resistance enhancement coefficient $\beta_s = \frac{\text{side resistance of the grouting pile}}{\text{side resistance of the non-grouting pile}}$, and the side frictional resistance of the pile refers to the corresponding value of the last point on each $Q-s$ curve in Fig. 3.

It is known from Figure 3 and Table 4 that when the height of the cement slurry increases, the bearing capacity is increased as well. When the permeating height is 1.35 m, the bearing capacity will increase by 18%, and it will not increase obviously as the permeating height continues to increase. When the permeating height is 12.15 m, the calculated bearing capacity is increased by 24%.

As the permeating height increases, the average frictional resistance increases in the range of 12 m above the pile end. When the permeating height is 1.35 m, the friction resistance enhancement coefficient in the range of 12 m is 1.12. When the permeating height is 4.05 m, it is 1.31. When the permeating height is 12.15 m, it is 1.66.

6. Discussion on the value of $\beta_s, \beta_p$ in the calculation of bearing capacity of post-grouting super-long bored pile

The numerical value shows that the enhancement coefficient of the pile end resistance is 1.25 when the grouting diffusion radius at the pile end is 2.25 m (2.5 $d$). When the grouting height is 12.15 m, the average frictional resistance enhancement coefficient in the range of 12 m is 1.66. With the numerical calculation enhancement coefficient $\beta_s = 1.66, \beta_p = 1.25$, the standard value of the bearing capacity of a single pile is 9830 kN according to formula (2). If $\beta_s, \beta_p$ are taken according to the Standard[8], the standard value of the ultimate bearing capacity of the post-grouting pile calculated by the formula (2) is 12632 kN.

It can be seen that even if the pile end diffusion radius is 2.5 $d$ and the grouting height reaches 12.0 m, the numerical value of bearing capacity of 9830 kN is much smaller than the calculated bearing capacity of 12632 kN calculated by the Standard[8].

Through simulation, it is found that when the grouting radius at pile end is 1.5 $d$ and the permeating height is 4.05 m, $\beta_s = 1.31, \beta_p = 1.17$ are obtained, and the calculated bearing capacity 9102 kN of the post-grouting pile is close to the measured bearing capacity 8800 kN.

7. Conclusion

(1) After the grouting diffusion radius at the pile end exceeds 1.5 $d$, the increase of bearing capacity is no longer obvious. Even when the grouting radius at the pile end reaches 2.5 $d$, the pile end resistance increases by no more than 30%, which is less than the end resistance enhancement coefficient $\beta_p$ given by the Standard.

(2) Through the reversion analysis of numerical calculation, when the grouting diffusion radius at the pile end is 1.5 $d$ and the permeating height from the pile end is 4.05 m, the enhancement coefficients of the side resistance and the end resistance are respectively $\beta_s = 1.31, \beta_p = 1.17$. Then the bearing capacity is calculated with $\beta_s = 1.31, \beta_p = 1.17$ according to the formula of the Standard, which is close to the measured value of bearing capacity of the post-grouting pile. The simulation calculated $Q-s$ curve is similar to the measured $Q-s$ curve.

(3) Super-long pile with post-grouting will increase the bearing capacity, but the improvement value should not be too large. The range of grouting diffusion (reinforcement) is limited, and the load is finally transferred to the surrounding soil outside the reinforcement. The surrounding soil without reinforcement still has the original physical and mechanical parameters, and the thickness of the compression layer under the pile end has not changed significantly, so it is difficult to change the bearing capacity and deformation characteristics of the grouting pile substantially.

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