Grouting effect evaluation of fractured rock mass based on borehole televiewer observation

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Abstract. Grouting is a common means to improve the strength and anti-seepage performance of fractured rock mass. Due to crack concealment, evaluating the grouting effect is a critical problem. An evaluation method of the grouting effect based on borehole televiewer observation is proposed. The optical image of the borehole wall is obtained using a borehole televiewer observation, and the fracture-filling characteristics in the measured image are recognized. The evaluation index is established based on the number of filled and unfilled cracks, defined as the borehole fracture-filling index (BFFI). By analyzing the relationship between BFFI and packer permeability test results, the evaluation standard based on BFFI is established. The evaluation method is applied to a grouting test of a hydropower station’s fractured rock mass. The results show that (1) the grouting effect evaluation results of the packer permeability test and BFFI methods correlate well. (2) The grouting effect evaluation method not only visually shows the filling characteristics of grouting but also quantifies the grouting effect.

Keywords: grouting effect evaluation; borehole televiewer; cracks; packer permeability test; fractured rock mass

1. Introduction
Grouting is a common technical process in anti-seepage reinforcement treatment of fractured rock mass, improving the rock mass quality and forming a new stone body with high strength, anti-seepage, and good chemical stability. It can fill the cracks, consolidate the surrounding rock, plug the water inrush, and is efficient to ensure engineering safety. However, the grouting effect is invisible, limiting the development of grouting effect evaluation. A reasonable and effective method for grouting effect evaluation is critical to ensure the grouting quality. Commonly, grouting effect evaluation adopts a mechanical test for consolidation effect and pressure water test for seepage prevention effect. These methods are targeted by detecting the corresponding effect index, but limitations exist. Especially, in abnormal detection results, it is challenging to analyze the cause and lack a comparison of other visual results.

Some scholars have studied new methods for grouting effect evaluation. Fransson et al. (2007) proposed a new parameter to assess hydromechanical effects in single-hole hydraulic testing and grouting. Hernqvist et al. (2009) analyzed the APSE tunnel’s grouting results on original cored borehole data drilled before the tunnel was constructed. Salimian et al. (2017) conducted a systematic comprehensive study on the effect of consolidated grouting on the mechanical behavior of cracks. Zhang et al. (2017) proposed a new set of analytical solutions for predicting the effect of grouting on
ground and shield tunnel behavior because of steady water inflow into a tunnel in saturated clay. Zhang et al. (2012) established the relationship between the speed increase rate of rock mass after consolidation grouting and the wave velocity before grouting. They proposed that the relation between the wave velocity increase rate and the wave velocity before grouting can predict the consolidation grouting effect of rock mass. Gao (2004) used the rock integrity index to evaluate the effect of bedrock grouting. Most grouting effect evaluation methods are indirect and nonvisual. Filling cracks with grouting fluid is the most direct reflection of the grouting effect. How to observe the filling degree of cracks and conduct quantitative identification is critical for grouting effect evaluation. In this paper, borehole televiewer technology is used to observe crack filling after grouting and identify the filled and unfilled cracks. A new grouting effect evaluation index named the borehole fracture-filling index (BFFI) is proposed. A correlation study between the water pressure test results and BFFI is conducted, and the grouting effect evaluation standard based on the BFFI is established. The method is verified and practicable in engineering practice.

2. Cracks from borehole televiewer observation

Borehole televiewer observation is a common geophysical prospecting method in boreholes. It can reflect the rock mass structure from the borehole wall image, especially the crack filling condition after grouting (Figure 1). The borehole televiewer is based on the optical principle and can detect inside the borehole and record undisturbed borehole wall video data. The optical images are more visual, and we can recognize the crack trace by digital image processing (Han et al. 2016; Wei et al. 2007; Han et al. 2015; Yuan et al. 2020).

The borehole image is a color image of the borehole wall formed by transforming the panoramic image. The difference in light reflection from structures, such as rock mass, crack openings, and cement filling, show obvious differences. According to the cement filling feature in cracks, the cracks in the borehole image can be divided into filled and unfilled cracks (Figure 1). Unfilled cracks are dark on the borehole image because of the open and less reflection of light. Filled cracks are gray on the borehole image because of the cement filling.

Because of the limitation of fracture recognition accuracy from borehole images, this study explains the following. (1) Under the premise of crack groutability, microcracks are easier to be filled; therefore, normal cracks (width greater than 0.1 mm) are the principal factors affecting the grouting effect. The object of this paper is normal cracks. (2) The length of the trace formed in the borehole image is short, and the cracks observed in the borehole image are mostly filled or unfilled, rarely half-filled. This paper does not consider half-filled cracks.

![Figure 1. Schematic diagram showing how the borehole televiewer observes the fracture-filling condition](image)

3. Cracks from borehole televiewer

3.1. Evaluation index based on the fracture-filling condition

The most direct reflection of the grouting effect is the cement filling in fractures. Using the characteristics of fractures to evaluate the grouting effect, judging the fracture-filling condition is
critical. The borehole televiewer can observe and quantify the fracture-filling condition, reflecting the grouting effect to some extent.

Taking a borehole image of a certain length as the study object, \( N_1 \) is the number of filled cracks, and \( N_2 \) is the number of unfilled cracks. The more filled cracks there are, the better the grouting effect; therefore, the number of filled cracks is positively correlated with the grouting effect. However, the more unfilled cracks there are, the worse the grouting effect; therefore, the number of unfilled cracks is negatively correlated with the grouting effect. Therefore, a grouting effect evaluation index based on the number of filled and unfilled cracks is established, defined as the BFFI. Equation (1) shows the calculation.

\[
BFFI = \frac{N_1 - N_2}{N_1 + N_2}
\]  

BFFI has four features.

1. When the fractures in the borehole are filled \((N_2 = 0)\), the BFFI result is 1; the grouting effect is the best.
2. When the fractures in the borehole are unfilled \((N_1 = 0)\), the BFFI result is \(-1\); the grouting effect is the worst.
3. When the numbers of filled and unfilled fractures are the same, the BFFI result is 0. However, the grouting effect varies with the number of unfilled fractures. Here, Equation (1) is inapplicable and should be analyzed separately.
4. Without considering (3), the BFFI values range between \(-1\) and 1. The higher the BFFI is, the better the grouting effect.

3.2. Evaluation standard based on BFFI
Permeability is the result of the pressurized water test reflecting the water permeability rate of the rock mass. It is the most used evaluation index of the grouting effect. The BFFI reflects the filling condition after grouting. The higher the BFFI value is, the better the grouting effect is and the smaller the water permeability rate. The two indices should have an inverse correlation.

Recently, authors accumulated numerous pressurized water test results from several grouting projects and corresponding borehole televiewer results. Taking each pressurized water test section as a study unit, the BFFI in the corresponding borehole image was calculated. In the coordinate system, taking the serial number of sample data as abscissa, and the permeability rate and BFFI as ordinate, the resulting curve is drawn (Figure 2).

![Figure 2](image)

Figure 2. Corresponding relationship between the permeability rate and BFFI

Figure 2 shows the inverse relationship between the permeability rate and BFFI. Where the permeability rate has an extreme value, the BFFI also has an extreme value. Some functional relationship might exist between the two indices. Taking the BFFI as the abscissa and the permeability rate as the ordinate,
rate as the ordinate, the relationship scatter diagram is drawn (Figure 3). Except for several abnormal points in the relationship scatter diagram, most sample points conform to a good fitting curve. After eliminating the abnormal points, the relationship curve between the two indices is drawn (Figure 4). The cubic polynomial can better fit the relationship between the two indices and the coefficient of determination $R^2 = 0.9894$; therefore, the fitting degree is good.

![Figure 3. Scatter diagram of the permeability rate and BFFI](image)

![Figure 4. Relationship curve of the permeability rate and BFFI](image)

Through curve fitting, the empirical function relationship between them is

$$y = -13.019x^3 + 26.037x^2 - 17.929x + 4.5695$$

(2)

Using the conventional permeability rate standard, the corresponding BFFI can be calculated using Equation (2). Generally, the water permeability design standard of the dam foundation rock mass is 1–5 Lu. Based on Equation (2), according to the BFFI calculated using each permeability rate design standard, the grouting effect evaluation standard based on BFFI is established (Table 1).

| Permeability rate | BFFI |
|-------------------|------|
| 5 Lu              | −0.023 |
| 3 Lu              | 0.102 |
| 1 Lu              | 0.334 |

4. Case study

The Tongzilin hydropower station is the last in the lower reaches of the Yalong River, a tributary of the Yangtze River. The dam’s bedrock is new to weakly, weathered tonalite migmatite, with many unfilled joints and fissures. Before grouting the fractured rock mass, a grouting test was conducted in a bid section to understand the grouting characteristics and indices to guide grouting construction.
After grouting, four boreholes (ZK10, ZK12, ZK16, and JC-1) were selected to conduct a pump-in test and borehole televiewer. Taking the pump-in test section as the basic study unit, the permeability rate and BFFI of each study unit were compared. To compare the two indices more intuitively, the BFFI is taken as the abscissa and the permeability rate as the ordinate. The results of each research unit are drawn into the coordinate system in the form of coordinate points (Figure 5). For the standard 5 Lu, the red area in the coordinate indicates that it meets the evaluation standard of the permeability rate, and the blue area indicates that it meets the evaluation standard of the BFFI.

![Comparison of the two evaluation methods](image)

**Figure 5.** Comparison of the two evaluation methods

Let A be the set number of research units meeting the permeability evaluation standard (red area) and B be the set number of research units meeting the BFFI evaluation standard (blue area). The coordinate area meeting any evaluation standards is the union of blue and red areas (Equation (3)).

$$N_{A \cup B} = 24$$  \hspace{2cm} (3)

The coordinate area meeting the two evaluation standards is the intersection of red and blue areas (Equation (4)).

$$N_{A \cap B} = 20$$  \hspace{2cm} (4)

The coincidence degree $R$ is defined as the ratio of the number of sample points meeting both evaluation criteria and the number of sample points meeting any evaluation standards (Equation (5)).

$$R = \frac{N_{A \cap B}}{N_{A \cup B}} = 0.833$$  \hspace{2cm} (5)

The higher the $R$-value is, the more consistent the results are of the two evaluation methods. The results show that the BFFI evaluation results correlate well with the permeability rate evaluation results. The BFFI can reflect the effect of grouting to a certain extent, verifying the feasibility of using this method to evaluate the grouting effect.

The borehole wall image can show the filling degree in the cracks, verifying the permeability rate accuracy. It can also be an analysis basis for permeability rate abnormality. From Figure 6(a), the cracks in the borehole image is filled when the BFFI of this section is 0.832; therefore, the grouting effect is good. The permeability rate from the pump-in test is 0.45 Lu; therefore, the grouting effect is
good. The results of the two methods are consistent. From Figure 6(b), the cracks in the borehole image are unfilled when the BFFI of this section is $-0.158$; therefore, the grouting effect is bad. However, the permeability rate from the pump-in test is 0.83 Lu; therefore, the grouting effect is good. The results of the two methods are inconsistent. Therefore, it is proposed to use the secondary pump-in test and cause analysis of unfilled cracks to verify the results.

![Filled cracks](image1.png)
![Unfilled cracks](image2.png)

(a) Filled cracks  
(b) Unfilled cracks

**Figure 6.** Filling feature of cracks in borehole image

5. Conclusion
The difference between filled and unfilled cracks can be identified using a high-precision borehole wall image. According to the influence of different filling conditions, an evaluation index of the grouting effect based on the BFFI was established. The correlation between the permeability rate and BFFI results is fitted using the cubic polynomial. The BFFI method's evaluation standard was established according to the conventional pump-in test's evaluation standard. The evaluation method was applied to a hydropower project. The two methods correlated well, verifying the feasibility of the BFFI method. Using borehole televiewer technology to evaluate the grouting effect breaks through the limitation of a single evaluation index and provides a new idea and method for comprehensively evaluating the grouting effect.

**Declaration of competing interest**
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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