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Study on Grouting Simulation Test of Water-permeable Rock Mass in Qingdao Metro Excavation Open Pit

Jianwei Zhang[1], Wenqiang Zhao[2], Ye Pan[2*], Jiaqing Wang[1], Ning Wei[2], Qing Du[1]

[1]Qingdao Metro Group Limited Second Construction Branch, Qingdao, China
[2]Qingdao Metro Planning and Design Institute Co., Ltd., Qingdao, China
**Corresponding Author. Email: Panye2120@163.com*

Abstract. Due to the water leakage problem of the rock layer that passes through the open foundation pit of Qingdao Metro, an indoor grouting model test was carried out. The grouting effect of cement-based slurry and cement-sodium silicate double sludge in fractured rock mass was systematically investigated using a self-designed visual tailings water injection simulation system. SEM and XRD microanalysis reveal the binding mechanism and hydration products of magmatic rock interfaces. The results showed that the injection effect of the cement-sodium silicate sludge was best when the injection pressure was 0.3 MPa and the water-cement ratio was 0.8, and the injection pressure had a significant effect on the diffusion area of the sludge. The research results can provide a theoretical basis and technical support for the management of leaks in the foundation pits of the Qingdao Metro.

Keywords: permeable rock mass, grouting simulation, slurry-rock interface, Qingdao Metro

1. Introduction

Qingdao Metro open-cut foundation pits are mostly located in the combination of bedrock and soil-rock, with developed rock joint cracks and strong water richness, making the construction of traditional water-stop curtains difficult and the problem of water leakage in the foundation pit prominent. Specifically, leakage will not only significantly reduce the bearing capacity of the foundation, leading to increasingly serious deformation of the foundation pit, but also directly damage the overall stability of the supporting structure [1].For example, the collapse of the subway foundation pit project in Chaoyang District, Beijing, and the collapse of the foundation pit retaining wall in Haizhu Square, Haizhu District, Guangzhou City, Guangdong Province [2].Therefore, solving the leakage problem is an important challenge in the current engineering field.

At present, the main anti-seepage method is the surface closure method [3], Crack filling method [4], grouting method [5]. Among them, grouting technology is a commonly used seepage control method, which injects slurry into the cracks or pores of rock and soil to improve strength, reduce permeability, and control deformation. Relevant scholars have begun a series of studies on it and have achieved some results. Li [6] et al. proposed a method for the quantitative calculation of cementing in a sand bed, which aims to provide a theoretical basis for the design of cement reinforcement. This method is of great significance for the prevention of disasters such as sand

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surges. Wei [7] et al. studied the flow diffusion law of cement mortar in the gravel layer under the masonry slope protection, and discussed the influence of grouting pressure and grouting amount on the flow diffusion form and overall filling effect of cement mortar with different flow degrees. The results show that the grouting diffusion pattern is horizontally symmetrically distributed around the grouting hole, and is preferentially filled downward along the gravity direction and then escapes upward. The grouting pressure limit value and effective diffusion range are restricted by the slurry fluidity and formation porosity, and the effective filling rate of more than 83% can be achieved at 2 MPa pressure in constant pressure grouting mode, which meets the requirements of engineering reinforcement. Cement mortar has a good effect on grouting diffusion of crushed rock. Zhang [8] et al. proposed new method to strengthen the rock mass that has broken under self-stress. Ordinary cement-based grouting materials shrink by themselves as a result of the hydration reaction, which greatly reduces the grouting reinforcement effect of the broken rock mass. The self-stress injection method can improve the density of the slurry and improve the stress state of the rock mass. Zhang [9] et al. studied the influence mechanism of the filling degree of rock mass with coarse fractures on the strength of the renovated rock mass. The results showed that the grouting diffusion mode was controlled by crack roughness (JRC), slurry viscosity and grouting pressure, among which JRC dominated the non-uniformity of the diffusion path, slurry viscosity affected the flow stability, and grouting pressure determined the diffusion range. The strength of the rock mass increases with the increase of filling degree and roughness, and the evolution mechanism of compressive and shear strength is manifested as the morphological transformation of the plastic zone and the redistribution of shear stress, respectively. This conclusion is applicable to grouting design and strength prediction of fractured rock mass. However, there is a lack of research on the physicochemical interaction between slurry and rock particles at the microscopic scale, and the interfacial bond strength, which is difficult to reveal the essential mechanism of grouting.

Based on the research project of water seepage prevention and control technology in Qingdao Metro foundation pit, this paper carried out grouting model tests on permeable rock mass, analyzed the grouting effect of cement-based and cement-water glass under different slurry types and grouting pressures by simulating the grouting process indoors, and revealed the mechanism of the slurry-rock interface in combination with microscopic testing technology, in order to provide a scientific basis for on-site grouting construction.

2. Manuscript preparation

2.1. Grouting material preparation and performance testing

P.O 42.5 ordinary silicate cement and sodium-based water glass (modulus 2.8~3.2) were selected for the test, and the water-cement ratio was fixed at 0.8. The slurry is prepared using NJ-160 mixer, first dry mix cement and admixture for 2 minutes, then add water and stir slowly for 2 minutes, and finally stir quickly for 2 minutes to make a homogeneous slurry. The test items include: water separation rate; setting time; fluidity; Rheology.

2.2. Grouting simulation test system and design

In this paper, a complete set of visual water-rich fracturing zone grouting test simulation system is designed and fabricated according to the main characteristics of fractured permeable rock mass, which is mainly composed of a permeable rock formation simulation platform, groundwater supply and test grouting device.

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2.3. Permeable rock mass simulation platform

A 1000 mm×1000 mm× 1000 mm fractured formation simulation platform was designed, which was mainly made of 10 mm thick steel plate, which could meet the requirements of maximum grouting pressure of 10 MPa. The top surface and one side are anchored with high-strength bolts, with movable tie rods, the joints are sealed with 2mm thick rubber gaskets, and the other surfaces are seamlessly welded. The other three sides are equipped with grouting visualization windows of different heights, using high-strength plexiglass, the length and width of plexiglass are 250 mm×100 mm, and the bottom of the plexiglass is 250 mm, 500 mm and 750 mm from the bottom of the model box respectively. A grouting hole with a diameter of d=50 mm, a water inlet with a diameter of d=10 mm, and an injection hole with a diameter of d=10 mm are reserved on top of the simulated level. Two drains with a diameter of d=10 mm are reserved at the bottom of the sides. Simulation platform for breaking permeable rock formations, such as Figure 1shown.

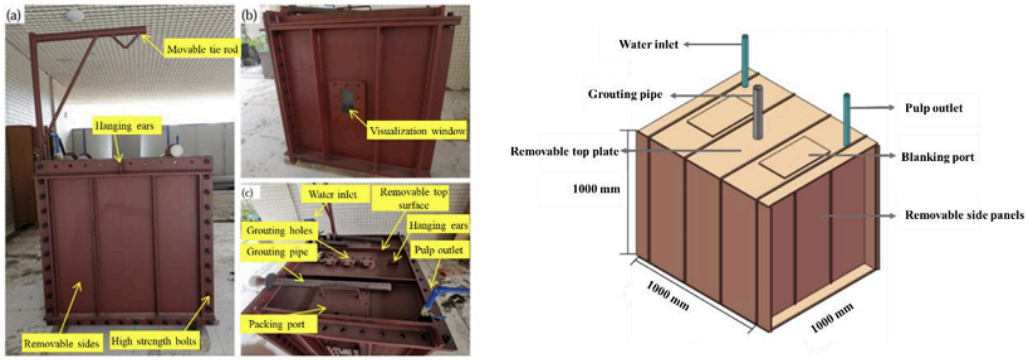

Figure 1. Simulation platform for broken permeable rock formations

2.3.1. Simulation and grouting method of broken rock mass

This article uses coarse sand, melon stone, and crushed rock to simulate the broken rock mass, and the particle size distribution area is 0.5 mm~50 mm. Coarse sand: melon stone: the crushed stone is mixed completely and evenly in a ratio of 1:2:3 and then filled inside the simulation base of the broken rock mass, as shown in the Figure 2. In order to ensure the accuracy and comparability between the tests of each group, the final void rate error of the simulated fractured rock layer in each group of tests is required to be controlled at ±3%, otherwise the simulated fractured rock layer needs to be refilled. It is required to fill to the top of the model box until it cannot be filled, and follow the principle of surface filling.

In order to investigate the effect of different grout slurries on the grouting effect of the broken rock mass, a cement-water-glass sludge with a standard cement-based grouting sludge with a water-cement ratio of 0.8 and a final grouting pressure of 0.3 MPa was selected for the injection test. To investigate the effects of different spray pressures on the spray effect, the final spray pressure was set to 0.1 MPa and 0.5 MPa based on the cement-water-glass seal slurry. A total of 4 sets of grouting and reinforcement designs in the interior were made from broken permeable rock formations.

DOI: 10.54254/2755-2721/2025.28382



Figure 2. Simulation of permeable rock strata in fracture zone

2.3.2. Microstructure analysis

After 28 days of curing, scanning electron microscopy (SEM) was used to detect the microstructure of the sludge interface, and X-ray imaging (XRD) was used to analyze the types and contents of liquefaction products.

3. Results and analysis

3.1. Grouting material properties

The water separation rate of ordinary cement slurry was 12.3% and the cement water glass slurry was 5.8%, and the latter had better stability. The initial curing time of cement water glass lurry ≤ 2 minutes and the final curing time ≤ 5 min, which has the characteristics of fast curing and is suitable for a dynamic water environment.

3.2. Grouting effect analysis

The cement-water glass slurry had the largest diffusion range under 0.3 MPa grouting pressure, and the slurry was filled with filling. The diffusion range of ordinary cement slurry is small, and there are obvious water separation channels. When the grouting pressure rises to 0.5 MPa, the slurry diffusion range is further expanded, but it may cause rock mass splitting, and the upper limit of pressure should be controlled in combination with the actual project.

3.3. Microstructure analysis of magma-rock interface

It is the microstructure of SEM before and after the injection of the broken rock mass. It shows Figure 3 a that the surface porosity of ungrouted sandstone is high. Figure 3 b shows that most of the pores of the silt-rock interface after grouting are filled with a large number of flocculated gels, and the pores contain some larger calcite crystals perpendicular to the interface and extend to the inside of the rock, which can effectively improve the cementative strength of the magma-rock interface. In addition, some of the silt goes deep into the rock and undergoes complex chemical reactions with some ions present in the rock to produce a certain amount of hydration products, thus makes the slurry-rock interface denser, improves the cementing ability of the slurry-rock interface, and increases the van der Waals force between the slurry-rock interface.

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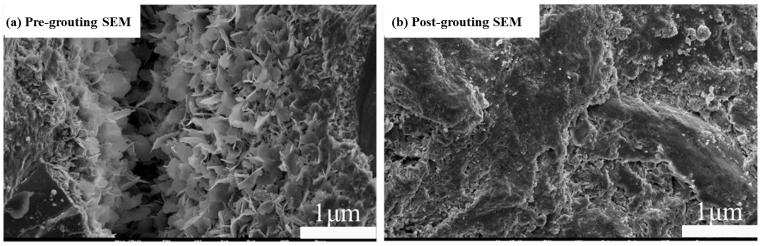

Figure 3. SEM microstructure before and after grouting of broken rock mass

When comparing the microstructure of the magma-rock interface with the rock-silt boundary surface model proposed by previous authors, it is found that the microstructure of the igma-rock interface is basically aligned with Jie Songshan's model, as shown in the Figure 4. The magma-rock interface is close to the contact layer with a thickness of about 2~3 μm on the surface of the rock, and some calcium hydroxide and a small amount of gel products grow perpendicular to the surface of the rock mass. The contact layer has a large amount of calcium hydroxide crystals, calcium aluminum and a small amount of gel products with a thickness of about 10~20μm, which is the enrichment zone and the weak effect zone. The moisture products of the interface are intertwined and arranged, and the partial liquefaction increases perpendicular to the rock surface, which can improve the shear strength of the slurry-rock interface.

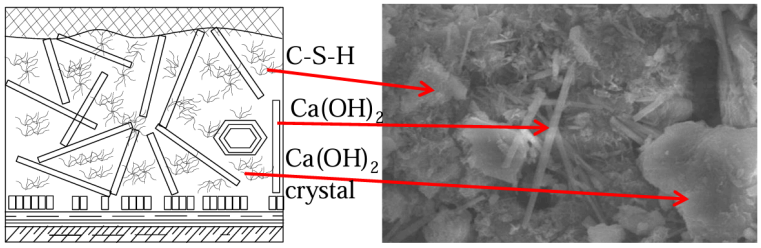

Figure 4. Comparison of magma-rock interface models

Figure 5 shows the microstructure of that slurry-rock interface after grouting with cement-based slurry and cement-water glass grouting materials, respectively. Figure 5 shows that the porosity of the slurry-rock interface after the reinforcement of cement-based grouting materials is relatively high, the density is low, and the content of calcium hydroxide and calcium alum is less, which is mainly due to the slow hydration reaction and high water separation rate of ordinary cement slurry. Comparing Figure 5 b, it found that the hydration products at the slurry-rock interface increase significantly after the reinforcement of cement-water glass slurry, and a large amount of calcium hydroxide, cementitious products and calcium alum are closely intertwined, so that the slurry-rock interface is closely connected into a whole, which effectively improves the bonding strength of the interface.

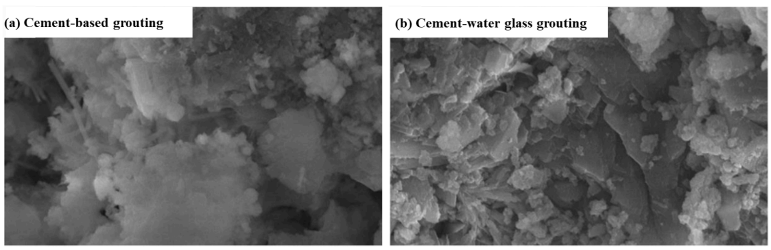

Figure 5. Comparison of slurry-rock interface with different grouting materials

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3.4. XRD phase analysis

In the preliminary analysis, the microstructure of the rock mass interface is analyzed, and it can be seen that in the process of injection and reinforcement of the fractured rock mass, the grouting hardens, so that the filling, skeleton, and binding of the fractured rock mass are fully utilized. However, the sludge can also undergo complex chemical reactions with fractured rock masses to form new liquefaction products, which changes the types and quantities of liquefaction products at the interfaces. In order to determine the changes in the hydration products of the magmatic rock interface after injection and reinforcement of the crushed rock mass, magmatic rock interface samples were selected in this section after injection and reinforcement of the cement water glass slurry, and the physical and chemical composition analysis was performed using X-ray diffraction technique. Figure 6 shows the XRD spectra of the magma-rock interface of cement, water, glass slurry, grouting, reinforced broken rock mass.

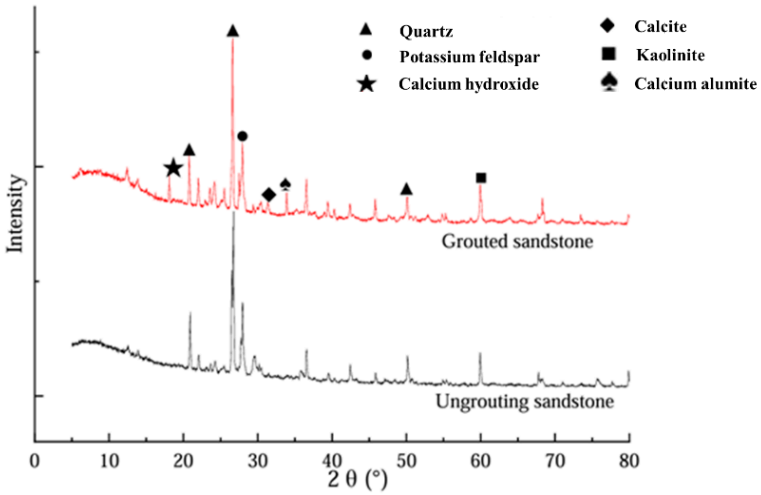

Figure 6. XRD spectra of rocks before and after grouting

As you can see in the figure, the first and second peaks before and after grouting are quartz and potassium feldspar, respectively, mainly because sandstone contains mainly oxygen, silicon, potassium and carbon. By comparing the XRD spectra before and after injection, it can be observed that the two peaks increase at 2θ=18.12° and 2θ=34.16° respectively, calcium hydroxide and calcite, which are mainly liquefaction products formed by the hydration reaction of cement, water, and glass. In addition, the peaks of potassium feldspar and kaolinite can be clearly improved, indicating that the penetration of cement water glass sludge into the rock can stimulate the activity of other elements and produce a certain amount of potassium feldspar and kaolinite, which improves the adhesion of the magmatic rock interface. The new peak is calcite around 2θ=31°, mainly due to the chemical reaction between the calcium ions in the slurry and the carbon ions in the rock to form calcite.

4. Summary

In this study, a grouting simulation test of predominantly fractured permeable rock mass was performed, revealing the amplification mechanism of various slurries, such as traditional cement-based grouting and cement-water-glass slurry in fractured rock formations, and the microstructure

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and physical and chemical composition of the solid rock-stone mass interface of the injection were analyzed by SEM and XRD microscopy. The main conclusions are as follows:

(1) According to the interior grouting model test, when the water-cement ratio is 0.8 and the final grouting pressure is 0.3 MPa, the grouting reinforcement effect of the cement water glazing material is better than that of traditional cement-based materials, and the different grouting materials have a significant effect on the reinforcement effect of grouting. At the same time, it has been observed that the higher the injection pressure, the larger the diffusion area of the sludge and the more adequately the empty spaces, pores and cracks of the fractured rock mass are filled, which indicates that the injection pressure has a certain effect on the reinforcement effect of the injection.

(2) The microstructure of the magma rock mass interface is obtained by SEM microscopy, and compared with the existing classical rock-cement sludge boundary surface transition zone model, it is observed that the magma-rock interface model is similar to the Jiesongshan model, and the type of cementation of the magmatic rock interface has been determined. The magmatic rock interface is dominated by CSH gel, CH and AFt, which have both physical filling and chemical cementation, which significantly improves the integrity and impermeability of the rock mass.

(3) XRD microscopy was used to compare the physicochemical composition of magmatic rock interfaces before and after grouting reinforcement, and after grouting, new chemical products were discovered that revealed the mechanism of grouting reinforcement of fractured rock masses.

(4) The research results can provide the basis for the selection of grouting materials and the optimization of process parameters in similar projects in Qingdao Metro.

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