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Grouting reinforcement mechanism and experimental study of cement quick-setting slurry infiltration

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Abstract: According to the sand treatment of cement single liquid penetrant reinforcing effect is poor and the problem of quick setting slurry splitting grouting to control the deformation of the ground surface. For the study on the C-S grouting reinforcement master the quantitative relationship between the factors and the physical and mechanical properties of reinforcement. Choose the cement water glass fast setting slurry. By using different injection medium effective diameter and different grouting pressure conditions, carry out sand grouting test. Study on the variation law of single axial compressive strength and permeability coefficient of stone body strengthened by grouting. Through the analysis of the influence of the plasmid size, the grouting pressure and the diffusion distance. It reveals the strengthening factors of C-S grout penetration grouting and the strengthening mechanism of different physical and mechanical indexes, and the quantitative relationship between them is obtained by regression analysis, and using PFC numerical calculation, the article explores the mechanism of grouting reinforcement. The effective diffusion range of cement based quick setting slurry grouting is put forward. The method for determining the parameters of grouting reinforcement is given, and the results are successfully applied in Qingdao Metro. The research results have certain reference significance for the development and improvement of the mechanism of penetration grouting reinforcement.

1 Introduction

With the rapid development of urban underground engineering in China, the problem of easy collapse of tunnels through the Quaternary sand layer seriously hampers the construction process. Due to the complexity of the objective conditions, the city has very high demands on upheaval of the earth surface and pipelines. And due to the complexity of the rock medium, its permeating or splitting grouting reinforce mode directly affects the reinforcement effect and the controlling situation of surface upheaval. How to control the slurry diffusion range and to prevent surface and pipeline upheaval by infiltration grouting under the precondition of ensuring grouting effect is a worldwide technical problem in grouting engineering field.

The researchers abroad carried out relevant researches early. The former Soviet scholars selected chemical slurry for a large number of infiltration grouting tests in porous media under the condition of no water. By injecting the chemical slurry into the different graded sands, he studied the correlation among the grouting parameters, the slurry diffusion and the properties of the sand. Z.ssda, J.Canou neglected the influence of geostress and studied on infiltration grouting simulation, which based on the framework role of soil and infiltration effect of porous media. They put forward the infiltration theory model considering the percolation effect of porous media, proposed a new predictable injecting formula and expressed the correlation among grouting pressure, sand gradation and water-cement ratio.

Some Chinese scholars have studied the law of slurry diffusion in infiltration grouting by simulation tests, and obtained correlation among the grouting parameters. Northeastern University studied the law of pressure distribution and diffusion during the porous media infiltration grouting process by grooved reverse oval cylindrical test-bed, and concluded that slurry pressure decays with the increase of diffusion distance. Yang Ping carried out sandy cobble stratum grouting research and put forward the correlations among the slurry diffusion radius, the consolidating strength of stone, grouting parameters and rock and soil properties. Qian Ziwei studied the basic law of filling and infiltration of weak cemented porosity media chemical slurry. The variation law of permeability coefficient, porosity and compressive strength of different effective particle sizes and fineness modulus before and after grouting were studied.

The researches above have promoted the development of grouting reinforcement theory and engineering practices, pointed out the law of grouting diffusion and treatment in the formation of porous media, but the exploration of grouting reinforcement mechanism are mostly qualitative researches, less involved grouting factors and mechanical properties. The strengthening law of solid performance among different grouting factors was not involved. The grouting material used in osmotic grouting is mainly composed of single cement slurry or chemical slurry , and it is not concerned with the infiltration grouting reinforcement of quick-setting grout.

In this paper, cement-sodium silicate slurry is used as the research object, and a quick-setting slurry method is proposed. Based on grouting reinforcement experiment, the parameters of sand injection layer before and after cement-sodium silicate grouting are analyzed. The uniaxial compressive strength and permeability coefficient of sand layer are compared with its effective diameter, grouting pressure and diffusion distance. By studying the influence of these three on the reinforcement parameters of sand layer, the action mechanism of the stress concentration on the different mechanical indexes is revealed. By using the discrete element PFC numerical simulation, the grouting reinforcement mechanism is deeply revealed. The effective range of cement-sodium silicate grout infiltration grouting reinforcement is put forward, and correspondingly the determination method of cement-sodium silicate grout infiltration grouting reinforcement parameters is given, which provides the foundation for the study of infiltration grouting reinforcement mechanism under the unified theoretical framework and provides innovative theoretical guidance to prevent surface and pipeline upheaval by infiltration grouting.

2 Test Scheme

The grouting test of cement-sodium silicate slurry infiltration grouting is carried out by two grouting control factors (effective diameter of injection medium and grouting pressure). Along the diffusion direction from the grouting port position, which called diffusion distance, to segment the core, the single-axis compressive strength and permeability coefficient were measured respectively. The mechanism and quantitative analysis of cement-sodium silicate slurry infiltration grouting reinforcement were carried out.

2.1 *Test Materials*

Basic materials in field test are as follows:

(1) Cement

Using P.O.42.5 cement, which is produced by Qingdao Zhonglian Cement Co., Ltd., in line with "General Portland cement" (GB175-2007) standards.

(2) Sodium silicate

The sodium silicate is a commercially available sodium silicate with modulus M = 3.0, sodium silicate Baume degree is 38 ° Bé and density is 1.37g / cm3.

Determination of initial setting time of slurry: CS slurry is quick-setting cement-based grouting material, the initial setting time is determined by the drop needle method, the measuring instrument is cement final setting time tester and temperature change curing box. Ratio of test water-cement slurry is 1: 1, room temperature is 20 ℃. When the initial setting time is determined, the cement and the sodium silicate are poured into the circular mold according to the ratio, and the stirring is carried out uniformly. The mixing process simulates the effect of the double liquid mixer in the grouting project. When the C-S slurry is no longer flowing, it is considered that the initial setting time is reached. The test results of the C-S slurry initial setting time are shown in Figure1.

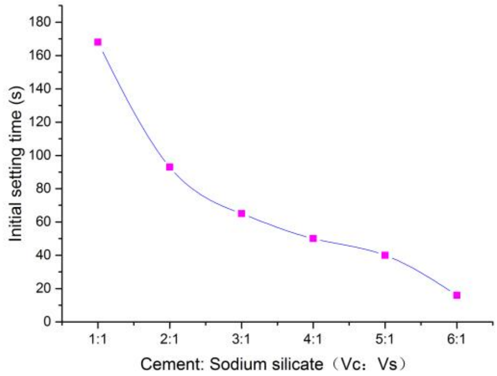


Fig.1 C-S slurry initial setting time

2.2 *Design level of test factors*

The permeability of cement-sodium silicate slurry in sand layer is mainly controlled by three factors, namely, slurry property, effective particle size of sand and grouting pressure.

(1) Slurry property is an important factor influencing grouting effect of sand layer. The cement-sodium silicate slurry is used in this experiment and the influence of slurry on the grouting effect is mainly controlled by its injectability and gel time. However, this test is carried out under the condition that the medium can be injected and the initial setting of cement-sodium silicate slurry. Based on feasibility and initial setting time, the test chose the quick-setting slurry with C-S ratio of 2:1.

(2) The effective particle size of the injected media directly affects the injectability of C-S slurry, and plays an important role in controlling the distance and intensity of grouting. In this study, the river sand was sieved to obtain the medium with different particle diameters. The average diameter of the particles was 0.6 ~ 0.85mm, 0.85 ~ 1.18mm, 1.18 ~ 1.7mm and 1.7 ~ 2.36mm respectively.

Table 1 The parameters of different particle size of sand layer

Sand sample	Particle size（mm）	Effective diameter D_0（mm）	Osmotic coefficient /0.01cm·s^{-1}
1	0.6-0.85	0.74	7.16
2	0.85-1.18	1.02	9.86
3	1.18-1.7	1.44	16.52
4	1.7-2.36	2.03	31.12

(3)Grouting pressure and slurry diffusion ability are closely related to directly determine the advantages and disadvantages of grouting effect. As the CS slurry must be two-liquid grouting, it is difficult to achieve constant pressure grouting. This test uses constant flow grouting to study the regularity of the final pressure of grouting on the CS slurry penetration grouting effect. In the test, the final pressure of grouting notes P = 0.5MPa, P2 = 1MPa, and P3 = 1.5MPa respectively.

In summary, in order to study the cement-sodium silicate slurry infiltration grouting reinforcement mechanism, the experimental design 12 groups of grouting test, test design as follows:

Table 2 Quick-setting slurry infiltration grouting reinforcement design test level

Group No.	Effective diameter	Grouting pressure
1	1	0.5
2	1	1
3	1	1.5
4	2	0.5
5	2	1
6	2	1.5
7	3	0.5
8	3	1
9	3	1.5
10	4	0.5
11	4	1
12	4	1.5

The grouting rate was set at a constant grouting rate of 3 L / min during the test.

3 C-S Slurry in One-Dimensional Infiltration Grouting Simulation Test

In order to study the grouting reinforcement mechanism of cement-sodium silicate slurry under different grouting pressure and different effective sand diameters, a one-dimensional visualized penetration grouting simulation experiment device was designed. As shown in Figure 2 and 3, the test device consists of infiltration grouting pipe, test stand, manual injection pump, grouting recorder and other parts.

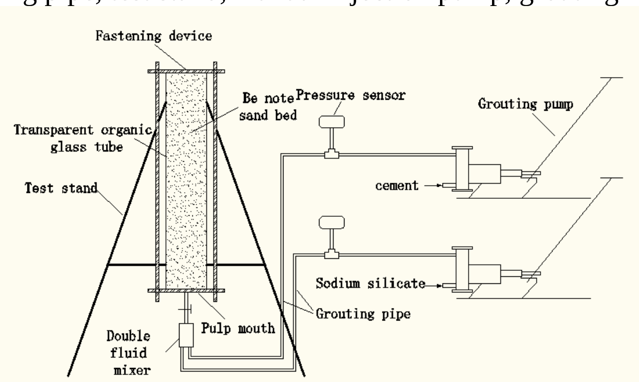


Fig.2 Test unit diagram

Fig.3 A one-dimensional infiltration grouting simulation test system

(1) grouting simulation test

In order to realize the visualization of the slurry diffusion process, the permeable grouting tube is made of transparent plexiglass tube, arranged vertically. The slurry enters from the bottom of the plexiglass tube, the length of whose is 2m, the inner diameter is 10cm. The infiltration grouting tube is filled with a designed effective diameter of the sand. In order to ensure the injection process of the media particles do not move as a whole due to the diffusion of the grouting, a fastening device is provided on the upper and lower sides of the infiltration grouting pipe, and the fastening device allows the slurry to enter and exit, but is not allowed to pass through the media particles. Thereby fixing the injected medium, while using the grouting recorder to control the grouting rate and grouting pressure.

According to the experimental design table, penetration grouting reinforcement tests were performed and grouting process of slurry diffusion morphology shown in Figure 5. During the process, the slurry moves up from the bottom of the infiltration grouting tube. From the final sampling results compared with the injection medium and plexiglass tube wall of the slurry retention situation, we found the diffusion slurry at the front of plexiglass tube wall are permeable grouting slurry, indicating that the grouting process in line with the one-dimensional grouting model.

(2) sampling location and method

After the simulation of the grouting test, the media was injected into the plexiglass tube, and the physical and mechanical parameters were tested after 3 days. The concrete steps of coring method are as follows:

1) After the grouting, the plexiglass tube was segmented. The length of the sections was 20cm, 50cm, 80cm and 110cm from the grout outlet;

2) Take the coring machine to take the core of each section. The core's position is from 5 to 15cm away the grout outlet, grouting and solid sampling shape for the cylindrical shape, length 10cm, diameter 5cm;

3) With the same step 2) the cores were taken at a distance from the grout outlet 35-45cm, 65-75cm and 95-105cm respectively.

4)The YA-2000B electric screw digital pressure tester and rock penetrant analyzer by Jinan Haiweier Instrument Co., Ltd. were used to measure the uniaxial compressive strength and permeability coefficient of grouting reinforcement respectively.

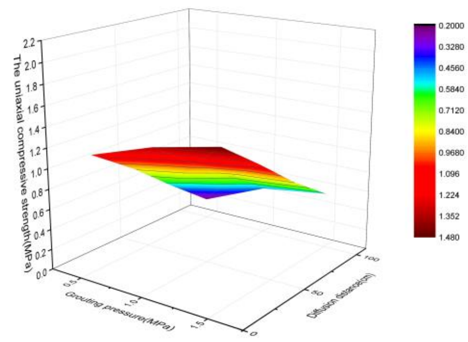
Fig.4 A one-dimensional infiltration grouting simulation test core position

4 Grouting Reinforcement

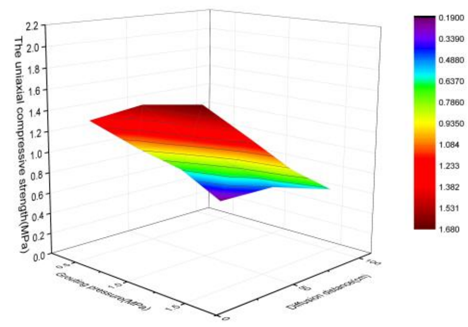
4.1 *Analysis of Uniaxial Compressive Strength of Osmotic Grouting Reinforcement*

According to the test data, the relationship between the uniaxial compressive strength and the grouting pressure and the diffusion radius of the grouting reinforcement under the condition of the effective diameter of the injected medium is shown in Fig. 5

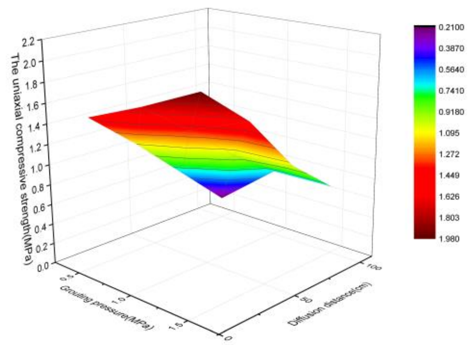
The strength of the grouting and solidification of the sand layer is supported by the skeleton of the loaded sand, the interstitial filling and the volume compression of the media, and is characterized by uniaxial compressive strength. Based on the effect of single grouting factor on the uniaxial compressive strength of grouting stone, the effect of uniaxial compressive strength of cement-sodium silicate slurry infiltration grouting reinforcement is obviously improved in Figure 5, indicating that the cement-sodium silicate slurry can be well cemented with the sand layer of the injected media. The grouting effect of cement-sodium silicate slurry is significant to sand reinforcement, but with the grouting pressure and diffusion distance are different, the effect of grouting reinforcement is quite different. The general trend is that the uniaxial compressive strength of grouting reinforcement increases with the increase of the effective diameter and the grouting pressure of the grouting medium, decreases with the increase of the diffusion distance.



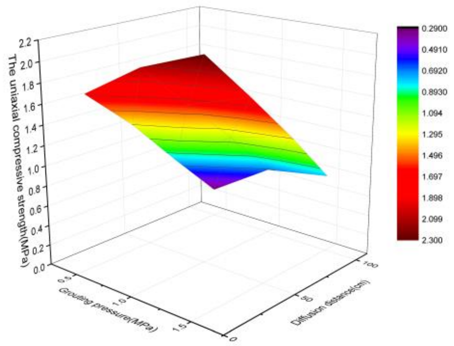
(a)The effective diameter of the injected medium is 0.74 mm



(b)The effective diameter of the injected medium is 1.02 mm



(c)The effective diameter of the injected medium is 1.44mm



(d)The effective diameter of the injected medium is 2.03mm

Fig.5 The relationship between grouting factors and strength under different effective diameter of the medium

4.2 *Analysis of control factors of grouting reinforcement strength*

The influence of different factors on the uniaxial compressive strength of grouting solid is different. The grouting parameters have the emphasis on the physical and mechanical indexes of grouting stone, that is, the influence of different grouting factors under the same physical mechanics parameters is different. From Figure 6, we can see the relationship between the grouting factor and the strength of the different diameters of the injected medium.

(1) Cement-sodium silicate slurry infiltration grouting can significantly improve the uniaxial compressive strength of sand, the most obvious attenuation of the intensity is the diffusion distance;

(2) The uniaxial compressive strength and diffusion distance of cement-sodium silicate grout infiltration grouting show linear attenuation of magnitude, and the injection pressure and the effective diameter of the sand layer of the injected medium also obey the law of power function growth, but its sensitivity is not strong;

(3) Limit diffusion distance of C-S slurry is about 1m. It is difficult to sample the sand at the distance of 1m under the test condition, and the uniaxial compressive strength is lower.

The comprehensive analysis shows that cement-sodium silicate slurry infiltrates into the sand layer to form the sand-slurry mixed stone body, which can greatly improve the uniaxial compressive strength, in which the grouting pressure and the effective diameter of the injected sand layer are good for grouting. The sensitivity of reinforcing strength is low, and the diffusion distance is very sensitive to penetration grouting reinforcement. The reason is that cement slurry is infiltrated into the injected sand layer before the initial setting time of cement-sodium silicate slurry, and the main factor for the increase of grouting pressure is the self-coagulation of the slurry, and the grouting pressure is not sensitive to the compression effect of the injected medium. Meanwhile, the cement-sodium silicate grouting is mainly filled, and the effective grain size of the sand injection layer has little effect on the filling effect. The infiltration distance of sodium silicate slurry is limited, and the diffusion of the slurry along the permeating direction is extremely limited, and the intensity of the slurry is very sensitive.

According to the basic function formula of the grouting reinforcement strength of the cement slurry, the compressive strength of the sandstone body under the grouting pressure, the effective diameter and the diffusion distance of the injected medium are compared with the corresponding compressive strength of the injected sand layer then get the following relationship:

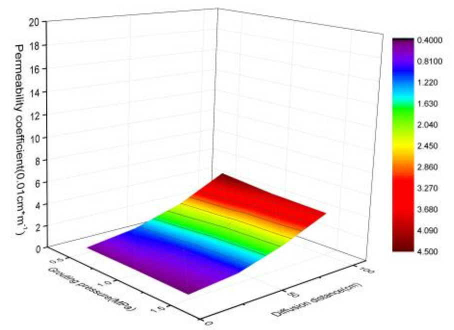
$$P = 1.24p^{0.25} - 0.01L + 1.21d^{0.42} - 0.58 \quad (1)$$

Where P is the uniaxial compressive strength of the sandstone body, in MPa; p is the grouting pressure in MPa; d is the effective diameter of the injected medium, in mm; L is the diffusion distance in cm.

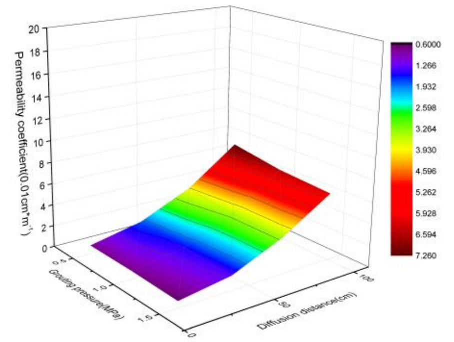
4.3 *Analysis of Permeability Coefficient of Grouting Reinforcement*

According to the test data, the relationship between the permeability coefficient and the grouting pressure and the diffusion distance of the grouting solid is obtained according to the effective diameter of different media in Figure 6.

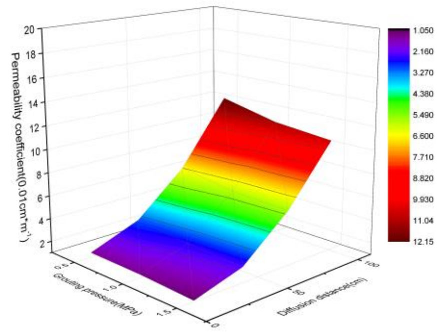
The permeability of grouting and solidification is supported by the skeleton of the injected sand layer, the gap filling and the volume compression. The permeability coefficient of cement-sodium silicate infiltration grouting is obviously improved. Define permeability improvement coefficient of grouting reinforcement: n = permeability after grouting Y / permeability coefficient Y0 before grouting. It can be seen from the calculation that the coefficient of permeability improvement is about one order of magnitude, which shows that the cement-sodium silicate slurry can be well cemented with the injected sand after the gel infiltration, and the effect of cement-sodium silicate slurry infiltration grouting on the permeability of sand layer is remarkable. But with the difference of effective diameter, grouting pressure and diffusion distance, the permeability improvement effect is different. The general trend is that the permeability coefficient increases with the increase of effective diameter of the medium, increases with the increase of grouting pressure , but decreases with the increase of the diffusion distance.



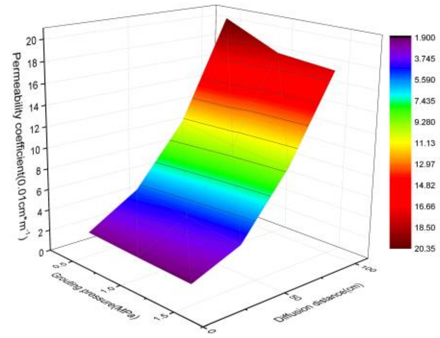
(a)The effective diameter of the injected medium is 0.74mm



(b)The effective diameter of the injected medium is 1.02 mm



(c)The effective diameter of the injected medium is 1.44mm



(d)The effective diameter of the injected medium is 2.03mm

Fig.6 The relationship between grouting factors and The permeability coefficient under different effective diameter

4.4 *Analysis of Control Factors of Permeability Coefficient in Grouting Reinforcement*

The effects of different factors on the permeability of solid after grouting reinforcement are different, and the grouting parameters had an emphasis on the permeability enhancement of grouting stone. From Figure 6, we can see the relationship between the grouting factor and the permeability coefficient under the effective diameter of different media.

(1) Cement-sodium silicate slurry infiltration grouting factors can increase the permeability of sand layer by order of magnitude, the most direct influence is by diffusion distance, and secondly by the effective diameter of sand layer;

(2) The permeability coefficient, diffusion distance and the effective diameter of the injected sand layer of the cement-sodium silicate slurry infiltration grouting increase exponentially. The grouting pressure basically obeys the law of power function attenuation, but its sensitivity is not strong;

(3) The ultimate diffusion distance of the C-S slurry is about 1 m. Under the experimental conditions, taking the sand layer with diffusion distance of 1 m is more difficult and the permeability coefficient is higher.

The comprehensive analysis shows that cement-sodium silicate slurry is injected into the sand layer, then forms the sand-slurry mixed stone body, which can greatly improve the permeability of grouting stone body. The grouting pressure is less sensitive to the permeability of the grouting reinforcement, while the diffusion distance and the effective diameter of the injected sand layer are completely opposite.

The reason is that the precondition of cement-sodium silicate slurry infiltration grouting is that the slurry enters into the sand layer before the initial setting time of the cement-sodium silicate slurry. The main factor of the grouting pressure is the self-coagulation of the slurry, and the grouting pressure is not sensitive to the compressive effect of the injected media. Unlike the uniaxial compressive strength of the grouting reinforcements, one of the main factors controlling the permeability of grouting and consolidation is the degree of sand filling and slurry-sand bonding. As the effective diameter of the sand layer increases, the interface area of the single slurry-sand is increased. Under the same condition, the bonding capacity decreases, the permeability decreases and the permeability coefficient increases. Therefore, the permeability of slurry and solid is greatly affected by the particle size, the diffusion of cement slurry is very limited along the infiltration direction, and the permeability is very sensitive.

According to the basic function formula of cement slurry on grouting reinforcement coefficient [20], an one-to-one correspondence among the grouting pressure, the effective diameter, the diffusion distance, and the permeability coefficient of sandstone body after grouting reinforcement is got as follows:

$$\kappa = 0.0004L^2 + 0.47p^{-0.15} + 0.83d^{1.5} - 0.82 \quad (2)$$

Where κ is the permeability coefficient, the unit is 0.01cm·m^{-1}; p is the injection pressure in MPa; d is the effective diameter of the medium being injected, in mm; L is the diffusion distance, in units of cm, removing the big points of error.

5 Effective Spreading Range of Cement-Sodium Silicate Slurry Infiltration Grouting Reinforcement

The uniaxial compressive strength of the cement-sodium silicate slurry infiltration grouting will decay rapidly along the diffusion distance. Therefore, only the soil grouting effect within a certain range near the grouting hole can meet the practical engineering requirements. In order to improve the infiltration grouting reinforcement theory and guide the engineering practice, the effective diffusion range of cement-sodium silicate slurry infiltration grouting reinforcement strength is put forward.

Based on the spatial distribution and the target requirements of grouting effect, the effective diffusion range of grouting under different grouting parameters can be determined, and the corresponding grouting parameters can be determined according to the grouting effect required by the project. The steps of determining the effective diffusion range of sand layer is as follows:

(1) to obtain the effective diameter of the injected medium according to the geologic parameters of the stratum;

(2) to determine the target value of grouting effect evaluation index, that is, uniaxial compressive strength and permeability coefficient of grouting stone body;

(3) to determine the grouting pressure, according to the project on the surface and pipeline deformation, to determine the maximum grouting pressure by a comprehensive analysis;

(4) to calculate the grouting diffusion distance $L_1$and L_2 according to formula (A) (B) respectively under the limited grouting pressure and the target value in step (2), and to choose the smaller one as the effective reinforcement radius $L_0 = (L_1, L_2)_{\min}$.

6 Engineering Application

This research has been applied in the left and right lines ZSK39 +263.26 ~ ZSK39 + 255.56, YSK39 +263.96 ~ YSK39 +250.56 from Qingdao Beer City Subway Station to Miao ling Road Station with the depth of 11.0- 12.0m and the total length of 21.101m. According to geological survey data, we found that the main stratum media in this section includes the Quaternary surface layer and coarse gravel sand layer. Because of its low bonding strength, the self-stability of coarse sand layer is poor when it is as the tunnel structure of the vault and side walls, so it is easy to collapse and drop piece if the subway goes through. At the same time, the section is located below Hong Kong Road whose traffic is is heavy. In the case of improper selection or lack of control of support and waterproofing measures, the sand layer will emit with water in the influence of dynamic vehicle load on the ground, or will cause collapse or sinking. Pipelines of heat, gas and others are intensive under Hong Kong Road, so it has high requirements on the surface uplift.

Based on the actual situation of this subway section, considering the poor effect of traditional single cement grouting, the high cost and pollution of chemical slurry and the difficulty to control the surface uplift by splitting grouting of the cement-sodium silicate slurry, the infiltration reinforcement of cement-sodium silicate slurry was put to use. The results show that the effective diameter of the sand layer is 1.5mm. According to the requirement of excavation strength and permeability, the strength of grouting reinforcement is 1.5MPa, and the permeability coefficient is 0.045cm / s. According to the cement-sodium silicate slurry infiltration grouting parameter determination process, the effective diffusion L_1=72.00cm , L_2=80.62cm , so the effective range is $L_0 = \left(L_1, L_2\right)_{\min}$ =72.00cm . Then design the grouting according to the above grouting parameters.

After the grouting treatment, the surface subsidence monitoring results show that the surface uplift is 7mm during the grouting process. The uniaxial compressive strength and permeability of the samples after the reinforcement of the grouting were found to be less than 10% with the design value. The infiltration reinforcement of cement-sodium silicate slurry not only reinforced the sand layer of tunnel vault, but also controlled the surface deformation, ensuring the safety of the project.

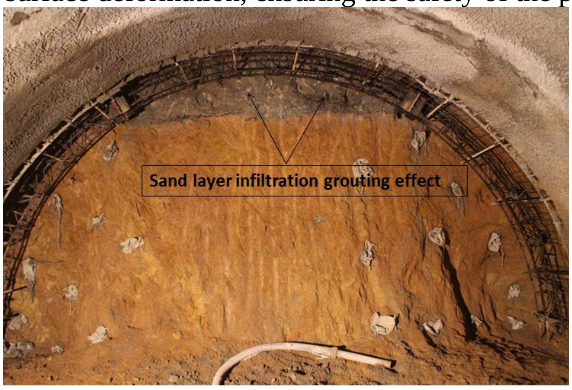


Fig.7 Quick-setting slurry infiltration grouting reinforcement

7 Conclusion

Based on the difficulties in sand-grouting treatment and upliftment control of surface and pipeline, through the experimental study of cement-sodium silicate slurry infiltration grouting, the response mechanism of grouting main factors on the physical and mechanical parameters of grouting stone was studied, and the corresponding parameter determination method was carried out. Finally the conclusions are as follows:

(1) Uniaxial compressive strength of cement-sodium silicate slurry grouting can significantly improve the uniaxial compressive strength of sand layer. The uniaxial compressive strength and diffusion distance of cement-sodium silicate grout infiltration grouting show linear attenuation of magnitude, and the injection pressure and the effective diameter of the sand layer of the injected medium also obey the law of power function growth, but its sensitivity is not strong. Under the experimental conditions, it is difficult to sample the sand layer with the diffusion distance of 1m, and the uniaxial compressive strength is very low.

(2)Cement-sodium silicate slurry grouting can increase the permeability of sand layer, and the permeability coefficient and diffusion distance of the stone body increase exponentially with the effective diameter of the sand layer. The grouting pressure obeys the law of power function attenuation, but its sensitivity is not strong.

(3) According to the analysis of grouting reinforcement effect, the effective diffusion range of cement-sodium silicate slurry infiltration grouting is put forward. Correspondingly, the method of determining the infiltration grouting reinforcement parameters is given, and successfully implemented in Qingdao subway.

(4) The method of cement-sodium silicate slurry infiltration grouting reinforcement proposed new ideas for a unified theoretical framework of infiltration grouting reinforcement mechanism, and provided innovative theoretical guidance for solving the surface and pipeline uplift and other problems in engineering .

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