Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 2648732, 9 pages
https://doi.org/10.1155/2019/2648732

Research Article

Research on Disaster-Control Method of Metro Station in Soft Fluid-Plastic Stratum

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Received 12 September 2018; Revised 7 December 2018; Accepted 14 February 2019; Published 1 April 2019

Academic Editor: Khalid Abdel-Rahman

Soft and broken ground is a common geological condition for subway pit water damage. The complex hydrogeological environment is the main cause of frequent disasters. It relied on the inrush water project of the soft fluid-plastic stratum in the pit of the Shang Yuanmen station in Nanjing. And based on the geological data and the actual site of the project, the station was evaluated for hazards and analysis of major and difficult points. Combined with a variety of geophysical exploration methods, the source of water in the foundation pit and the key areas for pulp reinforcement was obtained. Based on field tests and indoor tests of grouting reinforcement, the parameters before and after grouting reinforcement were analyzed. The effect of material proportioning and grouting pressure on the parameters of stratum reinforcement was studied. It revealed the effect of the behavioral mechanism of material properties and grouting pressure on different mechanical indexes. It creatively proposes a localized controlled grouting process and uses COMSOL modeling to explain its reinforcement mechanism. In addition, foundation pits applied a full set of monitoring system. Finally, a complete set of comprehensive control methods were formed for water inrush in soft fluid-plastic stratum of complex urban strata. Then, the methods are implemented at the project site. Practice has proved that this method successfully seals the inrush water and reinforces foundation pits while ensuring the safety of foundation pits and surrounding construction pipelines. It is hoped that this method can be used as a reference for similar projects.

1. Introduction

During the construction of urban underground projects, they often pass through water-rich and weak formations. Among them, the formation of soft a fluid-plastic stratum is typical. Because of the poor self-stabilization of the stratum and the low strength of cement, it is easy to lose stability under the influence of engineering disturbances and groundwater and induce landslides. Major engineering disasters such as flooding and inrush water and mud [1–3] have resulted in casualties, economic losses, and delays in the construction period. During the construction of underground engineering in the soft fluid-plastic stratum, it is likely to cause cracks and collapses in urban roads and cause damage to underground pipelines and buildings.

During the process of underground engineering crossing the rich water-weak stratum, the grouting reinforcement method is usually used to improve the physical and mechanical properties of the formation so that it can meet the requirements of the project construction. In view of the problem of grouting reinforcement in the soft fluid-plastic stratum, many scholars have conducted research studies on the engineering properties and management of grouting techniques and grouting materials [4, 5]. Yang et al. [4] studied the grouting improvement problem of the high water level soft fluid-plastic stratum based on the strength of grouting material reinforcement, initial setting time, and fluidity requirement. Du and others [6, 7] passed the indoor matching test. The permeation characteristics and change law of weathered crushing rock mass under different clay content and different axial pressure were studied. Yang et al. and others [8–10] studied the mechanical properties of after-grouting reinforcement of broken rock samples. The influence of slurry on the grouting effect was studied in related experiments. Liu and Liu et al. [11, 12] established the grouting material selection basis and grouting parameter determination method in grouting treatment through the tracer test analysis method. Ren and others [13–16] studied the deformation and strength of weak and broken rock mass after consolidation by grouting and considered that the deformation and strength of rock mass depend on factors such as the injected rock mass and grouting material. The above studies have promoted the development of grouting reinforcement theory and engineering practice, but all of them are based on targeted research of the soft fluid-plastic stratum, and lack of systematic research on disaster management methods, especially disaster management research under complex urban environments is even rarer.

This article relied on the inrush water project of the soft fluid-plastic stratum in the pit of the Shang Yuanmen station in Nanjing. And based on the geological data and the actual site of the project, the station was evaluated for hazards and analysis of major and difficult points. Combined with a variety of geophysical exploration methods, the source of water in the foundation pit and the key areas for pulp reinforcement was obtained. Based on field tests and indoor tests of grouting reinforcement, the parameters before and after grouting reinforcement were analyzed. The effect of material proportioning and grouting pressure on the parameters of stratum reinforcement was studied. It revealed the effect of the behavioral mechanism of material properties and grouting pressure on different mechanical indexes. It creatively proposes a localized controlled grouting process and uses COMSOL modeling to explain its reinforcement mechanism. In addition, foundation pits applied a full set of monitoring system. Finally, a complete set of comprehensive control methods were formed for water inrush in soft fluid-plastic stratum of complex urban strata. Then, methods are implemented at the project site. Practice has proved that this method successfully seals the inrush water and reinforces foundation pits while ensuring the safety of foundation pits and surrounding construction pipelines. It is hoped that this method can be used as a reference for similar projects.

2. Project Overview

2.1. Engineering Introduction. Shang Yuanmen station [17] is located in the Nanjing Metro China, about 400 m from the Chang Jiang River. The station pit is adjacent to two civil buildings. There are national defense optical cables and water supply pipelines below the pavement. Therefore, the surrounding buildings and the underground pipelines of the road are extremely complicated. When the excavation was carried out to a depth of 18 m, multiple water inflow points were exposed, and water inflow was gradually increased. The maximum water inflow from a single gushing point reached 50 m^3/h. The water was turbid and contained mud. The total inflow of water exceeds 100 m^3/h of all station. Continuous water inflow has caused huge safety hazards for excavation of subway pits, which seriously affects the construction progress of the project. The location of the station and the scene of the inrush water disaster are shown in Figure 1.

Geological exploration data indicate that the main strata are silty sand and soft plastic-flow-shaped silty clay, with poor foundation uniformity, which is a typical soft fluid-plastic stratum. The physical and mechanical properties of the stratum are shown in Table 1.

2.2. Engineering Difficulties

(1) The foundation pit is within the impact zone of the Linjiang Crushing Zone. The water channel inside the fracture zone is complex. If only the gushing point is grouted, groundwater will migrate to the surrounding area, increasing the risk of flooding in the foundation pit.

(2) The bottom layer of the foundation pit mainly consists of the soft fluid-plastic stratum. The stratum is loose and the strength is low. At the same time, the foundation pit is covered with a thin layer of rock and soil, and it is not stable and safe. In the grouting process, the slurry diffusion is difficult to control, and the grouting process is strictly required.

(3) The structural framework has been erected on the construction site. Improper selection of grouting pressure and grouting amount in the grouting process will lead to floor uplift and uplift of the pillars, which will seriously affect the stability of the support structure.

3. Geophysical Exploration

In order to find out the distribution of rock and soil and groundwater in the fractured zone and to identify the main channels leading to flooding disasters in the foundation pit, a trans-hole resistivity CT, high-density resistivity, and transient electromagnetic detection methods were used. A full range of exploration of the project affected area was conducted.

The distribution of major anomalies is shown in Figure 2. It can be seen from the figure that the range between curve A1A2 and curve D1D2 is the major anomaly zone explained by geophysical exploration. It is inferred that the strata in the anomaly zone are broken, and the weak rock mass develops. And there is a local water-rich area. In the area of AD, the crushing of rock mass and the degree of water content are divided into 3 small areas, of which the area of CD is the most serious; area of AB is the next, and finally the area of BC.

4. Grouting Reinforcement Field Test

4.1. Grouting Parameters Design. The grouting material uses cement-water glass slurry (C-S slurry). The grouting parameter selection mainly includes the C-S ratio and the grouting termination pressure. The C-S slurry adopts the common ratio of 2 : 1, 3 : 1, and 5 : 1. According to the engineering design experience, the grouting pressure is twice the water pressure. The water pressure of the test area is 0.2 MPa, and 0.5 MPa is selected as one of the field test grouting

(a) (b)

Figure 1: Station location and water inflow of excavation.

Table 1: Physical and mechanical characteristics.

Layer number	Layer name	Status	c (kPa)	$E_{s1\text{-}2}$ (MPa)	ϕ (°)	ω (%)	K_0 (cm/s)	e	μ	γ (kN/m^3)
5b4~3	Clay	Soft fluid-plastic	7	3.86	2.9	34.8	6.5×10^{-6}	0.993	0.32	18.4

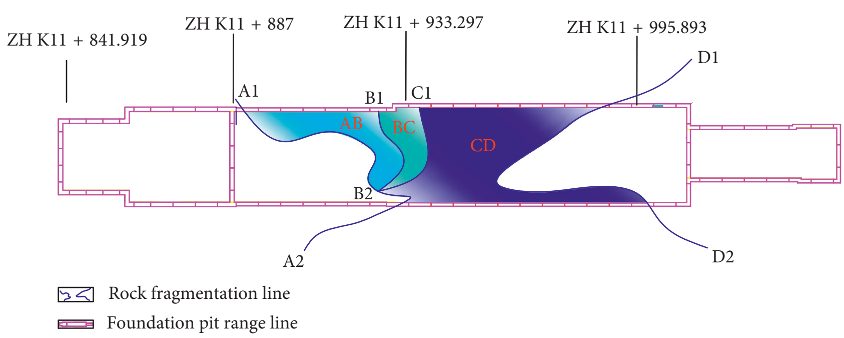

Figure 2: Result of comprehensive geophysical prospecting.

pressures. Grouting parameter settings are shown in Table 2. The preliminary construction data show that when the grouting pressure reaches 1.5 MPa, the internal lattice column uplift data of the pit and the concrete support axial force data are close to the warning value. The upper limit of the grouting pressure is set to 1.5 MPa. Three grouting pressures of 0.5 MPa, 1 MPa, and 1.5 MPa are selected. The pulp parameter design is shown in the following table.

Table 2: Grouting parameters of field test.

No.	W : C	Grouting pressure	C : S
t-1		0.5	2 : 1
t-2		0.5	3 : 1
t-3		0.5	5 : 1
t-4		1	2 : 1
t-5	1 : 1	1	3 : 1
t-6		1	5 : 1
t-7		1.5	2 : 1
t-8		1.5	3 : 1
t-9		1.5	5 : 1

4.2. Sample Collection. The samples were taken from 4 to 6 m below the basement of the subway. The coring position was 50 cm from the drill hole. Each group of grouting bored three groups of cores.

In order to test the strength of grouting stones, the core drilling time was 3 days after the grouting was completed. A total of 54 rock samples were taken at the site. After the cores were recorded, the cores were transported to the laboratory for maintenance. The temperature of the moisture curing tanks was 26°C ± 1°C, and the relative humidity was not less than 90%. Rocks were selected for this test. A cylindrical standard test block (5 cm × 10 cm) was made of cores, 6 test blocks for each group, a total of 162 test blocks, 18 test blocks for each grouting hole. The 28 d physical and mechanical parameters of grouting stones were tested.

4.3. Result Analysis. The test method was used to test parameters such as the elastic modulus (E), cohesion force (c), internal friction angle (φ), and permeability coefficient (k) of the grouting reinforcement stones. And the physical and mechanical properties of the strata after grouting reinforcement were obtained. Each data point was measured by the average of 9 samples under the same conditions. The measured data are shown in Figure 3.

Analysis shows the following:

(1) The mechanical properties of the soil after grouting reinforcement depend on the mechanical properties of the grouting material, and the two laws are synchronous

(2) When the difference in material properties is not large, the improvement of soil mechanical properties after grouting reinforcement is basically unchanged

(3) The permeability of soil is not sensitive to the influence of material properties, and there is no significant difference in the degree of permeability change of different proportions of materials

Therefore, if there is no order of magnitude difference in the performance of various materials, high-performance grouting materials do not need to be deliberately selected, which can save a certain amount of economic investment. Therefore, the CS slurry ratio is 3 : 1.

When the grouting pressure was 1.5 MPa, the performance before and after grouting reinforcement under the influence of different material ratios was analyzed. When the CS volume ratio $Vc : Vs$ was 3 : 1, the performances before and after grouting were analyzed under the influence of different grouting pressures. The relationship is shown in Figure 4.

(1) Grouting can significantly improve the mechanical parameters of the soil, but with particular emphasis on the elastic modulus, which increases two orders of magnitude; followed by the cohesion, an order of magnitude increase.

(2) With the linear increase of grouting pressure, elastic modulus, cohesion and internal friction angle also basically obey the law of linear growth, but the sensitivity is not strong.

(3) After soil reinforcement, the permeability is more sensitive to the impact of grouting pressure. Under the experimental conditions, the pressure is increased by 3 times and the impermeability of the soil is increased by nearly 3 times.

According to the comprehensive analysis, after the slurry is injected into the soil, a soil-slurry mixed stone body is formed, which can greatly increase its elastic modulus. However, an increase in grouting pressure indicates that the soil compaction degree is large and does not significantly improve its elastic modulus. The cohesion and internal friction angle have similar rules. And for permeability, grouting pressure results in greatly reduced porosity, so the permeability is closely related to pressure. In the water hazard treatment project, high grouting pressure should be used as far as possible in order to achieve the purpose of water plugging. Therefore, the project selected a grouting pressure of 1.5 MPa.

5. Localized Control Grouting Process

The basic principle of the local controlled grouting process is as follows: a high-strength textile geotextile sealing bag with a diameter of 40–60 cm is adopted on the jacket of the grouting pipe, which is a so-called control bag. With the grouting tube in the grouting hole, the slurry is injected into the sack through the grouting anther tube with pressure. As the slurry is continuously injected, the control bag is gradually opened in the foundation to form a pile with a diameter equal to the diameter of the sack. Diagram of the control bag is shown in Figure 5.

Under the restraint of the control bag, the slurry can all be confined within the design range, avoiding the phenomenon of stringing and running slurry, so it has higher construction efficiency. During the grouting process of the control bag, under the action of the grouting pressure, the slurry gradually fills the control bag to expand the volume of the control bag and simultaneously compress the surrounding rock and soil. Therefore, the rock and soil bodies undergo a certain lateral deformation, and the rock and soil bodies are compressed. The density of the rock and soil bodies is increased, and the original ground stress field also produces corresponding changes.

Based on the COMSOL numerical model, the displacement field, stress field, and plastic zone distribution during the grouting process were calculated. The calculation results are shown in Figures 6 and 7.

As can be seen from the figure, the stress distribution in the soil varies greatly at different horizontal positions. The horizontal radial stress along the two lines A and E is very small, and the maximum value is only 0.1 MPa. Observing the curve changes on the three lines B, C, and D, it can be seen that the control bag has a significant effect on the stress distribution of soil. In the area near the interface between the control bag and the soil, the stress in the soil is greatly improved compared with the line A and E. With the horizontal distance increasing, the radial stress shows a trend of nonlinear attenuation. The closer the area to the interface between the bag and the soil, the faster the rate of stress decays. At a distance of 1 m from the center of the bag, the overall stress decays to about 0.2 MPa. Within the range of 1 m from the center position of the control bag, the stress in the soil is significantly improved, so the ability of the soil to resist chapping of the slurry is greatly enhanced. Comparing the three stress curves of B, C, and D, it can be found that the three remain basically coincident. From this, it can be known that in a certain range on both sides of the middle of the control bag, the compaction effect of the control bag on the soil can be considered to be approximately the same. By increasing the length of the control bag, its vertical influence on the soil will be correspondingly increased, thereby enhancing the compaction effect on the soil and ensuring the

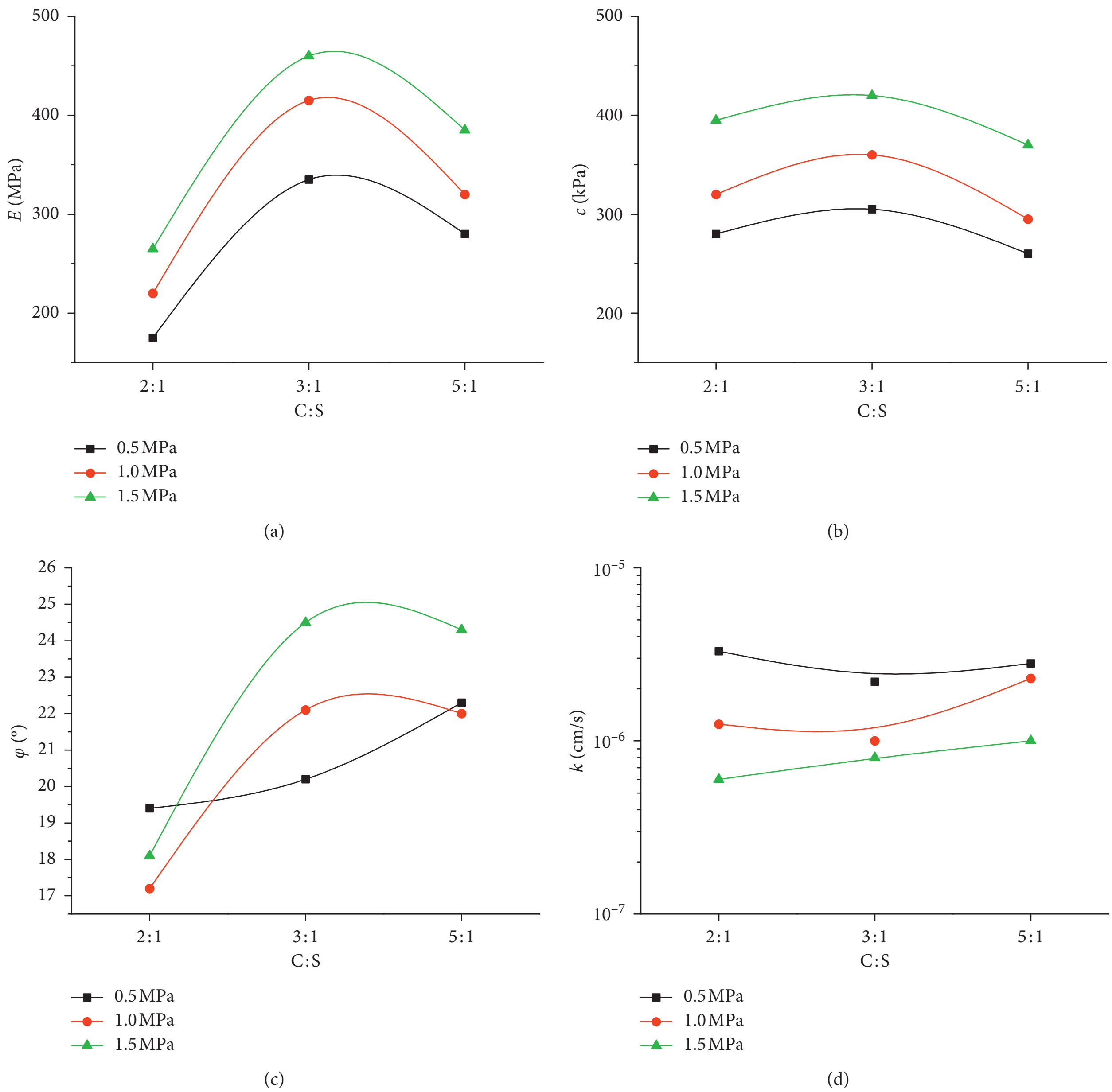

Figure 3: Relationship between mechanical properties of grouting and solid and the ratio of slurry.

smooth implementation of prestressed control of grouting in the formation.

6. Grouting Design

According to the geophysical exploration analysis, a grouting reinforcement zone is demarcated. The grouting parameters obtained by field tests are grouting pressure 1.5 MPa, cement-water glass slurry ratio 3 : 1, and drilling distance 1.5 m. The specific drilling design is shown in Figure 8.

7. Grouting Effect Evaluation

The stability of grouting and solids and the water inflow in the treatment area are the key indicators to measure the effect of grouting reinforcement. Therefore, after the completion of the grouting project, the method of monitoring the displacement of the column in the foundation pit, the monitoring of the water inflow, and the method of excavation shall be adopted for the project. The grouting reinforcement effect was evaluated.

Three columns (LZ10, LZ11, and LZ12) located in the grouting area were selected for monitoring to obtain the horizontal displacement and settlement curve of the column during the grouting process. The analysis shows that the horizontal displacements in the north-south direction and the east-west direction are all less than 15 mm, and the LZ10 vertical column is up to 45 mm in the vertical direction, and the rest of the columns are all less than 10 mm in height, which meets the stability safety standards for the columns.

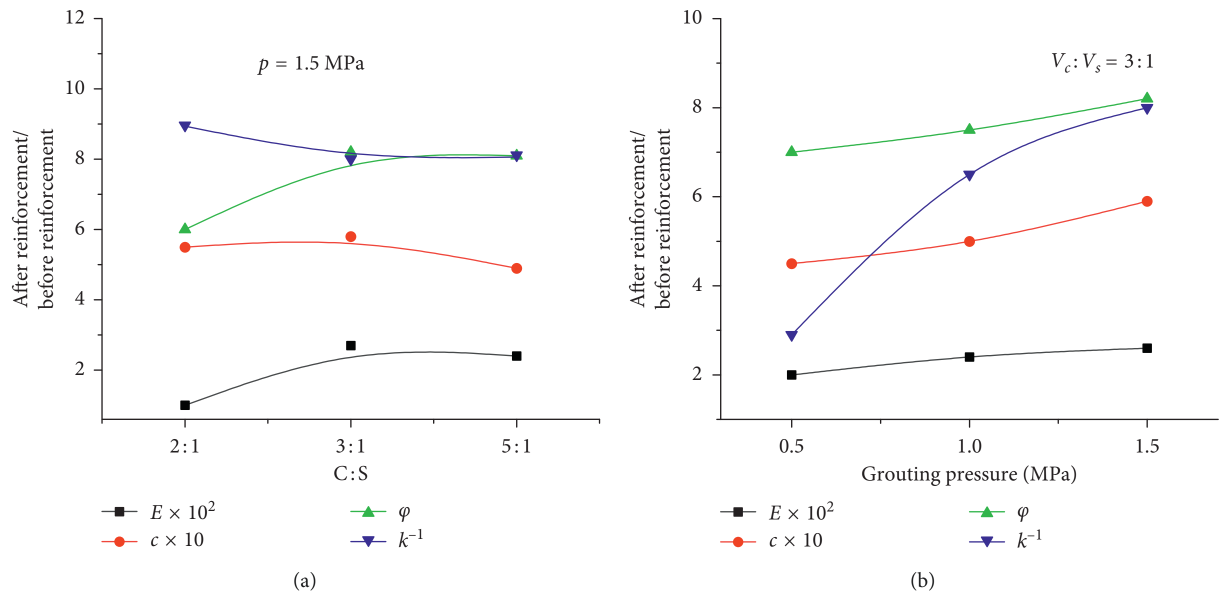

Figure 4: Relationship between performances before and after grouting reinforcement under different slurry ratio and grouting pressure.

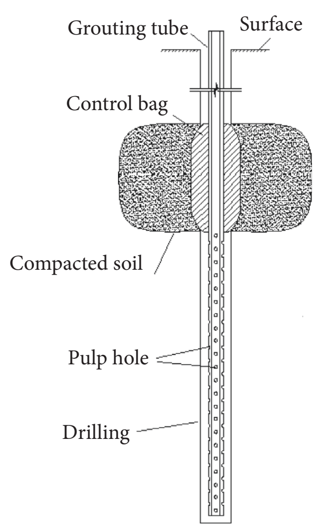

Figure 5: Diagram of control bag.

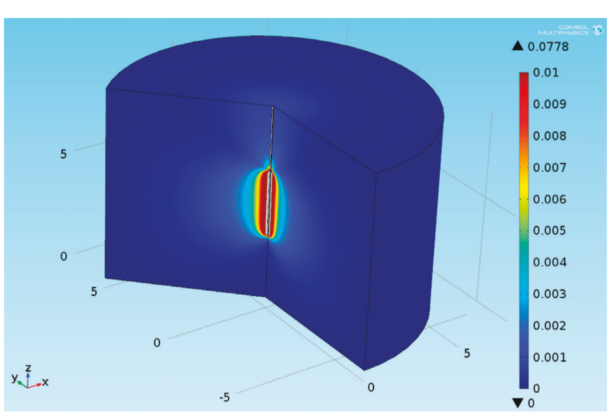

Figure 6: Displacement field changes in 3D of localized control grouting.

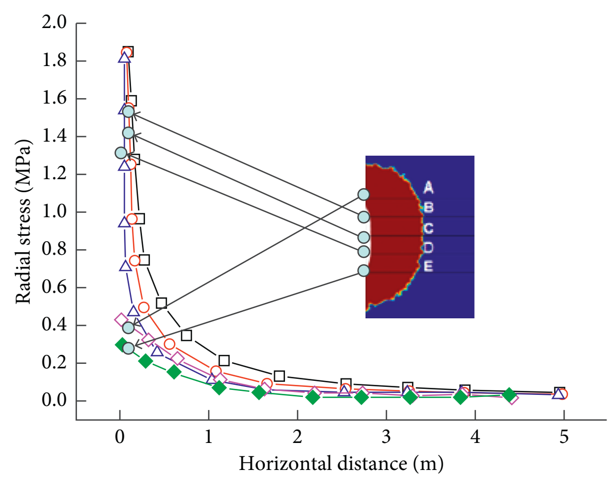

Figure 7: Radial stress distribution curves at different heights.

During the entire grouting process, grouting is performed. The pressure has been effectively controlled, and the disturbances in the horizontal and vertical directions of the pit have been small. Monitoring data of site are shown in Figure 9.

The change of water inflow in the treatment area directly reflects the water plugging effect of grouting reinforcement. The cofferdam measurement method is used to monitor the inflow of water in the treatment area. The change curve is shown in Figure 10.

With the progress of the grouting project, the amount of water inflow gradually decreased from 94 m^3/h to 4 m^3/h, showing a significant downward trend as a whole. And the rate of water inflow in the early period decreased more, and the rate of water inflow in the later period tend to be gentle. Water reduction rate is 96%, achieving the expected effect of blocking water. On-site excavation is shown in Figure 11. The weak formation was well reinforced.

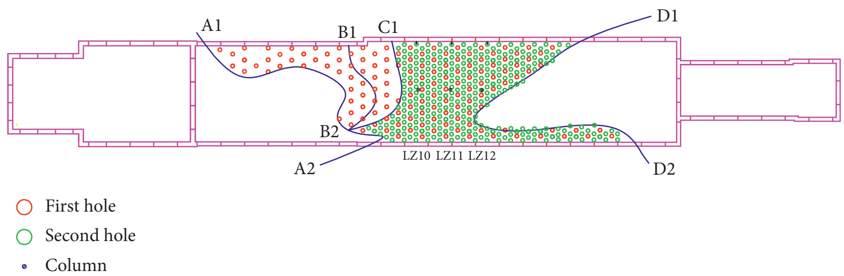

Figure 8: Drilling design of grouting reinforcement.

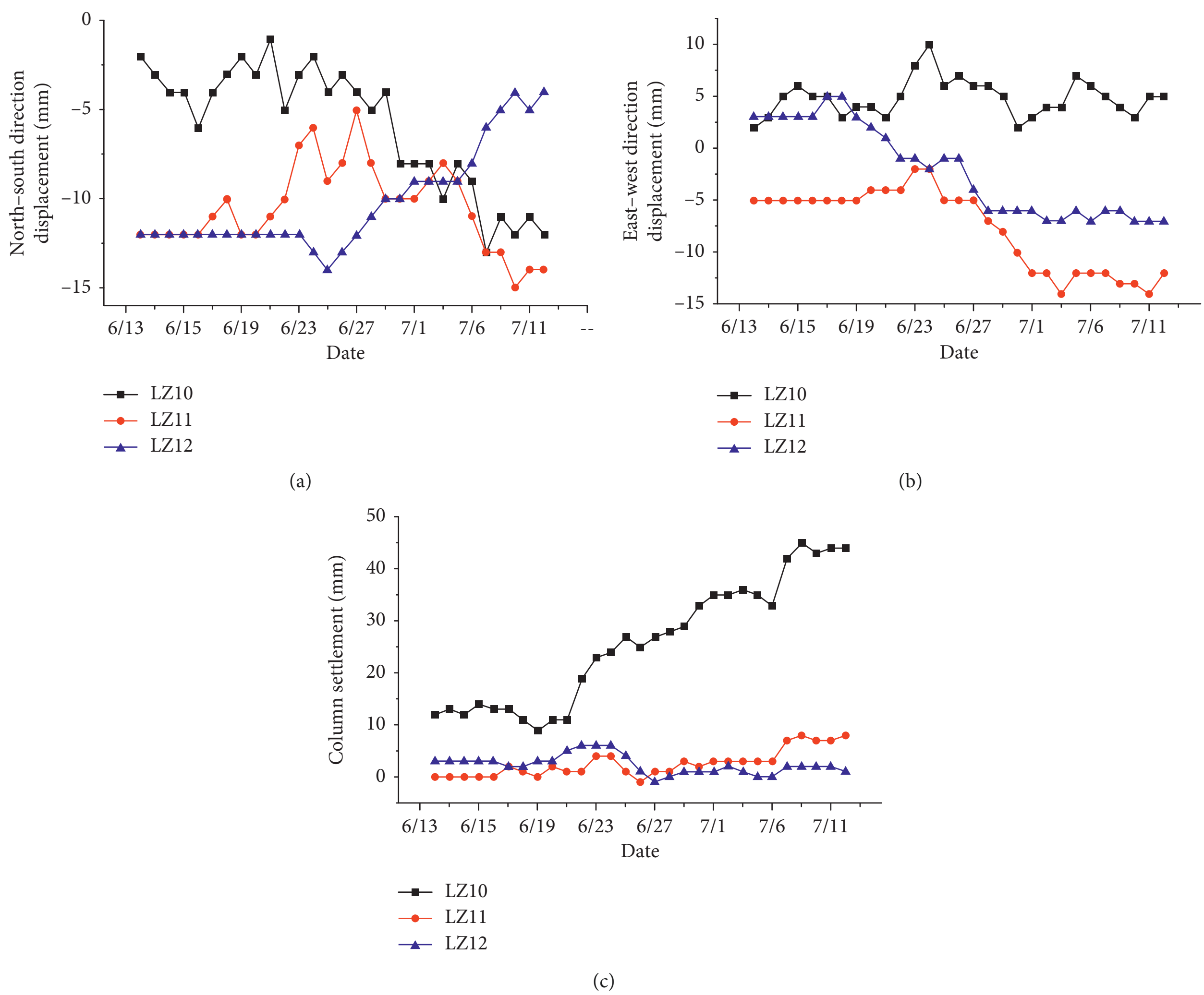

Figure 9: Monitoring data of site. (a) North-south horizontal displacement. (b) East-west horizontal displacement. (c) Column settlement.

The excavation after the completion of grouting is the most intuitive method for evaluating the effect of grouting reinforcement. During the excavation process, the grouting treatment area exposes a large number of pulp veins formed by compaction and cleaving. Analyzing the spatial distribution state of the plasma veins shows that the grouting method has strong applicability to the soft fluid-plastic stratum, has a significant effect on compaction and splitting during the grouting process, and plays a good compaction and consolidation structure for the soft rock and soil mass. As a support, the foundation pit is in a stable state after grouting treatment, achieving the purpose of reinforcement.

8. Discussion

In this paper, through the study of the soft fluid-plastic stratum, the comprehensive management method of inrush water disaster in the soft fluid-plastic stratum under complex urban conditions is proposed, which has certain reference significance for urban bad geological treatment. However,

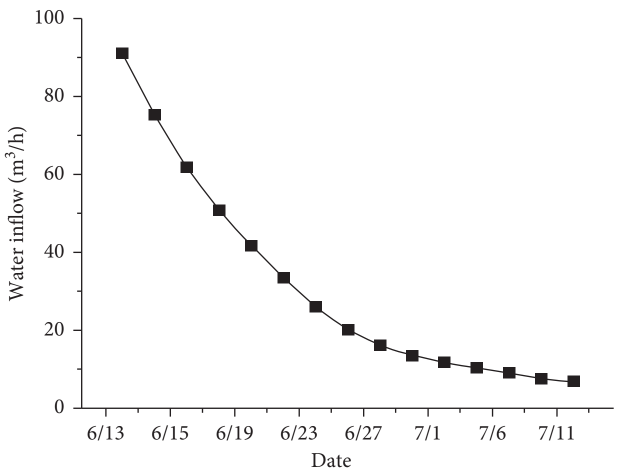

Figure 10: Curve of water inflow.

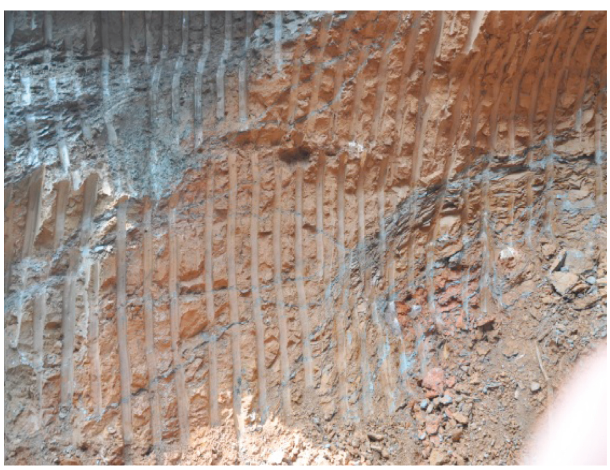

Figure 11: On-site excavation.

based on the characteristics of geotechnical engineering, large-scale model tests are difficult to truly restore the actual project. Therefore, the large-scale model test development is the focus of the next step of the project. In this paper, C-S slurry is mainly used. With the popularization of chemical materials, it is important to study the reinforcement mechanism of various materials on the soft fluid-plastic stratum, which is of great significance for breaking through the bad geological treatment in urban subway construction.

9. Conclusions

Geological data and actual analysis of the project site can initially determine the important and difficult points of the pit management and treatment ideas. A variety of geophysical explorations can be used to identify the source of groundwater inrush and key areas for grouting reinforcement.

The grouting effect has significantly improved the physical and mechanical properties of the rock mass in the stratum. According to field tests, a quantitative relationship was established between the grouting reinforcement factors and the improvement of the physical and mechanical properties of the soft fluid-plastic stratum.

The localized controlled grouting process is suitable for grouting reinforcement in the soft fluid-plastic stratum, which can effectively control the spread of slurry and ensure the effect of grouting reinforcement.

Based on geological analysis, geophysical exploration, field testing, and supporting grouting technology, a comprehensive treatment method for the foundation pit water in complex urban subways can effectively and quickly realize the foundation pit disaster prevention under the security of the foundation pit and surrounding construction pipelines, reducing the blindness of grouting and saving management costs.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The abstract has been published in JWE, May 1, 2018.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Key Research and Development Plan of China (2016YFC0801600) and National Natural Science Fund of China (51779133).

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