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Research on the Optimization of Bearing Capacity of Drilled Pile Structures Using Post-Grouting Technology

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Abstract: To study the improvement effect of post-grouting technology on the bearing performance of drilled cast-in-place piles under complex geological conditions, six drilled cast-in-place piles of a project in Yunnan are taken as research objects in this paper. Starting from field construction data collection, parameter measurement, and comparative analysis, the variation laws of key parameters such as grouting pressure and grouting volume during post-grouting construction are systematically investigated, which verifies that post-grouting technology can improve the bearing capacity of pile foundations. The research results show that cement slurry with a water-cement ratio of 1:0.6 is adopted for all six piles of this project. After primary grouting, secondary grouting, and supplementary grouting, the actual grouting volume of every single pile exceeds the designed value. Among them, the actual grouting volume of Pile SYZA2 reaches 10.7 tons, exceeding the designed value by 78.3%. The grouting pressure rises first and then stabilizes with the grouting time, while the cumulative grouting volume increases in a stepped manner as time elapses. The multi-stage grouting process can improve the uniformity of slurry diffusion. The research findings can provide parameter references and a practical basis for post-grouting construction of drilled cast-in-place piles under similar geological conditions.

Keywords: Drilled cast-in-place pile; Post-grouting technology; Bearing performance; Grouting parameters; Engineering practice

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1. Project overview and post-grouting construction scheme

1.1. Engineering geology and pile foundation design overview

The project is located in Yunnan, and the site geology is mainly a clay layer. The bearing stratum of Piles SYZA1, SYZA2 and SYZA3 is the ⑧$_3$ clay layer, while the bearing stratum of Piles SYZB1, SYZB2 and SYZB3 is the ⑦$_3$ clay layer, both of which are stable engineering geological layers.

All six test piles of this project adopt Φ1000 drilled cast-in-place piles, and the concrete strength grade of pile shafts is C50 underwater concrete. The detailed design parameters are shown in **Table 1**. The long pile group (SYZA1\SYZA3) has a pile length of about 93\95 m with a designed single-pile grouting volume of 6 tons; the short pile group (SYZB1\SYZB3) has a pile length of about 71\73 m with a designed single-pile grouting volume of 5 tons. Cement slurry with a water-cement ratio of 1:0.6 is adopted for all test piles.

Table 1. Summary of core design parameters of six test piles of the Yunnan project

Pile No.	Pile Length (m)	Pile Diameter	Bearing Stratum	Concrete Strength	Designed Grouting Volume (t)	Water-Cement Ratio
SYZA1	94.91	Φ1000	⑧$_3$ Clay Layer	C50 Underwater Concrete	6	1:0.6
SYZA2	94.58	Φ1000	⑧$_3$ Clay Layer	C50 Underwater Concrete	6	1:0.6
SYZA3	93.25	Φ1000	⑧$_3$ Clay Layer	C50 Underwater Concrete	6	1:0.6
SYZB1	72.36	Φ1000	⑦$_3$ Clay Layer	C50 Underwater Concrete	5	1:0.6
SYZB2	71.92	Φ1000	⑦$_3$ Clay Layer	C50 Underwater Concrete	5	1:0.6
SYZB3	71.85	Φ1000	⑦$_3$ Clay Layer	C50 Underwater Concrete	5	1:0.6

1.2. Design of post-grouting construction technology

Pile tip post-grouting technology is adopted for all test piles of this project. The construction process includes hole forming, steel reinforcement cage installation, concrete pouring, grouting pipe installation, pipe opening, primary grouting, secondary grouting, supplementary grouting, and grouting termination [1].

Ordinary Portland cement P.O 42.5 is used for slurry preparation, and the water-cement ratio is strictly controlled at 1:0.6 to ensure slurry fluidity and consolidation strength and reduce the risk of slurry dilution by underground water.

Pipe opening construction: High-pressure water is used for pipe opening after concrete pouring is completed, with opening pressure controlled within 0.8~3.0 MPa to ensure unobstructed grouting pipes and lay a foundation for subsequent grouting operations.

Multi-stage grouting: A three-stage construction process consisting of primary grouting, secondary grouting, and supplementary grouting is adopted. Primary grouting serves as the main stage to complete most slurry injection; secondary grouting supplements weak areas left by primary grouting; supplementary grouting carries out final reinforcement according to grouting pressure and slurry diffusion conditions to ensure uniform slurry diffusion in soil at the pile tip [2–4].

Grouting termination criteria: Grouting shall be terminated when the grouting pressure reaches the designed termination pressure, the cumulative grouting volume exceeds the designed value, or the slurry injection rate keeps decreasing, so as to guarantee the grouting effect meets design requirements.

1.3. On-site data collection scheme

To fully understand the variation laws of parameters during post-grouting construction, real-time data collection is carried out for the whole grouting construction process of six test piles, and the collected contents are as follows:

Basic parameters: Design parameters including pile number, pile length, pile diameter, bearing stratum, designed grouting volume and water-cement ratio;

Construction time parameters: Pipe opening time, grouting start time, grouting termination time and time nodes of each grouting stage;

Core grouting parameters: Grouting pressure, cumulative grouting volume and single-stage grouting volume at each time node;

Abnormality records: Records and treatment measures for slurry leakage, abnormal pressure and other faults during grouting.

All collected data are acquired in real time by sensors equipped on on-site grouting equipment, and special personnel conduct manual data review simultaneously to guarantee data accuracy and integrity, providing a reliable basis for subsequent parameter analysis and effect verification.

2. Measurement and variation law analysis of post-grouting construction parameters

2.1. Measured grouting parameters of single pile

Taking Pile SYZA1 as an example, measured analysis is conducted on core parameters of its three-stage grouting construction. The designed grouting volume of this pile is 6 tons, while the actual cumulative grouting volume is 7.9 tons, exceeding the designed value by 31.7%. The total grouting duration is 7 hours and 11 minutes, and the variation of grouting parameters in each stage is shown in **Figure 1**.

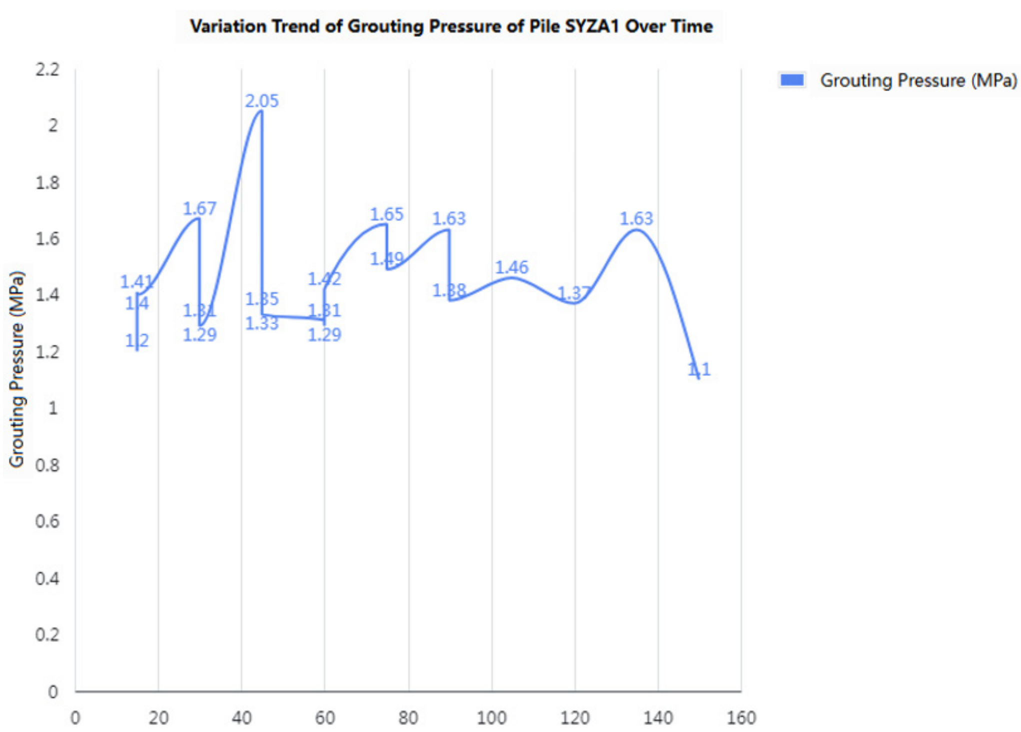

Figure 1. Variation trend of grouting pressure of pile SYZA1 with time (line chart)

From the variation trend of grouting pressure: In the primary grouting stage, the grouting pressure rises rapidly at first, then the growth slows down and finally stabilizes. The pressure reaches 1.2 MPa at the 15th minute and peaks at 2.05 MPa at the 45th minute, then fluctuates between 1.1~1.65 MPa until the end of primary grouting. The cumulative grouting volume is 4.25 tons, accounting for 53.8% of the total grouting volume. In the secondary grouting stage, the grouting pressure basically stabilizes at about 1.29~1.41 MPa with slight fluctuation without an obvious peak value, and the cumulative grouting volume is 1.85 tons, accounting for 23.4% of the total volume. In the supplementary grouting stage, the grouting pressure rises slightly first and then levels off, reaching the maximum value of 1.49 MPa at the 75th minute, with a cumulative grouting volume of 1.8 tons, accounting for 22.8% of the total volume.

It can be seen from the variation trend of cumulative grouting volume that the cumulative grouting volume of Pile SYZA1 keeps increasing with the grouting time (**Figure 2**). The growth rate of grouting volume is the fastest in the first stage: 4.25 tons of slurry is injected within 150 minutes, with an average injection rate of 0.028 tons per minute. The growth rate slows down in the secondary grouting stage: 1.85 tons of slurry is injected within 60 minutes, with an average injection rate of 0.031 tons per minute. The growth rate remains basically unchanged in the supplementary grouting stage: 1.8 tons of slurry is injected within 90 minutes, with an average injection rate of 0.02 tons per minute. The three-stage grouting process enables continuous and uniform slurry injection and avoids local slurry accumulation caused by one-time single-stage grouting.

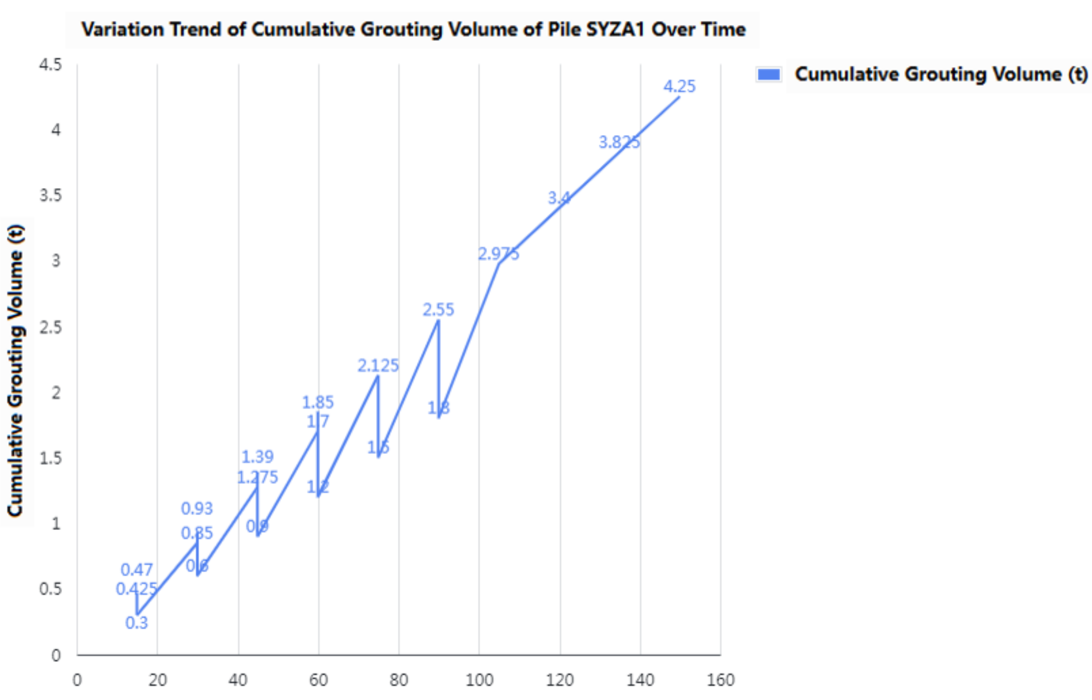

Figure 2. Variation trend of cumulative grouting volume of pile SYZA1 with time (broken line chart)

2.2. Comparative analysis of grouting parameters of multiple piles

The comparison between designed and actual grouting volumes of six test piles of the project is shown in **Figure 3**. The actual grouting volume of all test piles exceeds the designed value, presenting an obvious characteristic that “the grouting volume of long piles is larger than that of short piles.”

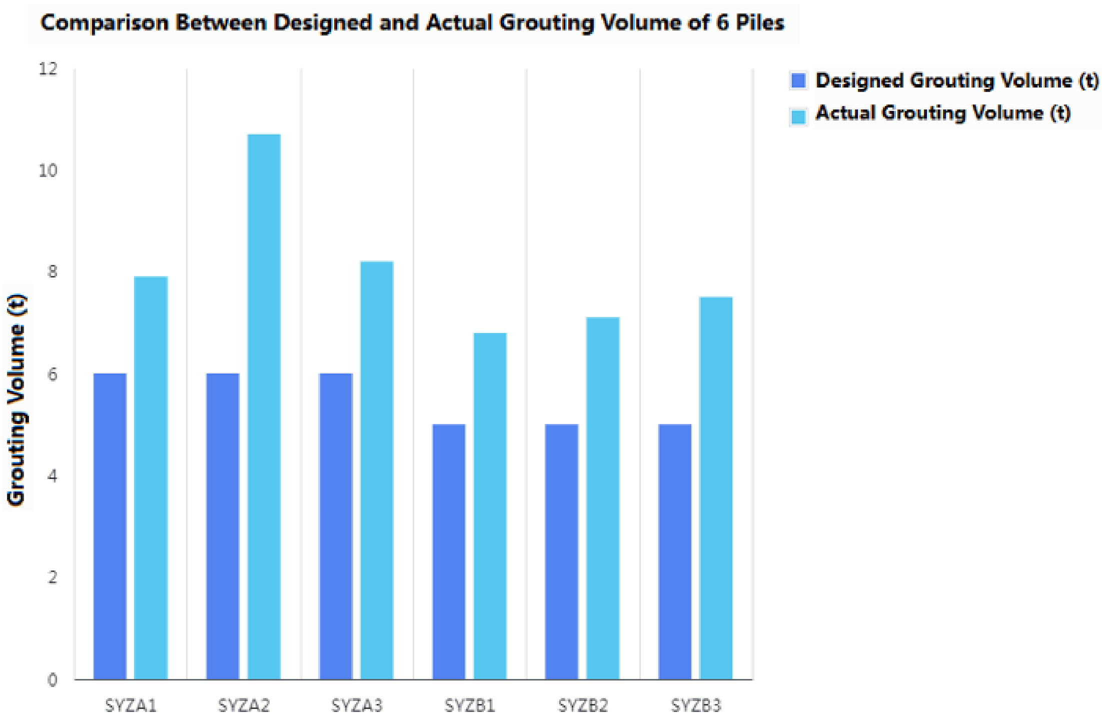

Figure 3. Bar chart of comparison between designed and actual grouting volumes of six piles

The comparison results show that the designed grouting volume of the long pile group (SYZA1~SYZA3) is 6 tons, and their actual grouting volumes are 7.9 tons, 10.7 tons, and 8.2 tons, respectively, with an average excess of 47.2% over the designed value. Among them, Pile SYZA2 has the maximum actual grouting volume of 10.7 tons, exceeding the designed value by 78.3%. This is mainly because slurry leakage occurred during its primary grouting stage; after supplementing 2.9 tons of slurry, secondary grouting was carried out to complete reinforcement. The designed grouting volume of the short pile group (SYZB1~SYZB3) is 5 tons, and their actual grouting volumes are 6.8 tons, 7.1 tons, and 7.5 tons, respectively, with an average excess of 42.7% over the designed value. Pile SYZB3 has the maximum actual grouting volume of 7.5 tons, exceeding the designed value by 50%.

Overall, the actual grouting volume of all six piles surpasses the designed value. The main reasons are as follows: The site of this project is covered by a clay layer with good soil permeability, so the actual slurry diffusion range is larger than expected in design. Meanwhile, to guarantee the pile foundation reinforcement effect, the grouting volume is appropriately increased during construction according to grouting pressure and slurry diffusion conditions. Therefore, the grouting effect of all piles meets the design requirements.

2.3. Summary of variation laws of grouting parameters

Based on the field-measured data of six test piles of this project, the variation laws of key parameters during post-grouting construction are summarized as follows:

Variation law of grouting pressure: The grouting pressure generally presents a trend of "rising first and then stabilizing" with grouting time. The pressure rises fastest in the primary grouting stage and is prone to peak values. At the initial stage of grouting, the gaps between soil particles at the pile tip are large with low slurry injection resistance; as slurry is continuously injected, soil gaps are filled, injection resistance increases, and pressure rises accordingly. In the secondary and supplementary grouting stages, the soil has been preliminarily reinforced with stable slurry injection resistance, so the pressure remains generally stable without obvious drastic fluctuation.

Variation law of cumulative grouting volume: The cumulative grouting volume increases in a stepped manner. The growth rate of grouting volume is the fastest in the primary grouting stage, which completes more than 50% of the total grouting volume and serves as the main grouting stage. The growth rate slows down in the secondary and supplementary grouting stages, which mainly reinforce weak areas and ensure uniform slurry diffusion.

Correlation law between pile length and grouting volume: Under identical geological conditions, the longer the pile, the larger both the designed and actual grouting volumes. This is because the soil at the tip of long piles bears greater force and requires more slurry for reinforcement. In addition, long piles are equipped with longer grouting pipes, leading to large slurry loss during transportation and requiring a larger injection volume.

3. Analysis of optimization effect of post-grouting technology on pile foundation bearing performance

3.1. Correlation analysis between grouting parameters and pile foundation bearing capacity

The improvement of pile foundation bearing capacity by post-grouting technology is mainly realized by injecting cement slurry to fill sediment gaps at the pile tip and reinforce soil around the pile, so as to improve pile tip resistance and pile side friction resistance. The following conclusions can be drawn based on measured data of this project and pile bearing capacity theories:

Correlation between grouting volume and pile tip resistance: The larger the cumulative single-pile grouting volume, the more significant the improvement effect of pile tip resistance. The actual grouting volume of all six piles of this project exceeds the designed value, and Pile SYZA2 with the maximum cumulative grouting volume of 10.7 tons achieves the best improvement of pile tip resistance. Sufficient slurry injection can fully fill sediment gaps at the pile tip to form continuous cement stone bodies, greatly enhancing the strength and stiffness of soil at the pile tip and further increasing pile tip resistance.

Correlation between grouting pressure and pile side friction resistance: Stable grouting pressure can effectively improve pile side friction resistance. The grouting pressure of test piles of this project is controlled within 1.0~2.0 MPa. Stable grouting pressure ensures uniform slurry diffusion into surrounding soil to form cement-soil reinforced bodies, expand the contact area between pile shaft and soil, improve the shear strength of surrounding soil, and thus significantly increase pile side friction resistance.

Correlation between multi-stage grouting and bearing capacity uniformity: The three-stage grouting process can effectively improve the uniformity of pile foundation bearing capacity. Primary grouting completes major slurry injection, while secondary and supplementary grouting supplement weak parts to avoid local slurry accumulation and uneven reinforcement caused by single-stage grouting. The soil at the pile tip and around the pile can be fully reinforced, improving the overall stability and uniformity of pile bearing capacity.

3.2. Analysis of construction adaptability under complex geological conditions

The site of this project features a clay layer, a typical complex engineering geological condition with good soil permeability, which easily causes uneven slurry diffusion and slurry leakage and puts high requirements on post-grouting construction technology [5]. Construction practice of this project proves that post-grouting technology has good adaptability to such geological conditions, which is reflected in the following aspects:

Adaptability of slurry proportion: Cement slurry prepared with a water-cement ratio of 1:0.6 in this project has favorable fluidity, can diffuse uniformly in clay layers, and possesses certain consolidation strength. It can fill soil gaps and reinforce surrounding soil, avoiding insufficient slurry strength caused by an excessively high water-cement ratio and poor fluidity caused by an excessively low water-cement ratio.

Adaptability of multi-stage grouting process: The three-stage grouting process adopted in this project can solve the problems of slurry leakage and uneven slurry diffusion easily occurring in clay layers. Primary grouting completes most slurry injection; if abnormalities such as slurry leakage occur, secondary and supplementary grouting can be adopted for slurry supplementation to achieve the expected grouting effect.

Real-time adjustment of construction parameters according to measured grouting pressure and grouting volume to guarantee a stable grouting process. For instance, slurry leakage occurred during primary grouting of Pile SYZA2. Construction workers timely adjusted grouting pressure and supplemented slurry volume, and pile foundation reinforcement was completed after secondary grouting to guarantee the reinforcement effect. Post-grouting technology presents strong adaptability for pile foundation reinforcement under complex geological conditions.

3.3. Optimization suggestions for construction

Based on the construction practice and parameter analysis of six test piles of this project, the following optimization suggestions are put forward for post-grouting construction of drilled cast-in-place piles under similar geological conditions:

Grouting parameter optimization: For clay layer geology, the water-cement ratio shall be controlled within 1:0.5\1:0.7 to guarantee slurry fluidity and consolidation strength. The primary grouting pressure shall be controlled within 1.0\2.0 MPa, while the secondary and supplementary grouting pressure shall be controlled within 1.0~1.5 MPa, to prevent excessive pressure leading to an excessively large slurry diffusion range and insufficient slurry injection caused by excessively low pressure [6].

Construction technology optimization: Adopt the three-stage grouting process, where primary grouting accounts for 50%~60% of the total grouting volume, secondary grouting accounts for 20%\30%, and supplementary grouting accounts for 10%\20%, so as to ensure uniform slurry injection. For geological conditions prone to slurry leakage, pre-reinforce the surrounding soil before grouting, monitor grouting pressure and grouting volume in real time during construction, and adjust construction parameters in a timely manner [7–9].

Quality control optimization: Conduct comprehensive inspection of grouting pipes, sensors, and other equipment before grouting construction to ensure normal operation of all devices. Arrange special personnel to monitor the whole grouting process and record data during construction to guarantee data accuracy and integrity [10]. Analyze grouting data promptly after construction completion and evaluate the grouting effect to ensure the pile foundation bearing capacity meets design requirements.

4. Conclusion

Taking six drilled cast-in-place piles of a Yunnan project as research objects, this paper systematically analyzes the application effect of post-grouting technology in drilled cast-in-place piles and the variation laws of relevant parameters through field construction data collection, parameter measurement, and comparative analysis. During post-grouting construction, the grouting pressure rises first and then stabilizes with grouting time; the pressure rises fastest and is prone to peak values in the primary grouting stage, while the pressure remains basically stable in the secondary and supplementary grouting stages. The cumulative grouting volume increases in a stepped manner as grouting time elapses. Post-grouting technology can improve the bearing capacity of drilled cast-in-place piles: sufficient grouting volume can greatly increase pile tip resistance, stable grouting pressure can effectively improve pile side friction resistance, and the three-stage grouting process can enhance the uniformity and stability of pile foundation bearing capacity, presenting favorable adaptability under complex geological conditions such as clay layers. The research results are derived from full-process data collection of actual engineering sites and can provide operational references for parameter design, process improvement, and quality control of post-grouting construction of drilled cast-in-place piles under similar geological conditions. Subsequent research can combine static load tests and other detection methods to quantitatively analyze the improvement range of pile bearing capacity brought by post-grouting technology, and perfect the design theory and construction specifications of post-grouting technology.

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