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Post-grouting bored pile technology

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Abstract. Post-grouting is an effective technology to modify the shortcomings of thick bottom slime and shaft mudcake for the slurry bored pile. Construction procedure, parameter selection and strengthening mechanism of post-grouting bored pile had been introduced in this paper. Development of study on physical and mechanical properties of surrounding soil post-grouted was summarized. The bearing capacity behaviour and deformation properties of the pile were also analyzed. It will provide some advice for the research and application of post-grouting bored pile.

1. Introduction

In1864, the United Kingdom firstly used the shaft cement grouting in Allihn Puri Bei mine to shut off water. From that time on, the grouting technology has been widely used in the foundation reinforcement and the treatment of bad geological phenomena. In 1961, Venezuela Maracaibo bridge foundation engineering used the grouting pipe to grout the pile foundation. This was the first report of the grouting technology's application in pile foundation reinforcement project. Because of the continual application of grouting technology in the construction of grouting piles, there are relatively perfect post-grouting bored pile construction technologies, including the pile-end grouting, the pile-surrounding grouting and the pile-end and pile-surrounding association grouting, are gradually formed[1, 2]. In addition, deeper and deeper researches on the optimization of post-grouting bored piles' construction technology, the reinforcement mechanism, the bearing capacity and deformation characteristics are done.

2. Construction technology of post-grouting bored pile

2.1. Construction process for post-grouting technology

The post-grouting bored pile technology means that after the borehole grouting piles are formed, a certain amount of cement serous fluid will be injected to the pile-surrounding mud cake, the pile-bottom sediment and the soil layer around the pile under certain pressure through the grouting pipe embedded in the pile body so that the bearing capacity of the pile foundation can be improved. When the pile-end and pile-surrounding association grouting way is used, in order to prevent the serous fluid from emerging along the pile-surrounding weak plane during the pile-end grouting process, the pile-surrounding grouting shall be used firstly for plugging before the conduction of the pile-end grouting.

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Similarly, when the multilayer pile-surrounding grouting way is adopted, operations shall be done from the top to down layer after layer.

2.2. Selection of grouting parameters

2.2.1. Grouting quantity. The grouting quantity is determined by the pile diameter, the pile length, the characteristics of soil layer around the pile and the bearing capacity's improvement requirements. LIU Jinli, etc[2] puts forward the following formula:

Pile-end grouting quantity:

$$G_P = \pi\left(h \cdot t \cdot d + \xi \cdot n_0 \cdot d^3\right)\times 1000 \tag{1}$$

Pile-surrounding grouting quantity:

$$G_s = \pi\left[t \cdot (L-h) + \xi \cdot m_0 \cdot n_0 \cdot d^3\right]\times 1000 \tag{2}$$

In the formula, d means the pile diameter; L means the pile length; h means the upward returning height of the serous fluid along the pile surroundings during the pile-bottom grouting operations; t means the thickness of the serous fluid wrapped in pile surroundings and its value is related to properties of soil around the pile and the construction quality of the grouting pile. The value range is generally between 5mm and 20mm. n_0 is the natural porosity of the pile-bottom soil or the pile-surrounding soil. ξ is the grouting rate and its value for gravels and medium sand is between 0.3 and 0.7 while that is between 0.2 and 0.3 for clayey soil, floury soil and sandy silt. m_0 is the number of cross sections of the pile-surrounding grouting petals. According to the point distribution situations of the longitudinal wave, the value of m_0 is 1/4 of the number of the grouting points.

2.2.2. Grouting pressure. Grouting pressure refers to the biggest pressure to be used when the earth's surface does not rise and the foundation piles are not greatly lifted. The grouting pressure value is related to the density, strength and initial stress of the soil layer, the borehole depth, the grouting location, the grouting sequence and other factors. Some of the factors are difficult to predict. Therefore, they shall be determined by the on-site pile testing. The grouting pressure of soil layers with good groutability is under 4MPa generally while that of the soil layer with bad groutability is between 4MPa and 8MPa.

2.2.3. Concentration of the serous fluid. Serous fluid with different concentration may have different behavioral characteristics. Thin paste (with the water-cement ratio of about 0.8:1) has strong fluidity which is suitable for permeating and strengthening pile-surrounding and pile-bottom loose soils. Serous fluid of medium concentration (with the water-cement ratio of about 0.6:1) mainly plays the role of filling, densification and compaction. Thick slurry (with the water-cement ratio of about 0.4:1) is used for dehydration of cement serous fluid already injected [3]. Thus, more than one grouting can be done and the cement serous fluid can be injected from thin to thick one level after another. In addition, the method of corresponding grouting pressure can also be used to enhance the grouting effect.

Engineering practice shows that if the thick slurry with the water-cement ratio of 0.5~0.55 is used; better grouting effects can be achieved.

2.3. Applicable soil layer of grouting

The serous fluid has different diffusion areas in different soil layers. Therefore, the selection of the grouting soil layer has a significant influence on the improvement range of the bearing capacity of the post-grouting bored pile. The coarser the soil particles are, the larger permeation range of the serous fluid will be. If the pile-end supporting layer belongs to the thin gravel layer, the diffusion radius of the grouting can reach more than 3.5 times of the pile diameter [3]. In soil layers with small soil particles, the serous fluid is not distributed continuously and it is not uniformly filled. Most of them are distributed with thin stratified structures. In addition, their thickness varies greatly and it is relatively hard to mix the slurry and the soil particles. The contrastive analysis of a large amount of on-site static load pile testing results shows that the increasing range of the pile-bottom grouted pile's bearing capacity will increase when soil particles of the pile-end supporting layer become larger. The gravel layer is the most ideal pile-bottom grouting layer [4].

3. Post-grouting reinforcement mechanism

At present, in-depth researches have been done to the pressure grouting theory. The technology of the post-grouting bored pile is used as the grouting technology for the reinforcement of the pile foundation and its reinforcement mechanism is similar with that of the traditional grouting technology.

3.1. Mechanism of post-grouting cement serous fluid

(1) Permeation and solidification.
The serous fluid can be injected to a certain range of the sandy soils and gravelly soils with strong permeability and good groutability under low pressure so as to form the stone body with good structure and high strength, to expand the pile-end bearing area and to enhance the pile-end bearing capacity.

(2) Cementing mud cake.
During the pile-surrounding grouting process, the cement serous fluid will squeeze and split off weak mud cakes around the pile and will cement near the piles again so as to form bamboo-like cement reinforced bodies of high strength and to tighten them near the pile. Generally speaking, its thickness is between 2mm and 20mm [2], which is shown as Figure 1.

(3) Filling.
The serous fluid with large concentration will be used to fill soil pores and to compact the pile-surrounding soils with strength reduced because of stress relief and the pile-bottom loose sediment under certain pressure so as to reduce the porous ratio, to solidify the soil again and to enhance the compressive strength of the soil. They can be shown in Figure 2.

(4) Cleaving reinforced strips.
When the grouting pressure is high, the cement serous fluid can overcome the soil resistance and have a cleaving effect on the soil layer, which will form the mesh stone, have the reinforced function to the soil and reduce the non-uniform sedimentation of the pile group. They can be shown in Figure 3.

Through the in-house model experimental study, GAO Wensheng [4] concludes that if the pile-end serous fluid is injected to the floury soil to form the cement stone body, they are out-of-shape and basically belong to the compaction grouting. If the pile-end serous fluid is injected to gravel layer, it will uniformly permeate, will spread to the gravel layer and will condense with the gravel to form the low-grade concrete so as to largely form a rounded expansion chassis on the pile-bottom supporting layer and this belongs to the permeation grouting.

Figure 1. Reinforcement effect of shaft mudcake

Figure 2. Seep-in and compaction effect

Figure 3. Spliting effect

3.2. Changes of physical and mechanical properties of the soil after the grouting process

After the grouting process, the effective stress, the internal friction angle and the cohesive force of the soil mass will be enhanced and the shearing strength of the soil mass will also be increased. Changes of physical and mechanical properties of the soil are closely related to the grouting quantity. Zhang Zhongmiao, etc [5] conduct laboratory experiments on mud-cement mixed soil samples which have been solidified for 30 days. When the cement mixing amount increases from 10% to 40%, the moisture content of the mud soil samples will drop from 253.5% to 63.6%; the porous ratio will drop from 7.52 to 2.25; the compression modulus will be improved from 1.86MPa to 8.96MPa; the cohesive force will be enhanced from 2kPa to18kPa and the internal friction angle will be enlarged from 0.5° to 19°. Through in-house laboratory investigation, MA Hailong [6] concludes the relationship among changes of the muddy clay weight, the permeability coefficient, undrained shear strength, the internal friction angle, the unconfined compressive strength, the coefficient of compressibility and the compression modulus and the cement mixing amount. When the cement mixing amount is 20%, the compression modulus can be enhanced for 40 times. These two experiments all use the homogeneous cement soils formed by intensively mixing the fine-grained soil and the cement serous fluid as the objects of study. There are great differences between it and the heterogeneous cement soil formed in the practical grouting project.

In soil layers with small soil particles, the cement paste is discontinuously distributed and non-uniformly filled. They are mostly distributed with the thin stratified structure and their thickness does not vary greatly, which is generally between 0.2cm and 20cm. In addition, it is forbidden to mix the slurry and the soil particles [7]. The grouting reinforced bodies formed in sandy soils and other soil layers with more coarse-grained soil particles and good permeability tend to have high strength. In laboratory model experiments, GAO Wensheng [4] conducts uniaxial compressive strength test to the pile-end grouting reinforced body in the gravel supporting layer and the average ultimate strength he measured is 11.46MPa, which is equivalent to the concrete with the strength level of C15.

After the grouting process, changes of physical and mechanical parameters of soils also lead to changes of soil yield functions. Under the effect of the external loads, the elastic range of the rock and earth mass significantly becomes larger while the yield range of the plastic shear strain and the yield range of the volumetric strain becomes more geographically dispersed rather than relatively centralized before the grouting. In addition, the overall size becomes relatively small, but the stability and bearing capacity of the rock and earth mass are greatly enhanced [8].

4. Deformation characteristics of bearing capacity of post-grouting bored piles

After the grouting process, because of the difference of the grouting soil layer, the grouting types, the length-diameter ratio of the pile and the construction technology, the bearing capacity of the grouting pile can be improved for 20% to 150% [4] or more.

For common grouting piles, their ends often display the penetrating shear failure and their load sedimentation curves have obvious inflection points. The post-grouting bored pile strengthens the pile-end loose sediment and the pile-end disturbed soil layers, removes the pile-bottom "cushion" and forms a pile-end reinforced body of large strength. It is generally shown as the local shear failure and the load sedimentation curve tends to be mild. In addition, the sedimentation amount also reduced, which is shown in Figure 4 [9]

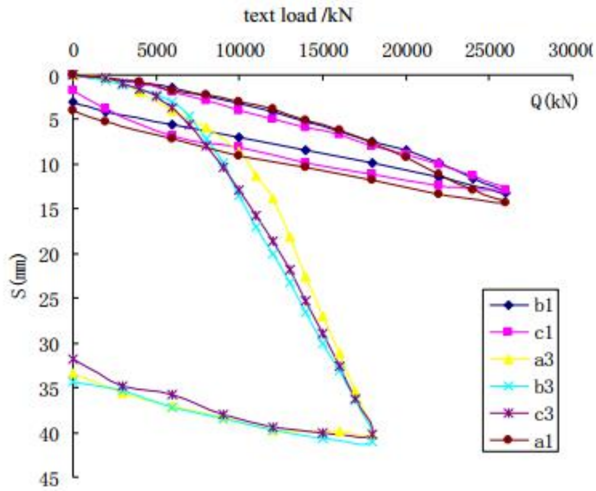

Figure 4. Comparison in load-settkenebt curves

Notes: a1, b1 and c1 are non-post-grouting bored piles while a3, b3 and c3 are post-grouting bored piles.

Pile-end and pile-surrounding bearing capacities are all enhanced to different degrees. After the serous fluid of the pile-surrounding grouting cement solidify the mud cake, a hard shell layer tightly fixed on the pile body will be formed. Gao Wenling [4] does a direct shear test relative to the pile body and he measures that the ultimate shearing strength when there is a relative slippage between the pile- surrounding reinforced body and the pile body is 780kPa, which is about 10 times of the pile-surrounding frictional resistance of good foundation soil. In addition, he judges that the shear failure envelope between the pile and the soil will inevitably occur outside the pile-surrounding reinforced body, which means that the grouting has a "Diameter Expansion Effect" on the grouting pile. After the grouting process, the improvement of the compression modulus of the pile-surrounding soils, the reinforcement of the pile-surrounding shear weak surface and the "Diameter Expansion Effect" of the pile all help enhance the pile-surrounding ultimate frictional resistance. The pile-end grouting will solidify the pile-bottom loose sediment. The high strength cement soil at the bottom of the pile will be connected with the pile body and play the "Base Expansion Effect". Besides, the total end resistance will be significantly increased. The seepage consolidation and the cleaving stiffening effect of the post-grouting strengthen soil layers of the pile-bottom sliding surfaces, improving the cohesive force of the soil and its internal friction angle and enhancing the pile-end bearing capacity.

The grouting has an obvious effect on load transmission characteristics of piles. Under the pile top load effect of the non-grouted pile, the axial force will pass down gradually and the lateral resistance will also be played from top to bottom. After the pile-top displacement reaches a certain degree, the resistance will begin to take effect. However, under the pile-end pressure effect, the grouted pile exerts a prestressing force to the pile from bottom to top. In addition, the pile-end soil body and the soils around the pile of some range finish some deformations in advance. This way can make the pile-end resistance plays its role from the beginning, which will fully play the strength of the soil and greatly enhance the bearing capacity and reduce the sedimentation amount.

5. Conclusion

(1) Deep theories and experiment researches have been done to the post-grouting reinforcement mechanism. The cement serous fluid can enhance the soil strength through permeation, compaction, glue joint and cleaving effect. Under the effect of the load, the elastic range of the soil will be enlarged while the plastic range tends to be relatively dispersed.

(2) The post-grouting brings obvious changes to grouting piles' characteristics. Because of the "Diameter Expansion Effect" and the "Base Expansion Effect" generated by the grouting, the pile-surrounding frictional resistance and the pile-end resistance are greatly increased. After the grouting process, the grouting pile-end resistance is played in advance and the time difference between them is reduced.

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