Flow Characteristics of Deep Fractured Rock Mass under Water-Rock Mass Coupling

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Abstract. The deeply fractured rock mass exists in the environment of in-situ stress and high seepage pressure, and they are prone to seepage-slipping failure. Therefore, it is of excellent engineering value and theoretical significance to study the nonlinear seepage evolution of fractured rock mass under water-rock mass coupling. This paper taking the persistent fracture granite as a tested sample, a series of seepage tests of persistent fracture granite under different seepage pressures were carried out. The nonlinear seepage evolution of fractured granite with different JRC values under water-rock mass coupling was studied, and the 3D reconstruction of the fracture surface was carried out after the experiment. The influence of the roughness degree of fracture surface on the permeability of fractured rock mass is investigated. Based on the experimental results, the non-darcy flow behavior of the fractured granite is analyzed by using the quadratic function-type Forchheimer formula. The results show that the permeability of the fractured granite increases nonlinearly with the increase of seepage gradient when the volume flow rate over 20mm3/s; The research results are of great significance for the study of nonlinear seepage evolution of rock mass with different JRC values under high in-situ stress and high seepage pressure.

1. Introduction
With the reduction of the earth's surface resources and the improvement of human engineering technology, hydropower projects and coal mine projects are gradually advancing to the depths of the earth. For example, the vertical excavation depth of the Baihetan Hydropower Station powerhouse is larger than 260m; the excavation depth of the underground powerhouse in the Jinping I Hydropower Station is 110–300 m; the maximum excavation depth of the diversion tunnel in the Jinping II Hydropower Station is larger than 2525 m. Deep-buried rock masses often under complex geological environments condition, such as high in-situ stress and high seepage pressure. So deep-buried rock masses often have huge amounts of joints, which are prone to burst, water gushing and shear-slipping damage. Therefore, studying the seepage law of rock masses is a hot issue and scientific frontier in engineering fields, it is also an essential basis for predicting the amount of water inrush from deep-buried rock masses.

Many scholars have studied the seepage law of fractured rock by conducting a large number of experiments, which is the basis for studying the seepage characteristics of fractured rock masses[1][2][3]. Snow[4][5] proposed the cubic law of fracture based on the Navier-stokes equation,
which can analyze the basic seepage characteristics. Furthermore, Louis[6] modified the cubic law by experimental study. However, the fracture joint surface is uneven in practical engineering, which has certain undulation, so the cubic law based on smooth plates is not exact enough. To study the influence of roughness, hydraulic opening and contact area on the seepage law, many scholars have carried out a lot of researches. Zhang et al.[7] and Wang et al.[8] studied seepage characteristics of rock mass with different JRC fracture roughness by the Boltzmann method. Chen[9] used CT scanning to study the influence of fracture opening and seepage pressure on seepage law, the result was fitted by the Forchheimer equation. Based on the seepage experiment of intersecting fractures, Liu et al.[10] established a discrete fracture network (DFN) model and calculated the critical conditions of nonlinear seepage by adopting the local cubic law. Wang et al.[11] and Zhang et al. [12] carried out experimental researches on the seepage characteristics of the through-filling fracture model with different apertures. Ma et al.[13] studied the seepage properties of fractured rocks under different confining pressures. Zhang et al.[14] carried out an experimental study on the seepage law of Maokou limestone samples under different confining pressures.

In addition, many scholars have carried out a lot of related studies on the influence of fracture morphological characteristics on seepage characteristics[15]. Based on the fractal dimension theory, fracture morphological and seepage tests, Duan et al.[16] found that the permeability of the fracture surface decreases with the increase of the fractal dimension. To study the relationship between effective stress, JRC values and single-fracture permeability, He et al.[17] conducted a series of tests on artificial cement samples with different JRC values. To study the seepage characteristics, Fan et al.[18] used three-dimensional scanning to obtain fracture surface morphology parameters and reconstructed model to conduct a series of seepage experiments. Based on the gray scale theory to determine the fracture roughness of the concave shape, Gan et al.[19] studied the relationship between the concave degree and the correction coefficient of the cubic law is established. Based on the image digital technology, Liu et al.[20] carried out the recognition of sandstone seepage characteristics. To study the non-Darcy flow in deformable rough-walled fractures, Chen et al.[21] carried out a series of water flow tests through twelve granite fracture samples with different roughness under confining stresses.

Based on the above research results, it is found that the JRC characteristics of the fracture, the confining pressure and seepage pressure have great effects on the seepage characteristics of rock masses. At present, previous research on the permeability characteristics of artificial fractured surface with different JRC characteristics is generally carried out under low confining pressure and seepage pressure. However, few studies on the nonlinear permeability characteristics of naturally fractured rock masses, especially for deep-buried rock masses that are often under high in-situ stress and seepage pressure. This article specially carried out five nonlinear permeability tests of granite with different intersecting fractures under high seepage pressure and high confining pressure. Firstly, five intersecting fracture samples with different joint roughness coefficient (JRC) were obtained by conducting a series of shear tests. Secondly, the seepage characteristics of intersecting fracture was studied by conducting a series of seepage tests under high confining pressure and seepage pressure. Thirdly, the relationship between three-dimensional roughness characteristics of fracture and its permeability characteristics under high seepage pressure and confining pressure were obtained.

2. Experimental equipment and methods

2.1. Experimental equipment
A series of seepage tests of fracture were conducted on the Rock Multi-Field Coupling Triaxial Rheological System (ROCK-50HT system), which in the Guangxi University of Science and Technology (figure 1). This system can not only carry out conventional mechanics experiments, but also carry out temperature-fluid-mechanics-chemistry coupling and other multi-field coupling experiments. This system has three independent loading system for axial pressure, confining pressure and seepage pressure, which is provided by a high-precision servo electronically controlled high-
pressure pump. The maximum value is 300, 60 and 50 MPa for axial pressure, confining pressure and seepage pressure.

Figure 1. The Rock Multi-Field Coupling Triaxial Rheological System (Rock 600-50HT system).

2.2. Experimental methods
To study the nonlinear permeability law of deep fractured rock mass under high water pressure and high in-situ stress, this paper conducted a series of seepage tests, in which the experimental methods as showed in figure 2.

First of all, to obtain the special intersecting fractures with different JRC values, a series of shear tests were conducted on the granite by using the ROCK 600-50HT system, in which the normal stress was set to 5, 10, 15, 20 and 25 MPa. The normal stress was applied at a rate of 0.1 MPa/s until it reached the setting value, and then the shear stress was applied at a rate of 0.05 mm/s until the granite sample has a shear failure point. After the shear test, the normal stress was increased to 30 MPa at a rate of 0.1 MPa/s, and the shear stress was set to zero.

Secondly, a series of seepage tests were conducted, the seepage pressure between the two ends of the specimen was set to 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20 MPa. The seepage pressure was applied at a rate of 0.15 MPa/s until it reaches to setting value. In every conducting seepage pressure period, the permeability of the specimen was collected and recorded when the seepage is stable.

2.3. Determining the JRC value of intersecting fracture
To study the influence of JRC value on the seepage characteristics of the deeply fractured rock mass, this paper carried out a three-dimensional morphology scanning on the failure surface of granite [23]. This article used a portable scanner GD-3Ds composed of a scanner and a signal receiving computer, as shown in figure 3. Based on the principle of binocular stereo vision and the optical measurement method of blue fringe projection, it can accurately capture the details of the feature points on the joint surface and calculate the scanned three-dimensional point cloud with high density.

Figure 2. The test loading method.  
Figure 3. The portable scanner GD-3Ds.
Before scanning, the scanner is calibrated with a cross plate. The results of manual scanning will be displayed on the computer receiving terminal in real-time. Observe and manually stitch the scanning results from different angles. After scanning, importing all point cloud data into software Geomagic Studio (the reverse engineering processing software), selecting the relevant research area, performing noise reduction processing and encapsulating it into a surface, and then importing the discrete points into software MATLAB, and the three-dimensional reconstruction of the joint surface is obtained.

For the joint surface morphology obtained by three-dimensional scanning, the JRC value of fracture is determined by using the root mean square calculation method. Firstly, select 25 curves of point cloud data splicing along the shearing direction on the joint surface of the through fracture with a spacing of 2mm, and calculate the JRC value of each curve by the following formula [22]:

\[
Z_i = \sqrt{\frac{1}{(n - 1)} \sum_{j=1}^{n} \left( \frac{z_{i,j} - z_{i,j-1}}{x_{i,j} - x_{i,j-1}} \right)^2}
\]

\[
\text{JRC} = 32.2 + 32.47 \lg Z_i
\]

Where: \(Z_i\) is the root mean square of the slope, which mainly reflects the roughness of the fracture surface; \(x_{i,j} - x_j\) is the interval between data points, \(n\) is the number of statistical points per curve, and \(Z_i\) is the z-axis coordinate of each curve. Then, the JRC value of the joint surface is the average value of JRC calculated from 25 curves.

2.4. Specimen preparation
This test specimen is hard granite. After drilling, cutting, and grinding, five cylindrical specimens with a diameter of 50mm and a height of 86.5±0.5mm were obtained. As shown in figure 4, the density of the measured sample is 2.60g/cm³.

![Figure 4. The tested samples.](image)

3. Results and analysis

3.1. Shear stress-shear displacement characteristics
Five shear tests were carried out, the shear stress-shear displacement curves were obtained, which shown in figure 5. It can be seen from figure 5 that the characteristics of shear stress-shear displacement curve under different normal stresses is the same. As the shear displacement increases, the shear stress increases and then gradually decreases after reaching shear strength. The overall shear stress-shear displacement curve can be divided into the following two stages:

(1) Pre-peak stage: This stage is the shear stress from the beginning to shear strength. In this stage, as the shear displacement increases, the shear stress gradually increases until it reaches shear strength. The shear strength is mainly up to the normal stress. With the gradual increasing of normal stress, the maximum value of shear stress gradually increases. When the normal stress is 5, 10, 15, and 20MPa, the shear displacement of the sample is 1.305, 0.347, 1.538 and 1.335mm respectively, the shear
strength is 39.90, 80.98, 106.52, 110.86MPa respectively. In comparison, when the normal stress is 10MPa, the shear displacement of the specimen is the smallest.

(2) Post-peak stage: This stage is from shear strength to the complete failure. In this stage, as the shear displacement increases, the shear stress-shear displacement curves under different normal stresses has the same trend. Under normal stress condition, the shear stress of hard granite decreases slowly with the increase of shear displacement. The normal stress in this stage has a particular influence on the characteristics of the shear stress-shear displacement curve, which lead to the joint surface is uneven and have a different JRC value.

![Figure 5. Shear stress-shear displacement curve of granite under different normal stresses.](image)

3.2. Joint characteristics of failure granite

As shown in figure 6, the morphological characteristics of failure granite after shear tests under different normal stresses. The joint surface of the granite was scanned by a three-dimensional surface scanner GD-3Ds, which conducted a noise reduction process, so that a reconstructed digital image was obtained, which is entirely consistent with the surface morphology of the joint surface. The joint characteristics parameters of failure granite under different normal stresses were obtained, as shown in table 1.
JRC=13.84 (normal stress=5MPa)  JRC=10.86 (normal stress=10MPa)  JRC=10.05 (normal stress=15MPa)  JRC=3.41 (normal stress=20MPa)

**Figure 6.** The joint characteristics of failure granite.

The joint surface characteristics parameters of failure granite under different normal stresses were obtained, which is listed in table.1. It is found that when the normal stress is 5MPa, the overall undulation of the fracture surface is the biggest. Its maximum peak height and valley depth are 6.372mm and -0.857mm, respectively, then the drop is 7.229mm. The JRC value of failure surface under the normal stress of 5MPa is 13.84 which calculated by equation 2, it obviously has larger convex and concave shapes. When the normal stress is 20MPa, its maximum peak height and maximum valley depth are 3.498mm and -0.264mm, respectively, then the drop and JRC value are 3.762mm and 3.41, respectively. The overall undulation of the fracture surface is the smallest, the surface is concave, the overall fracture morphology is a small wave-shaped morphology. Overall, as the normal stress gradually increases, the JRC value of the joint surface successively decreases.

**Table 1.** The joint characteristics parameters of failure granite under different normal stresses.

| Normal stress | JRC value | Maximum peak (mm) | Maximum valley depth (mm) |
|---------------|-----------|--------------------|--------------------------|
| 5MPa          | 13.84     | 6.372              | -0.857                   |
| 10MPa         | 10.86     | 4.033              | -1.574                   |
| 15MPa         | 10.05     | 4.139              | -0.746                   |
| 20MPa         | 3.41      | 3.498              | -0.264                   |

4. Seepage characteristics under high confining pressure and high seepage pressure

4.1. **Seepage characteristics of joint surface**

As shown in figure 7, the relationship between seepage pressure and permeability of fracture joint surface with different JRC value under the confining pressure of 30MPa. As the seepage pressure increases, both the rate and increase rate of permeability for joint surfaces with different JRC value gradually increases. The seepage pressure - permeability curves of joint surfaces with JRC=3.41 and JRC=13.84 are relatively close, while those with JRC=10.05 and JRC=10.86 are relatively close. When under the same seepage pressure, the permeability of fracture joint surface for JRC=10.05 is the maximum, while that for JRC=13.84 is the minimum.

Under the same seepage pressure, the permeability of fracture joint with different JRC value is different, it shows that the roughness has a great influence on the permeability. the permeability of the
fracture joint surface with JRC=10~11 is the maximum, that is, the resistance to the seepage process of granite is smaller.

Combined with the topography feature of the reconstructed digital image which processed by Geomagic Studio noise reduction, it can be found that the joint fracture surface with slight fluctuation has relatively slight resistance to seepage through the joint surface, that is the permeability is relatively big. The joint fracture surface with large fluctuation or small fluctuation but small wave-shaped morphology has a relatively large resistance to the seepage process of granite, that is the permeability is relatively small.

Comparing the fracture joint with JRC=10.05 and JRC=10.86, which has relatively slight fluctuation and similar JRC value, it is found that the fracture joint surface with JRC=10.05 is relatively smooth, and there is no big bulge and pit, the resistance to the seepage process of granite is tiny and the permeability is relatively big. The fracture joint surface with JRC=10.86 has a significant local bulge and pit perpendicular to the seepage direction, the resistance to the seepage process of granite is relatively big and the permeability is relatively tiny.

![Figure 7. The relationship between seepage water pressure and permeability.](image)

4.2. Seepage characteristics of joint surface

To study the seepage characteristics of joint surface with different JRC value, the inlet seepage pressure in the seepage test is constant (20 MPa), while the outlet pressure is set to 10MPa, 8MPa, 6MPa, 4MPa and 2MPa. The seepage pressure gradient analysis at both ends of the granite specimen is strictly controlled to study the relationship between pressure gradient and volume flow as shown in figure 8.

It can be seen from figure 8, when the pressure gradient changes from 114.94 to 206.90MPa/m, the volume flow rate corresponding to the fracture joint surface of JRC=13.84 is range from 8.21 to 9.90 mm3/s. The volume flow rate corresponding to the fracture joint surface of JRC=3.41 is range from 7.17 to 8.26 mm3/s. The permeability characteristic curve of JRC=13.84 and JRC=3.41 are both approximate to a straight line, so the linear fitting was conducted and those fits are both greater than 0.993. Therefore, the seepage behavior of the joint surface with JRC=13.84 and JRC=3.41 has linear characteristics when the volume flow rate is low.

Similarly, under the same seepage pressure gradient, the volume flow rate of the joint fracture surface with JRC=10.86 varies from 15.52 to 25.20 mm3/s, while that with JRC=10.05 varies from 17.81 to 28.08 mm3/s. Although the JRC value is very close, the corresponding volume flow rate has a certain difference when under the same seepage pressure gradient. Conducting linear fitting for the relationship curve between seepage pressure gradient and volume flow rate of the joint fracture surface with JRC=10.05 and JRC=10.86 when the volume flow rate less than 20 mm3/s, those fits are both greater than 0.993. It means that the pressure gradient and the volume flow rate show a linear relationship at this condition.
To the volume flow rate is \(20.38 \sim 25.20 \text{mm}^3/\text{s}\) and \(20.54 \sim 28.08 \text{mm}^3/\text{s}\) for the joint fracture surface with JRC=10.05 and JRC=10.86, conducting a nonlinear function fitting \((\Delta P=AQ+BQ^2)\), and those fits are above 0.998, which shows that the pressure gradient has a non-linear relationship with the volume flow rate when it is greater than 20\(\text{mm}^3/\text{s}\). So it can be concluded that the non-linear relationship between pressure gradient and volume flow rate when it is larger than specific value, the value is 20.0\(\text{mm}^3/\text{s}\) and 10.0\(\text{mm}^3/\text{s}\) proposed by our research and Xiong[23], respectively. Furthermore, there is a certain order of magnitude difference between the function parameters A and B in nonlinear fitting, which is consistent with the parameter range pointed out by Xiong[23].

5. Conclusion
In this paper, a series of shear tests on granite were carried out to obtain some intersecting fractures joint model with different JRC values. Furthermore, to study the seepage characteristics of fracture joint surface, a series of seepage tests on the intersecting fractures joint model under high confining pressure and seepage pressure were carried out. The following conclusions were obtained:

1. Under different normal stresses condition, the JRC value of joint surface is different. As the normal stress gradually increases, the JRC value of the fracture joint surface decreases successively. The shear strength gradually increases with the increase of JRC, and the shear failure displacement is within 1\(\text{mm}\), which indicating that the shear failure of granite is a brittle failure.

2. Under different seepage pressures, the seepage characteristics of fracture joint surfaces with different JRC values is different. With the increase of seepage pressure, the permeability is gradually increasing. The different JRC value of the fracture joint surface produces different resistance effects on the permeability characteristics. When the undulation is large or it is wave-shaped morphology, the resistance to the seepage process of granite is huge and the permeability is relatively tiny.

3. In the relationship between the pressure gradient and volume flow rate of the fracture joint surface with different JRC values, linear fitting and non-linear fitting of Forchheimer equation were carried out. It is found that when the volume flow rate is greater than 20.0\(\text{mm}^3/\text{s}\), the relationship is nonlinear relationship. For fracture joint surface with JRC=10.05 and JRC=10.86, there is a transition between linear relationship and non-linear relationship, and the transition point is about 20.0\(\text{mm}^3/\text{s}\).

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References
[1] Zhou H, Hu D W, Zhang K 2014 Mecha-Nism and Theory of fluid solid coupling for porous and fractured rocks under high osmotic pressure. Bei-Jing: China Science Publishing Press.
[2] Ju Y, Zhang Q G, Yang Y M 2013 An experimental investigation on the mechanism of fluid flow through single rough fracture of rock. Science China Technological Sciences, 10 1144–1154.
[3] Qian J Z, Chen Z, Zhan H B, Guan H C 2011 Experimental study of the effect of roughness and Reynolds number on fluid flow in rough-walled single fractures: a check of local cubic law. Hydrological Process, 25 614–622.
[4] Snow D T 1965 A Parallel Plate Model of Fractured Permeable Media. Dissertation for Doctoral Degree. Berkeley: University of California.
[5] Snow D T 1969 Closure On Rock Fracture Spacings, Openings, And Porosities. Journal of the soil mechanics & foundations division . 95 880-883.
[6] Louis C 1972 Rock hydraulics in rock mechanics. New York: Springer Vienna.
[7] Zhang G, Tian Y, Li Y J 2019 Numerical study on the mechanism of fluid flow through single rough fractures with different JRC. Science in China: Physical Mechanics Astron,(in Chinese) 49 014701.
[8] Chen H H 2020 Experimental and theoretical studies of rock fracture seepage considering the three-dimensional morphology characterization. Nan Chang University, 2020.
[9] Liu R C, Jiang Y J, Li B, Yu LY, Du Y 2016 Nonlinear seepage behaviors of fluid in fracture networks. Rock and Soil Mechanics, 37 2817-2824.
[10] Wang P F, Tan W H, Ma X W 2019 Experimental study on seepage characteristics of consecutive and filling fracture with different roughness and gap-width. Rock and Soil Mechanics, 40 3062-3070.
[11] Zhang W, Zhou H, Guo W 2019 Experimental study on seepage characteristics of fractured rock mass and its electrical response. Journal of hydrologic engineering, 24 04019017.1-04019017.10.
[12] D Ma, Miao X X, Chen Z Q, Mao X B 2013 Experimental investigation of seepage properties of fractured rocks under different confining pressures. Rock Mechanics & Rock Engineering, 46 1135-1144
[13] Zhang Y, Hong X U, Ping L I, Zhang L, Zhao Y 2016 Experimental Study on Seepage Properties of Fractured Maokou Limestone. Mining Safety & Environmental Protection (in Chinese) 43 12-16
[14] Sheng T D, Chao J, Wei G Q, Yu W, Kang L 2017 Theoretical and experimental investigation of characteristics of single fracture stress-seepage coupling considering microroughness. Mathematical Problems in Engineering, 2017 1-12.
[15] Duan L L, Deng H F, Xiong Y 2021 Research on the influence of fracture surface morphology characteristics of rock mass on its seepage characteristics. Journal of Disaster Prevention and Reduction Engineering, 41 110-117.
[16] He Y L, Tao Y J, Yang L Z 2010 Experimental study on seepage characteristics of single fracture with different joint roughness coefficients. Journal of Rock Mechanics and Engineering, 29 235-3240.
[17] Fan H, Xie Y T, Zhou H, LU J J, WANG C 2020 Seepage characteristics of marble shear fracture. Journal of Shenyang University of Technology, (in Chinese), 42 464-469
[18] Gan L, Ma H Y, Shen Z Z 2021 Roughness characterization and cubic law correction coefficient fitting of concave fracture surface. Journal of Hydraulic Engineering, (in
Chinese), 52 420-431.

[19] Liu J, Tong H Y, Yang Y N 2020 Experimental study on visual seepage characteristics of sandstone fractures based on image digital technology. Chinese Journal of Geotechnical Engineering, 42 2024-2033.

[20] Chen Y F, Zhou J Q, Hu S H, Hu R, Zhou C B 2015 Evaluation of Forchheimer equation coefficients for non-darcy flow in deformable rough-walled fractures. Journal of Hydrology, 993-1006.

[21] Yin Q, LIU R C, JING H W 2019 Experimental Study Of Nonlinear Flow Behaviors Through Fractured Rock Samples After High-Temperature Exposure. Rock Mechanics and Rock Engineering, 52 2963–2983.

[22] Tse R, Cruden D M 1979 Estimating Joint Roughness Coefficients. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 16 303-307.

[23] Xiong F 2020 Study On Nonlinear seepage characteristics and hydrothermal coupling simulation of fractured rock mass. Wuhan University.