Grouting Reinforcement Technology of Weak Fractured Rock Mass in Subway Open-cut Station

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Abstract: In the process of subway open-cut station construction, excavation deformation seriously threatens the safety of municipal pipelines and buildings. To ensure the effectiveness of grouting reinforcement, drilling exploration and pressure water test were conducted on the basis of the grouting reinforcement project of the excavation of an open-pit station in Qingdao metro, the permeability coefficient and crack characteristics were studied, and the equivalent crack width was calculated on the basis of cubic law. To determine the injectability index of grout and realize the optimal selection of grouting materials, the statistical distribution law of the equivalent crack width was analyzed on the basis of the Pareto distribution, and an effective method of grout selection was proposed. The PQT curve in the grouting process was analyzed by flow dimension theory to realize the dynamic adjustment of the grouting process. Finally, the grouting reinforcement effect was evaluated on the basis of the core sample and borehole TV. Results show that if the permeability coefficient is subject to Pareto distribution with parameters tmin and k, then the distribution curve of the permeability coefficient in the logarithmic coordinate is a straight line; the equivalent crack width obtained on the basis of the cubic law is also subject to the Pareto distribution with parameters bmin and 3k. Therefore, the equivalent crack width distribution curve can be obtained to provide a basis for the grout selection.

1. Introduction
With the rapid development of national economy, the scale of urban underground traffic is growing, and the subway has entered a period of rapid rise. However, the fractured rock stratum is often encountered in subway construction, and excavation can easily lead to filled soil instability, excavation deformation, and ground subsidence. Influenced by tectonic action and catchment conditions, the permeability coefficient and water content in different sections
vary, making the description of the information of rock mass fractures difficult and thus increases the difficulties in selecting grouting materials, determining the slurry diffusion distance, and designing grouting schemes. For the abovementioned aspects, relevant scholars have conducted the following research. In terms of obtaining the permeability coefficient, Jiang Zhongming et al. deduced the calculation formula of the permeability coefficient of fractured rock mass through the single well one- and three-stage pressurized water methods [1]. Dae et al. established a linear regression estimation model for the permeability coefficient [2]. Jin Qing et al. measured the permeability coefficient of metamorphic layer with an improved permeability coefficient tester [3]. In terms of slurry diffusion, Ye Fei et al. deduced the spherical displacement permeation diffusion model for back-wall grouting and proved that the displacement effect has a negative impact on slurry diffusion [4]. Li Shucai et al. revealed the influence mechanism of filtration effect on slurry diffusion and effective reinforcement range [5]. Regarding the design of grouting treatment scheme, Miao Qiangqiang et al. summarized the classification of geotechnical grouting technology and the selection of grouting materials. Finally, they described in detail the application of grouting parameters and grouting end standards in geotechnical engineering through engineering examples [6]. At present, most research is devoted to the investigation of slurry diffusion radius, but research on the relationship between rock penetration information and slurry selection is few.

To solve the above problems and fully consider the inhomogeneity of rock mass fractures, this study analyzes the fracture information obtained from field tests, calculates the equivalent fracture width on the basis of the cubic law, and finds that the fracture follows the Pareto distribution. According to the statistical distribution law of equivalent gap width, an effective method of grouting material selection is proposed. Finally, the rationality of slurry selection and grouting scheme is verified by drilling core and TV exploration, which has reference significance for grouting theory and the practice of fractured rock mass.

2. Engineering situation

The length of the main excavation of the station in this project is 173.0 m. The width of the standard section is 19.7 m, and the depth is 17.8–18.7 m. Through drilling, the thickness of the quaternary in this area is revealed to be approximately 5.00 m, which is mainly artificial fill and cohesive soils, and the bedrock is mainly tuff. Tuff is strongly weathered, and cores are basically fragmented, as shown in Figure 1. The late Yanshanian granite intrusion occurs locally. The geological profile of the intrusive body and nearby strata is illustrated in Figure 2. Affected by tectonic action, the joints and fissures of the rock mass are well developed within the work area, and sandy-soil-like and massive cataclastic rocks are widely developed. On the east side of the station is the Mahao Canal, which has abundant groundwater. Two months before the grouting treatment, the cumulative change of five water level observation points reached the early warning and alarm values, and the cumulative change of the DSW03 observation point was −3025.00 mm. To ensure the safety of the project, the grouting reinforcements of the east and west sides of the excavation for the cracked rock mass within the work area.

Analysis of the difficulties in the reinforcement of this project: i. The stratum in the reinforcement target area is fractured rock. After structural action and long-term weathering, fissures are developed, rock mass integrity is poor, and fissure water is abundant, which has
high requirements for grouting effects. ii. Abundant buildings exist around the station section, and the surface uplift is sensitive. At the same time, it may be accompanied by slurry running and intrusion into the basement. These factors all seriously increase the difficulty of grouting reinforcement. iii. During the grouting process, the deformation of the side walls of the excavation and the surrounding pipelines must be strictly controlled.

Figure 1. Partial core morphology

Figure 2. Third stratigraphic geological section

3. Grouting injectability index
To obtain the fracture information of the rock mass for grouting material selection, the permeability coefficient and fracture characteristics are obtained through borehole exploration and pressure water test; equivalent gap width and its statistical distribution law are also calculated. According to the equivalent fractured width distribution curve, the grouting injectability index is determined. Finally, the grouting material is optimized, considering the slurry viscosity.

3.1 Geological drilling exploration and field pressure water test
Before construction, drill wells vertically within a length of 50 m along the excavation with a depth of 20 m. The fracture information of rock mass exposed by the borehole is obtained by coring. Some cores are illustrated in Figure 2. The number of cracks contained in each borehole is counted, and the results are displayed in Figure 3. To obtain specific rock mass permeability parameters, the pressurized water test is continued in the abovementioned boreholes. The test results are shown in Figure 4.
The broken rock mass is grouted and reinforced. First, slurry selection is needed to ensure that the slurry can enter the fractures. However, the number of fractures and the permeability coefficient cannot indicate whether the granular slurry can effectively penetrate into the formation. The key to the slurry diffusion effect is whether the diameter of the slurry particles is smaller than the crack width, which is difficult to measure directly. The concept of equivalent gap width is introduced below to characterize the crack width.

3.2 Statistical distribution of the equivalent crack width

The equivalent gap width for natural fractured rock mass can be calculated by cubic law, and its expression is as follows:

\[ b = \left( \frac{T^{1/2} \mu_w}{\rho_w} \right)^{1/3}. \]  

In the equation, \( b \) is the equivalent crack width, \( T \) is the permeability coefficient, \( \mu_w \) is the dynamic viscosity of water, and \( \rho_w \) is the density of water.

The difference in the permeability coefficient of each section is evident, which leads to a large difference in the calculated equivalent crack width of each section. Moreover, judging the choice of grouting material is impossible. Grouting reinforcement requires that the slurry can enter most of the rock fractures to form a whole for achieving the best reinforcement effect. Another requirement is an analysis of the statistical distribution law of the equivalent crack width.
width, and the fracture information obtained from individual borehole is analyzed as a whole. During the pressurized water test, the random error in measuring the permeability coefficient of each borehole can also be reduced by analyzing the permeability coefficient as a whole. Considering the above explanation, the equivalent crack width is obtained, and the statistical distribution law is analyzed using statistical methods to select the grouting material. According to the research theory of Gustafson et al., if few large cracks and many small cracks exist in the crack network, then the crack permeability coefficient is approximately subject to the Pareto distribution [7], and its expression is as follows:

\[ F(T) = P(T > t) = \left( \frac{T}{t_{\text{min}}} \right)^{-k}. \]  

In the equation, \( k \) is the parameter of Pareto distribution, \( t \) is the permeability coefficient, \( t_{\text{min}} \) is the minimum permeability coefficient, and \( P(T > t) \) represents the cumulative percentage content of the permeability coefficient greater than \( t \).

Taking permeability coefficient \( t \) as the abscissa and \( P(T > t) \) as the ordinate, the sample points are plotted in logarithmic coordinates. The results are illustrated in Figure 5. In the range of \( 10^{-9}–10^{-5}\text{m/s} \), the permeability coefficient is approximately a straight line in logarithmic coordinates. A linear regression analysis is performed on these data points to find the straight-line equation and fit the straight-line equation image. The calculated slope of the straight line is \(-0.450\), that is, the \( k \) value is 0.450, and the correlation coefficient is 0.886. The calculation result is presented in Figure 5. (The data of the last two points in Figure 5 have a large deviation and are discarded in the calculation.)

\[ \lg P(T > t) = -k \cdot \lg t + k \cdot \lg t_{\text{min}}. \]  

Evidently, the image of Equation (3) is a straight line in logarithmic coordinates, where \(-k\) is the slope of the straight line, proving the correctness of the above calculation results. If the permeability coefficient follows the Pareto distribution with parameters \( t_{\text{min}} \) and \( k \), then the distribution curve in logarithmic coordinates is a straight line with a slope of \(-k\) and a vertical intercept of \( k \cdot \lg t_{\text{min}} \).

From Equations (1) and (2) and the properties of the Pareto distribution function, the equivalent crack width follows the Pareto distribution with parameters \( b_{\text{min}} \) and \( 3k \):
In the equation, \( P(B > b) \) represents the cumulative percentage content of the equivalent crack width greater than \( b \), and \( b_{\text{min}} \) is the minimum value of the equivalent crack width. The logarithmic coordinate is used for drawing, the abscissa is the equivalent crack width \( b \), and the ordinate is \( P(B > b) \). The results are shown in Figure 6, which reflects the relative content of different crack widths in the rock mass and is a geometric figure that intuitively reflects the equivalent crack width of the rock mass. The uniformity of the crack width can be roughly judged according to the slope of the distribution curve of the equivalent crack width. The curve is steep, indicating that the crack width is similar, and the distribution of the equivalent crack width is relatively uniform. The curve is slow, suggesting that the crack width is different, and the distribution of the equivalent crack width is uneven.

**Figure 6. Distribution curve of the equivalent crack width**

### 3.3 Determination of grouting material considering viscosity

Figure 6 displays that the probability of equivalent crack width \( b \geq 100 \mu m \) is 0.83 (recorded as \( b_{83} = 100 \mu m \). \( b_{83} \) is called slurry injectability index.) Therefore, superfine cement is selected as the main grouting material. Considering the slurry injectability, two key material parameters exist: critical crack width \( (B_{\text{crit}}) \) and minimum plugging crack width \( (B_{\text{min}}) \) \[8\]. When the \( B_{\text{min}} \) of the slurry is greater than the crack width, the slurry cannot be injected into the crack. When the \( B_{\text{crit}} \) of the slurry is larger than the crack width and the minimum plugging gap width is smaller than the crack width, the diffusion of the slurry is affected by the filtration effect, and the final diffusion distance is reduced. When the \( B_{\text{crit}} \) of the slurry is smaller than the crack width, the diffusion of the slurry in the crack is mainly affected by the viscosity of the slurry itself, but not by the crack. In view of these conditions, pre-grouting tests are conducted on several commonly used superfine cements in Table 1. The results indicate that only 1250 mesh superfine cement slurry can be injected into the stratum, and other specifications of superfine cement exhibit a small amount of slurry injection and a large grouting pressure. An indoor test is also performed to determine the physical and chemical properties of the 1250 mesh superfine cement slurry. Three slurries with different water–cement ratios are tested. The main properties are shown in Table 2. To ensure the slurry diffusion and the consolidation strength, 1250 mesh superfine cement (water–cement ratio 1:1) are finally selected as the grouting material. Under the condition of water–cement ratio, \( B_{\text{crit}} = 80 \mu m < b_{83} = 100 \mu m \), the diffusion of the slurry in the crack is controlled by the viscosity of
the slurry itself. The slurry viscosity and $B_{\text{crit}}$ increase with time. $B_{\text{crit}}$ increases to $b_{31}$ after 104 min from the initial state of the slurry, and the slurry diffusion is always controlled by its own viscosity within 104 min.

### Table 1. Parameters of several kinds of superfine cement commonly used in engineering

| Model       | 600 mesh | 700 mesh | 800 mesh | 1000 mesh | 1250 mesh |
|-------------|----------|----------|----------|-----------|-----------|
| D50         | $\leq 6$ | $\leq 5.5$ | $\leq 4.8$ | $\leq 4.5$ | $\leq 4$  |
| D90         | $\leq 20$ | $\leq 17$ | $\leq 15$ | $\leq 12$ | $\leq 10$ |
| Average grain diameter ($\mu$m) | 6 | 5.8 | 5.2 | 4.5 | 4 |
| Specific surface area ($m^2/kg$) | 550 | 650 | 700 | 750 | 800 |

### Table 2. Parameters of 1250 mesh superfine cement slurry with different water–cement ratios

| Water–cement ratio | Slurry density ($kg/m^3$) | Yield stress ($Pa$) | Viscosity ($Pa\cdot s$) | $B_{\text{men}}$ ($\mu m$) | $B_{\text{crit}}$ ($\mu m$) |
|--------------------|--------------------------|---------------------|-------------------------|---------------------------|-----------------------------|
| 1.0                | 1510                     | $1.6^{2500}$        | $0.022^{22500}$         | 50                        | $80 + \frac{t}{312}$        |
| 1.5                | 1360                     | $1.01^{2500}$       | $0.037^{22500}$         | 44                        | $72 + \frac{t}{312}$        |
| 2.0                | 1270                     | $0.31^{2500}$       | $0.068^{22500}$         | 40                        | $66 + \frac{t}{312}$        |

### 4. Dynamic regulation of grouting parameters

The arrangement of grouting wells is as follows:

Six rows and 28 columns of grouting wells are involved in the radial grouting scheme on the west side of the excavation, with a total of 168 wells. The drilling depth is 3.5 m, the horizontal spacing is 1.6 m, and the vertical spacing is 2 m. The sealing length of the borehole orifice-pipe is 8 m. The inclination of the grouting wells is shown in Figure 7. The grouting scheme on the east side of the excavation is designed with a row of 18 grouting holes. The drilling depth is 20 m, the spacing is 2.5 m, and the sealing length of the borehole orifice-pipe is 8 m. The construction technology is forward sectional grouting (The first section is 8–14 m, whereas the second section is 14–20 m.) with 2 m pressure-isolating expansion mold bags.
Changes in grouting pressure and grouting volume during grouting are monitored in real time, and the PQT curve obtained by the theoretical analysis of flow dimension proposed by Gustafson et al. is introduced [9].

\[ W = \frac{Q t}{V}, \]  

(9)

where \( W \) represents the flow dimension, \( Q \) represents the flow rate, \( t \) means the grouting time, and \( V \) represents the slurry flow rate. When \( W > 1 \), it is a 3D fracture flow. When \( 0.45 < W \leq 1 \), it is a 2D fracture flow, and when \( W \leq 0.45 \), it is a 1D fracture flow. Therefore, in the grouting process, the flow dimension of the grout can be judged according to the PQT curve, and the parameters of injection grout can be adjusted in time. If \( W > 1 \), then the grout flows in a well-connected crack, and grouting wells should be added for grouting. If \( 0.45 < W \leq 1 \), then the slurry flow is in a 2D state, and the grouting amount should be appropriately increased. If \( W \leq 0.45 \), then the slurry flow is in a 1D state and usually, the fissure water can be blocked only by meeting the grouting pressure and grouting quantity requirements.

**Figure 8.** PQT curve of grouting well construction

\( W_{\text{max}} = 0.43 < 0.45 \) in Figure 8 is calculated by Equation (9), which shows that slurry flow is always in a 1D state, and the blocking of fissure water can be completed only by meeting the requirements of grouting pressure and grouting quantity according to the design. Facts suggest that the PQ of the whole grouting process in Figure 8 shows an inverse correlation trend, that is, the grouting amount gradually decreases as pressure increases, indicating that the slurry gradually blocks up the slurry running channel and loose area. When it is close to the designed grouting time, the grouting pressure reaches the design final pressure of 4 MPa; the grouting volume decreases rapidly; finally, the grouting reinforcement effect is satisfied.

### 5. Grouting reinforcement effect

After grouting reinforcement, no water flows out of check wells, and the core taken out from the well is illustrated in Figure 9. After the grouting is completed, the grout fills the cracks, and the fragmented rock before grouting is bonded into a whole by grout, making the core more complete than before. The comparison of borehole TV results before and after grouting is shown in Figure 10. Before grouting, the well wall is uneven, and a huge collapse occurs in the well, whereas after grouting, the well wall is smooth, and no collapse occurs in the well. The slurry fills the cracks and binds the broken rock blocks together. Therefore, the permeability coefficient and strength of the stratum meet the engineering requirements. The grouting reinforcement effect of this project for the fractured rock mass is good.
6. Conclusion
This article investigates the fractured rock mass grouting reinforcement design problem, and field experiment is conducted to obtain rock fracture information. The equivalent crack width is calculated by cubic law, and the statistical distribution law of the equivalent crack width is obtained on the basis of Pareto distribution analysis. Finally, the grouting material is optimized, considering the slurry viscosity, which is successfully applied in the project reinforcement. Some beneficial conclusions are obtained during the research process:

1. If the permeability coefficient of fractured rock mass obeys the Pareto distribution with parameters $t_{\text{min}}$ and $k$, then the distribution curve of the permeability coefficient in logarithmic coordinates is a straight line with a slope of $-k$, and the equivalent crack width obtained on the basis of cubic law obeys the Pareto distribution with parameters $b_{\text{min}}$ and $3k$. Parameter $k$ is obtained through linear regression, and then substituted into the Pareto distribution function. The statistical distribution law of the equivalent crack width can be obtained, thus providing the basis for the slurry selection.

2. According to the statistical distribution law of the equivalent crack width, the probability of equivalent crack width $b \geq 100 \mu m$ is determined as 0.83 (Marked as $b_{83} = 100 \mu m$. $b_{83}$ is called slurry injectability index.) Thus, the optimization process of slurry selection is realized. However, note that the $B_{\text{crit}}$ of slurry is less than a certain value of $b_{83}$ to ensure that the migration of slurry in the fracture is always controlled by its own viscosity.

3. The results of borehole TV and cores of rock show that the rock mass fracture is fully filled with grout, the loose body is reinforced, and the grouting reinforcement achieves a good treatment effect, thereby verifying the effectiveness of the adopted grouting reinforcement scheme.

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