Study on shear fracture flow capacity of hard brittle rocks

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Abstract. It is of great significance for the construction and operation of high head pumped storage power station, high dam project and deep tunnel project to master the seepage characteristics and laws of rock mass shear fracture. In this paper, the seepage characteristics of marble shear fractures are summarized as follows. (1) In the radial seepage test, the seepage process conforms to darcy's law, and there is a linear relationship between head pressure and flow. (2) The characteristics of local tensile failure in the cracks generated under low normal force during the shear process hinder the seepage. (3) The normal force has a significant influence on the fracture seepage. In the process of the normal force increasing from 36kN to 48kN, the seepage characteristics show a sudden change, and the contact form of the shear fracture surface changes, indicating that part of the seepage channel in this stage appears a closed phenomenon with the increase of the normal force, and a large area of closure is formed in the fracture.

1. Introduction

The essence of engineering seepage instability is that water enters into the pores and fissures of surrounding rock, which causes the redistribution of stress field of surrounding rock and increases the opening of original pores and fissures of surrounding rock, even create new cracks. In turn, the deformation of surrounding rock and provides a more powerful seepage path, adding to the seepage influence on surrounding rock. Under the condition of high water pressure, the mutual promotion between seepage and surrounding rock may cause outburst and water inrush, resulting in engineering accidents. Therefore, it is increasingly important to study the flow capacity and permeability of rock fractures[1]. Iwai et al.[2] found that the influence of roughness of fracture surface on fracture flow law was mainly related to contact rate of fracture surface area; Morteza Javadi et al.[3] studied the effects of shear on critical Reynolds number and nonlinear flow characteristics, and established a quantitative criterion for nonlinear flow by combining fushi's law and Reynolds number; Zhou et al.[4] conducted the seepage test on the fractured granite fracture surface and the sandstone samples with slight dislocation in the fracture surface; Zou et al.[5] studied the influence of shear fracture structure change and flow condition change on nonlinear flow. Li et al.[6] used the micro CT scanning technology to scan the tight sandstone samples, established the microscopic model that can finely depict the rock samples, and simulated the seepage characteristics of fluid in the rock pores. Single fracture is the basic element that constitutes the fracture network of rock mass, and the seepage law of
single fracture is the foundation of the seepage law of fractured rock mass. But at present, the study on seepage law of shear fracture in hard brittle rocks needs to be strengthened. The purpose of this paper is to study the flow capacity of shear fractures in hard brittle rocks. Therefore, taking marble as an example, the seepage characteristics of shear fractures in hard and brittle rocks are studied by controlling the infiltration flow, which provides a theoretical basis for the stability analysis of the surrounding rock of deep buried tunnel.

2. Experimental research

2.1. Test rock sample
In this experiment, samples were made of fine-grained marble, sample size for Φ50×100mm. The uniaxial compressive strength was about 125MPa by uniaxial compression test. The cylindrical sample was drilled with a diamond drill bit at a depth of 60mm and a bore diameter of 4mm. The finished sample is shown in figure 1. The longitudinal wave velocity of the cylindrical sample is between 2460 (m/s) and 2750 (m/s).

![Figure 1. Schematic of drilled Marble sample](image)

2.2. Direct shear test
Table 1 shows the values of normal stress and peak shear stress of samples J1~J4 in direct shear test. Normal stress σn and shear stress τ can be respectively as follows.

| Sample | Normal force (kN) | Normal stress (MPa) | Peak shear force (kN) | Peak shear stress (MPa) |
|--------|-------------------|---------------------|-----------------------|------------------------|
| J1     | 12.160            | 6.448               | 35.320                | 18.730                 |
| J2     | 12.140            | 6.425               | 41.056                | 21.772                 |
| J3     | 12.120            | 6.396               | 35.900                | 18.945                 |
| J4     | 12.120            | 6.385               | 40.280                | 21.221                 |

2.3. Fracture surface morphology analysis
The scanning of fracture surface is completed by Photographic 3d scanning system. The cloud data of crack fracture were obtained by this equipment, then import the cloud data into Geomagic Studio for mesh surface encapsulation. Finally, noise data outside the rock structure plane was deleted. Thus, the reconstructed digital image shown in figure 2 is completely consistent with the surface morphology of the fracture surface. From left to right, figure 2 shows the morphologies of shear sections formed by specimen J1, J2 and J3 under the normal pressure of 12kN. The shear fracture surface of J1 and J2 is relatively flat compared with that of J3. The local shear fracture surface of J3 presents the characteristics of tensile failure, with a large range of protrusions and grooves. Such local tensile failure characteristics may have a certain impact on the seepage characteristics of the fracture surface.
The calculation formula of three-dimensional roughness coefficient $Z_{2S}$[7] is shown in equation (1).

$$Z_{2S} = \frac{1}{(N_x-1)(N_y-1)} \left[ \sum_{i=1}^{N_x-1} \sum_{j=1}^{N_y-1} \frac{(z_{i+1,j} - z_{i,j})^2 + (z_{i,j} - z_{i-1,j})^2}{2\Delta x^2} \right]$$

Herein: $\Delta x$ and $\Delta y$ are the sampling interval in $x$ direction and direction respectively; $z_{i,j}$ is the Z direction coordinate of the sampling point; $N_x$ and $N_y$ are the number of sampling points in $X$ direction and $Y$ direction respectively.

The parameters of 3D morphology calculated by Matlab are shown in table 2. It can be seen that under the constraint of the same normal force, the roughness of fracture surface obtained by shear failure has a certain difference. According to the three-dimensional roughness coefficient $Z_{2S}$, the roughness of fracture surface $J_1$, $J_2$ and $J_3$ increases successively. Secondly, the peak difference of fracture surface $J_1$, $J_2$ and $J_3$ also increased successively. Therefore, the Matlab calculation results are consistent with the macro features shown in the Geomagic Studio processed reconstruction image of the fracture surface, that is, the roughness of the fracture surface $J_1$, $J_2$ and $J_3$ increases successively.

| Sample | $Z_{2S}$ | $R_s$ | Maximum height(mm) | Minimum height(mm) | Maximum height difference(mm) |
|--------|----------|-------|---------------------|--------------------|-------------------------------|
| $J_1$  | 0.2893   | 1.0371| 1.7996              | -1.6513            | 3.4509                        |
| $J_2$  | 0.3202   | 1.0475| 3.9244              | -1.6909            | 5.6154                        |
| $J_3$  | 0.3672   | 1.0562| 4.0739              | -1.8185            | 5.8925                        |
| $J_4$  | 0.3233   | 1.0462| 2.8525              | -2.9801            | 5.8327                        |

2.4. Fracture seepage test
The seepage test was carried out by the seepage test instrument as shown in figure 3. Before the test, the fracture surface of the shear sample was closed along the mark line, and the side of the sample with water injection channel was bonded to the seal gasket with epoxy resin glue. At the beginning of the test, normal force is applied to the fractured sample with a loading rate of 1kN/s. When the normal force is loaded to a predetermined value, open the water valve between the supplementary water tank and the water pump, fill the water pump with water, and close the water valve between the water pump and the supplementary water tank when the water pump is filled. At the beginning of seepage test,
open the water valve between the water pump and the rock sample and start the seepage test in the fracture.

3. Seepage characteristics of fracture surface under constant normal force

Constant normal force of 12kN was applied to shear samples J1, J2 and J3. After the normal force was loaded to a predetermined value, fracture seepage was started. The flow rate started from 1ml/min and rose to 15ml/min successively, and then the hydraulic head pressure under a series of flows was measured. Under the normal force of 12kN, the relation curve of flow-infiltration water pressure on the crack surface of specimen J1, J2 and J3 is shown in figure 4. It can be seen from the figure that in the seepage curve of specimen J1, J2 and J3, the head pressure increases linearly with the increase of flow rate, and the seepage process roughly conforms to Darcy law. In the seepage curve, with the increase of flow rate, the pressure growth rate of J1, J2 and J3 water heads was gradually accelerated. The seepage curves of J1 and J2 are relatively close, while the seepage curves of J3 show that the hydraulic head pressure is significantly higher than that of J1 and J2 at the same flow rate. This means that under the same head pressure, the seepage process in J1 and J2 fractures is easier than that in J3.

We find that there are two main reasons for this phenomenon: (1) as can be seen from figure 4, the roughness coefficients of J1, J2 and J3, Zs, increase successively, indicating that the roughness degree of fracture has a certain influence on seepage, that is, the greater the roughness degree of fracture surface, the greater the obstruction effect on seepage. (2) figure 5 is a schematic diagram of radial seepage, in which the black arrow represents the direction of seepage. It can be seen from the figure 5 that the local tensile failure characteristics in the J3 fracture surface hinder the progress of radial seepage in some directions, so as to create a seepage advantage channel. As a result, the seepage process is mainly parallel to the direction of protrusion and groove, while perpendicular to the direction of protrusion and groove, the seepage process is hindered. It can be inferred that the local
tensile failure characteristics generated during the shear process of marble will hinder the seepage process.

This is consistent with the test results in literature[8] that the tensile crack surface is relatively smooth and the two sides can contact closely under the action of pressure, resulting in a sharp decrease in the hydraulic opening.

Figure 5. Schematic diagram of radial seepage

4. Conclusion

The purpose of this paper is to study the relationship between the seepage flow rate, the seepage head and the normal constraint force of the fracture in the process of marble shear fracture seepage. The conclusions are as follows, which have certain guiding significance for the construction and operation of high head pumped storage power station, high dam project and deep tunnel project.

(1) In the radial seepage test, when the flow rate is within the range of 0~15ml/min, the seepage process is characterized by linear darcy flow, that is, the head pressure increases linearly with the increase of the flow rate.

(2) The local tensile failure characteristics generated during the shear process of marble hinder the seepage of shear fractures.

(3) In the process of fracture seepage, the influence of normal force on seepage is more significant than that of fracture surface morphology.

(4) During the increase of normal force from 36kN to 48kN, the contact form of upper and lower crack surface changed. During the process, some seepage channels closed with the increase of normal force, and a large area of stagnant water was formed in the fracture surface.

Based on the test method adopted in this paper, the author will carry out seepage test research on marble fractures with different sizes, and further verify and improve the results obtained in this paper.

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