Research Article

Seepage Flow Properties of a Columnar Jointed Rock Mass in a True Triaxial Experiment

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A columnar jointed rock mass is a type of rock mass with strong geometric anisotropy and high interface permeability. Its seepage characteristics pose new challenges to the construction and maintenance of the Baihetan Hydropower Station on the Jinsha River. The research object in this study is the columnar jointed rock mass (basalt) in the dam area of Baihetan Hydropower Station. Similar-material model samples of the columnar jointed rock mass with different column dip angles ($\alpha = 0^\circ \sim 90^\circ$) were prepared following a similar principle. A true triaxial seepage-stress coupling test was conducted to evaluate the seepage characteristics of similar-material samples with different dip angles under intermediate principal stress and minimum principal stress. The experimental results showed that the columnar jointed rock mass exhibited apparent seepage anisotropy. The relationship curve between the volume flow rate $Q$ and the pressure gradient $-\frac{dP}{dL}$ of the samples with different dip angles showed evident nonlinear seepage under intermediate principal stress, which could be well expressed using the Forchheimer equation. It shows the characteristics of a typical linear Darcy flow under minimum principal stress. The law of variations in the permeability of the samples with different dip angles under intermediate principal stress can be well expressed using the one-dimensional quadratic function equation $k = a + b \sigma^2 + c \sigma^2$, and the law of variations in the permeability of the samples with different dip angles under minimum principal stress can be well expressed using the logarithmic function $k = a + b \ln \sigma$. The permeabilities of the columnar jointed rock mass with dip angles of $0^\circ$, $15^\circ$, $30^\circ$, and $60^\circ$ were most sensitive to changes in stress, and the seepage characteristics increased in complexity after changes in stress.

1. Introduction

A columnar joint structure is a primary tensile fracture structure with a regular or an irregular columnar shape formed by volume shrinkage during rapid cooling of high-temperature lava. Columnar jointed rock masses are present in many large-scale water conservancies and hydropower engineering geological structures worldwide [1]. The Baihetan Hydropower Station is a massive hydropower project with a capacity of 10 million kW, ranking next to the Three Gorges Project and the Xiluodu project in China. Its bedrock in the dam site and high slope of intake mostly consist of massive basalt [2–5]. The rock mass exhibits strong geometric anisotropy and high interface permeability, in addition to discontinuity, heterogeneity, and nonlinearity, thus presenting new challenges to the safety and stability of engineering construction and subsequent operations [6–9].

Numerous studies have been conducted worldwide on the mechanical properties and anisotropic deformation and failure laws of columnar jointed rock masses [10–13].
However, a large number of practical engineering projects have shown that the damage and deformation of rock masses, as well as changes in the seepage field caused by engineering disturbance, are the main reasons for large-scale engineering instability and engineering geological disasters [14, 15]. The failure of the Malpasset arch dam in France and the large landslide in the upstream reservoir area of the Vajont arch dam in Italy are related to seepage fields [16, 17]. More than 90% of rock slope failures are linked to groundwater permeability, and 30%–40% of dam failures in water conservancy and hydropower projects are attributable to seepage [18–21]. Therefore, for water conservancy and hydropower projects involving columnar jointed rock masses, a mere analysis of their mechanical properties and stress deformation failure law is inadequate. Studying the seepage characteristics under stress is crucial and bears practical engineering significance.

Figure 1: Mold for creating the column and the standard curing box.

Fracture is the basic element that constitutes the fracture network in rock masses. The study of the law of seepage in a single fracture provides the basis for and is key to the study of the law of seepage in the fracture network in rock masses and coupling in the seepage and stress fields of fractured rock masses. Considerable research has been reported worldwide on the seepage characteristics of a single joint of rock masses. Romm et al. [22, 23] verified the applicability of the cubic law of laminar flow by conducting a seepage experiment of smooth parallel plates and found a linear relationship between the volume flow rate \( Q \) of the fluid and the pressure gradient \( \nabla p \). This linear relationship ignores the nonlinear fluid flow characteristics; however, natural joint surfaces are often curved and rough to a certain degree, hence the difficulty of meeting the assumption of the parallel-plate fracture. Therefore, Neuzil et al. [24–27] proposed a modified cubic law by incorporating different definitions of joint surface roughness. On the basis of the cubic law of ideal fracture seepage, Xu et al. [28] proposed the application of supercubic and subcubic laws to reflect the law of seepage in rough fractures. However, variations in the roughness and hydraulic opening of the joint surface under stress are highly complex, rendering the distribution of a joint gap width highly complex. Consequently, the theoretical calculation of the seepage–stress coupling of joints is impeded. Therefore, testing of rock samples indoors for exploring seepage characteristics under stress is both feasible and effective.

Liu et al. [29] conducted a flow test on a single-intersection cross-fracture model and evaluated the effects of fracture aperture, the surface roughness, and the number of fracture intersecting points on the change in the critical hydraulic gradient \( J_c \) of the nonlinear flow field. Xia et al. [30, 31] analyzed the nonlinear seepage characteristics of a single joint surface with different levels of roughness by indoor shear seepage testing. Wang et al. [32] conducted laboratory tests on the unstable seepage behavior of broken mudstone and determined that the pressure gradient was the external cause of the stable seepage in rock masses. Continuous migration and loss of particles lead to the progressive failure of the rock mass, and a sufficiently large pressure gradient prompts the sudden general instability of the rock mass. Ni et al. [33] combined JRC and 3D printing to produce samples with different roughness fractures; subsequently, they performed several hydraulic tests. The results showed that the Forchheimer coefficient was affected by the roughness to a certain extent, and a semiempirical Forchheimer equation considering the fracture aperture and roughness was derived. Liu et al. [34] performed conventional indoor triaxial seepage tests on fractured sandstone and analyzed its permeability characteristics. Liu et al. [35] conducted a seepage experiment on Jurassic weakly cemented sandstone and analyzed its permeability during seepage. Chao et al. [36] conducted a conventional triaxial cyclic loading and unloading seepage test on a similar material model of a columnar jointed rock mass, with inert gas as the measuring medium, to determine the relationship between permeability and confining pressure. He et al. [37] produced similar model samples of columnar jointed rock masses with different column inclination angles and performed seepage–stress coupling tests under equal confining pressure to examine the seepage characteristics of columnar jointed rock masses under maximum principal stress.
Studies on the seepage characteristics of multijointed rock masses, particularly columnar jointed rock masses, are rarely reported. Owing to its significant anisotropy, the columnar jointed rock mass cannot reflect its true seepage characteristics by uniaxial testing ($\sigma_1 > \sigma_2 = \sigma_3 = 0$) or conventional triaxial testing ($\sigma_1 > \sigma_2 > \sigma_3$). Therefore, a true triaxial seepage–stress coupling test for the columnar jointed rock mass needs to be conducted to determine the relationship between seepage characteristics and the intermediate principal stress and minimum principal stress, in addition to the change law of its permeability under stress change.

Therefore, in accordance with the principle of indoor similar-material model testing, a hexagonal prism was produced using ordinary Portland cement and river sand as similar materials and white cement with the same grade as that of the cementation material. Similar-material model samples of the hexagonal columnar jointed rock mass with different dip angles were produced. A true triaxial electrohydraulic servo seepage test machine was used to perform indoor tests to study the seepage characteristics of samples with different dip angles under intermediate principal stress and minimum principal stress and different hydraulic gradients. The aforementioned test was also performed to analyze the relationship between the permeability change law and its sensitivity to the change in stress and the dip angle of the column.

2. Sample Preparation and Test Equipment

2.1. Sample Preparation. In accordance with the similarity theory, ordinary Portland cement, river sand, and water were selected as the column materials of the similar-
material model, and the mass ratio was 1 : 0.5 : 0.4 [38]. An early strength water-reducing agent of 0.4% cement quality was added to ensure the workability and cohesiveness of the mortar, improve the strength of the column in the initial setting, and avoid column fracture during demolding. The bonding material between the columns consisted of a mixture of ordinary white Portland cement with the same quality and water in a ratio of 1 : 0.4.

A regular hexagonal prism with a side length of 15 mm was used in the test to simulate a natural columnar jointed cylinder. A self-designed and manufactured cylinder mold (Figure 1(a)) was used to create the sample columns. The cast column was a regular hexagonal prism with a side length of 15 mm and a height of 160 mm. The mold consisted of several resin plates. The two sides of the mold were attached to long bolts, and the middle was fastened with a clamp to ensure easy assembly and demolding after the column had solidified. The mold was placed in a constant-temperature box and then removed after 24 h. The demolded column (Figure 1(b)) was placed in a standard constant-temperature and constant-humidity curing box (Figure 1(c)) for 28 d. The cured columns were bonded together with the bonding material, and the bonded sample was placed in the curing box to continue curing for 28 d.

The cured bond model samples were cut and ground into cubic similar-material model samples of the columnar jointed rock mass, with a side length of 100 mm and column dip angles of 0°, 15°, 30°, 45°, 60°, 75°, and 90° (Figure 2).

2.2. Test Equipment. The testing equipment was a true triaxial electrohydraulic servo testing machine used to determine the rock fracture seepage (Figure 3). The testing machine consisted of five parts: the main engine, the infiltration water tank, the hydraulic source, the infiltration water weighing system, and the electronic control system. The testing machine adopted an electrohydraulic servo valve closed-loop control system, which could conduct the permeability testing of the rock under the triaxial loading. It could realize independent loading in three directions and meet the testing research requirements of the permeability characteristics of the rock (including seepage deformation and seepage failure).

2.3. Test Method and Test Scheme. In this test, the constant water head method was used for seepage testing. The principle involves applying a certain difference in water pressure to both ends of the rock sample and then collecting the fluid volume flowing out to calculate the flow rate.

Before the test, the sample was placed in a vacuum saturation device (Figure 4(b)). Distilled water was used for vacuum saturation for 24 h. The sample was encased with O-rings on the upper and lower permeable plates. It was wrapped in a latex membrane (Figure 4(c)) to ensure that the seepage water could pass only through the cracks of the rock mass and not flow in the transverse direction. The wrapped sample was loaded into the testing machine (Figure 4(d)). The fluid was assumed to be incompressible during seepage testing, which was conducted at a constant temperature of 23°C.

The setting in this experiment was that the intermediate principal stress \(\sigma_2\) was parallel to the direction of the column along the \(y\)-axis, and the minimum principal stress \(\sigma_3\) was
Figure 6: Relationship between volume velocity and pressure gradient for samples with different dip angles under intermediate principal stress.
Table 1: Fitting results of the nonlinear Forchheimer equation and calculated values of $k$ and $\beta$.

| Sample number | Intermediate principal stress $\sigma_2$ (MPa) | Fitting coefficient $a$ (Pas·m$^{-1}$·s$^{-1}$·10$^{11}$) | Fitting coefficient $b$ (Pas·m$^{-2}$·s$^{-1}$·10$^{12}$) | Evaluation coefficient $R^2$ | Intrinsic permeability $k$ (m$^3$) | Nonlinear coefficient $\beta$ (m$^3$) |
|----------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------|---------------------------------|---------------------------------|
|                |                                               |                                               |                                               |                                 |                                 |                                 |
| SS0°           |                                               |                                               |                                               |                                 |                                 |                                 |
| 1              | $6.043E-01$                                    | $-1.372E-02$                                  | 0.9987                                        | $1.58E-15$                      | $-6.81E+12$                    |                                 |
| 2              | $1.025E+00$                                    | $-1.575E-02$                                  | 0.9990                                        | $1.24E-15$                      | $-7.82E+12$                    |                                 |
| 3              | $1.270E+00$                                    | $-2.664E-02$                                  | 0.9989                                        | $1.00E-15$                      | $-1.32E+13$                    |                                 |
| 4              | $1.454E+00$                                    | $-4.462E-02$                                  | 0.9967                                        | $8.76E-16$                      | $-2.21E+13$                    |                                 |
| 5              | $1.329E+00$                                    | $-3.552E-02$                                  | 0.9955                                        | $9.59E-16$                      | $-1.76E+13$                    |                                 |
| 6              | $7.33E-01$                                     | $-8.43E-03$                                   | 0.9947                                        | $1.74E-15$                      | $-4.19E+12$                    |                                 |
| SS15°          |                                               |                                               |                                               |                                 |                                 |                                 |
| 1              | $4.928E-01$                                    | $-6.38E-03$                                   | 0.9963                                        | $2.58E-15$                      | $-3.17E+12$                    |                                 |
| 2              | $6.312E-01$                                    | $-6.41E-03$                                   | 0.9995                                        | $2.02E-15$                      | $-3.18E+12$                    |                                 |
| 3              | $8.609E-01$                                    | $-1.693E-02$                                  | 0.9991                                        | $1.48E-15$                      | $-8.41E+12$                    |                                 |
| 4              | $1.005E+00$                                    | $-2.438E-02$                                  | 0.9990                                        | $1.26E-15$                      | $-1.21E+13$                    |                                 |
| 5              | $9.069E-01$                                    | $-2.17E-02$                                   | 0.9963                                        | $1.40E-15$                      | $-1.07E+13$                    |                                 |
| 6              | $8.062E-01$                                    | $-1.77E-02$                                   | 0.9988                                        | $1.58E-15$                      | $-8.80E+12$                    |                                 |
| SS30°          |                                               |                                               |                                               |                                 |                                 |                                 |
| 1              | $6.127E-01$                                    | $-1.117E-02$                                  | 0.9993                                        | $2.08E-15$                      | $-5.55E+12$                    |                                 |
| 2              | $7.002E-01$                                    | $-8.04E-03$                                   | 0.9984                                        | $1.82E-15$                      | $-3.99E+12$                    |                                 |
| 3              | $8.38E-01$                                     | $-1.16E-02$                                   | 0.9995                                        | $1.52E-15$                      | $-5.80E+12$                    |                                 |
| 4              | $9.389E-01$                                    | $-1.647E-02$                                  | 0.9993                                        | $1.35E-15$                      | $-8.16E+12$                    |                                 |
| 5              | $9.683E-01$                                    | $-1.69E-02$                                   | 0.9975                                        | $1.31E-15$                      | $-8.40E+12$                    |                                 |
| 6              | $8.538E-01$                                    | $-1.48E-02$                                   | 0.9961                                        | $1.49E-15$                      | $-7.38E+12$                    |                                 |
| SS45°          |                                               |                                               |                                               |                                 |                                 |                                 |
| 1              | $3.786E-01$                                    | $-2.86E-03$                                   | 0.9990                                        | $3.36E-15$                      | $-1.42E+12$                    |                                 |
| 2              | $4.306E-01$                                    | $-1.05E-03$                                   | 0.9993                                        | $2.96E-15$                      | $-5.21E+11$                    |                                 |
| 3              | $5.286E-01$                                    | $-2.37E-03$                                   | 0.9992                                        | $2.41E-15$                      | $-1.18E+12$                    |                                 |
| 4              | $6.559E-01$                                    | $-7.29E-03$                                   | 0.9995                                        | $1.94E-15$                      | $-3.62E+12$                    |                                 |
| 5              | $6.896E-01$                                    | $-7.89E-03$                                   | 0.9990                                        | $1.84E-15$                      | $-3.92E+12$                    |                                 |
| 6              | $7.237E-01$                                    | $-8.73E-03$                                   | 1.0000                                        | $1.76E-15$                      | $-4.39E+12$                    |                                 |
| SS60°          |                                               |                                               |                                               |                                 |                                 |                                 |
| 1              | $7.790E-01$                                    | $-1.35E-02$                                   | 0.9996                                        | $1.63E-15$                      | $-6.74E+12$                    |                                 |
| 2              | $1.070E+00$                                    | $-2.39E-02$                                   | 0.9989                                        | $1.19E-15$                      | $-1.19E+13$                    |                                 |
| 3              | $1.211E+00$                                    | $-3.00E-02$                                   | 0.9997                                        | $1.05E-15$                      | $-1.49E+13$                    |                                 |
| 4              | $1.231E+00$                                    | $-2.99E-02$                                   | 0.9995                                        | $1.03E-15$                      | $-1.49E+13$                    |                                 |
| 5              | $1.116E+00$                                    | $-3.05E-02$                                   | 0.9991                                        | $1.14E-15$                      | $-1.51E+13$                    |                                 |
| 6              | $8.93E-01$                                     | $-2.07E-02$                                   | 0.9983                                        | $1.42E-15$                      | $-1.03E+13$                    |                                 |
Table 1: Continued.

| Sample number | Intermediate principal stress $\sigma_2$ (MPa) | Fitting coefficient $a$ (Pa·s m$^{-5} \times 10^{14}$) | Fitting coefficient $b$ (Pa·s$^2$ m$^{-7} \times 10^{22}$) | Evaluation coefficient $R^2$ | Intrinsic permeability $k$ (m$^2$) | Nonlinear coefficient $\beta$ (m$^{-1}$) |
|---------------|-----------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------|------------------------|-----------------------------|
| SS75°         |                                               |                                                 |                                                 |                               |                        |                             |
| 1             | 1.475E + 00                                   | −2.669E − 02                                    | 0.9964                                          | 8.643E − 16                   | −1.327E + 13          |
| 2             | 1.937E + 00                                   | −3.408E − 02                                    | 0.9965                                          | 6.582E − 16                   | −1.694E + 13          |
| 3             | 2.367E + 00                                   | −2.539E − 02                                    | 0.9982                                          | 5.388E − 16                   | −1.102E + 13          |
| 4             | 2.235E + 00                                   | −2.250E − 03                                    | 0.9982                                          | 5.705E − 16                   | −1.189E + 12          |
| 5             | 1.922E + 00                                   | 5.106E − 02                                     | 0.9999                                          | 6.634E − 16                   | 2.538E + 13           |
| 6             | 1.847E + 00                                   | 3.686E − 02                                     | 0.9992                                          | 6.903E − 16                   | 1.832E + 13           |
| SS90°         |                                               |                                                 |                                                 |                               |                        |                             |
| 1             | 1.044E + 00                                   | 5.900E − 03                                     | 0.9979                                          | 1.221E − 15                   | 2.932E + 12           |
| 2             | 1.759E + 00                                   | −3.364E − 02                                    | 0.9934                                          | 7.248E − 16                   | −1.672E + 13          |
| 3             | 1.835E + 00                                   | −2.783E − 02                                    | 0.9963                                          | 6.948E − 16                   | −1.383E + 13          |
| 4             | 2.039E + 00                                   | 1.251E − 02                                     | 0.9981                                          | 6.253E − 16                   | 6.218E + 12           |
| 5             | 2.149E + 00                                   | 4.235E − 02                                     | 0.9987                                          | 5.934E − 16                   | 2.105E + 13           |
| 6             | 2.041E + 00                                   | 8.260E − 03                                     | 0.9986                                          | 6.248E − 16                   | 4.105E + 12           |
Figure 7: Continued.
perpendicular to the direction of the column along the x-axis (Figure 5). The loading scheme was as follows:

1. Loading mode of the principal stress: force-controlled loading was applied. The specimen was first loaded to \( F_x = F_y = F_z = 1 \) kN. Subsequently, stress equal to \( \sigma_1 = \sigma_2 = \sigma_3 = 1 \) MPa was applied in three directions at a speed of 30 kN/min. During the test, \( \sigma_1 \) was first loaded to 6 MPa, \( \sigma_1 = 6 \) MPa and \( \sigma_3 = 1 \) MPa remained unchanged, and \( \sigma_2 \) was loaded to 6 MPa with a step size of 1 MPa. \( \sigma_1 = \sigma_2 = 6 \) MPa was then maintained, and \( \sigma_3 \) was loaded to 6 MPa with a step size of 1 MPa.

2. Loading method of the seepage water pressure: after each stage of stress loading became stable, the seepage water pressure \( \sigma_s \) was applied at 0.2 MPa and then increased to 0.8 MPa with a step size of 0.1 MPa.

3. Test Results and Analysis

3.1. Seepage Characteristics of the Columnar Jointed Rock Mass under Intermediate Principal Stress

3.1.1. Relationship between Volume Velocity and Pressure Gradient under Intermediate Principal Stress. According to the test scheme, the direction of the intermediate principal stress was transverse parallel to the column strike (Figure 5), keeping the axial \( \sigma_1 = 6 \) MPa and transverse \( \sigma_3 = 1 \) MPa unchanged and measuring the volume velocity of similar-material samples of columnar jointed rock mass under different pressure gradients. Figure 6 shows the correlation between the volume velocity \( Q \) and the pressure gradient \( -dP/dL \) of similar-material samples with different dip angles under intermediate principal stress.

In Figure 6, the velocity pressure gradient curves of the samples with dip angles of \( 0^\circ \), \( 15^\circ \), \( 30^\circ \), \( 45^\circ \), and \( 60^\circ \) exhibit...

\[
\begin{align*}
\text{SS60°} & \quad y = 2.139 - 0.612x + 0.082x^2 \\
& \quad R^2 = 0.9842 \\
\text{SS75°} & \quad y = 1.082 - 0.275x + 0.036x^2 \\
& \quad R^2 = 0.8882 \\
\text{SS90°} & \quad y = 1.531 - 0.428x + 0.047x^2 \\
& \quad R^2 = 0.8956
\end{align*}
\]
apparent nonlinear characteristics, forming a relatively smooth downward-bending curve. However, the velocity pressure curves of the samples with dip angles of 75° and 90° showed good linear characteristics. This observation indicates that under medium principal stress, the similar-material samples of the columnar jointed rock mass also presented obvious characteristics of seepage anisotropy.

For the nonlinear flow relationship in fractures and porous media, the Forchheimer formula is widely used because of its clear theoretical basis [39, 40]:

\[-\nabla p = aQ + bQ^2,\]  

(1)

where \(\nabla p = dP/dL\) is the ratio of the pressure difference \(P\) between the inlet and outlet and the length \(L\) of the sample; \(Q\) is the overall volume velocity at the outlet; \(a\) and \(b\) are the model fitting coefficients, representing the specific gravity of the water pressure drop caused by the linear and nonlinear terms during seepage testing, respectively; \(\mu\) is the dynamic viscosity coefficient of the fluid; \(k\) is the intrinsic

\[a = \frac{\mu}{kA},\]  

(2)

\[b = \frac{\beta\rho}{A^2},\]
Figure 9: Relationship between volume velocity and the pressure gradient in samples with different dip angles under minimum principal stress.
permeability of the rock; \( A \) is the flow area of the rock; \( \beta \) is the nonlinear coefficient; and \( \rho \) is the density of the fluid.

Table 1 lists the fitting coefficients \( a \) and \( b \), the coefficients of determination \( R^2 \), the values of the intrinsic permeability \( k \), and the nonlinear coefficient \( \beta \) of the fractured rock determined in Equation (2). The fitting evaluation coefficient \( R^2 \) under all testing conditions exceeded 0.99, indicating that the relationship between the volume velocity \( Q \) and the pressure gradient \( dP/dL \) of the similar-material samples with columnar joints under intermediate principal stress was highly suitable.

The seepage curves of the samples with dip angles of 0° to 60° revealed that as the intermediate principal stress increases, the nonlinear characteristics of seepage fitting curves of 30° and 45° dip samples decrease, demonstrating Darcy seepage characteristics similar to those of straight lines. However, the nonlinear characteristics of the fitting curves of the samples with dip angles of 0°, 15°, and 60° initially decreased and then increased. This trend indicates different variation characteristics and degrees of influence of the intermediate principal stress on the fracture structure of the samples with different dip angles. Consequently, seepage characteristics vary, hence the seepage anisotropy.

3.1.2. Relationship between Intrinsic Permeability and Intermediate Principal Stress. The relationship curve between intrinsic permeability and intermediate principal stress during seepage of similar-material samples having columnar joints with different dip angles is plotted in Figure 7.

In Figure 7, the seepage characteristics of the columnar jointed rock mass sample show obvious anisotropy. The law of variation in the inherent permeability of samples with different dip angles under intermediate principal stress can be classified into types I and II. In the U-shaped type I change curve (\( \alpha = 0°, 15°, 30°, 60°, 75°, 90° \)), the permeabilities initially decreased and then increased with an increase in intermediate principal stress. The stress when the permeabilities decreased and started to increase was defined as the
inflection point stress, with values of 5, 5, 6, 5, 4, and 6 MPa for the samples with different dip angles. For the L-shaped type II curves (α = 45°), the intrinsic permeability exhibited a monotonous decrease with an increase in the intermediate principal stress.

According to the variation characteristics of the permeability–stress curve, a quadratic polynomial of one variable is proposed to fit the testing data:

\[ k = a + b\sigma_2 + c\sigma_2^2, \]

where \( k \) is the intrinsic permeability of the rock; \( \sigma_2 \) is the intermediate principal stress; and \( a, b, \) and \( c \) are the model fitting coefficients. The evaluation coefficient \( R^2 \) under all testing conditions exceeds 0.89, and the fitting accuracy is high. These results indicate that the law of variation in intrinsic permeability of similar-material samples with the columnar jointed rock mass under intermediate principal stress can be expressed using a quadratic polynomial of one variable.

Figure 8 presents the relationship between the initial permeability \( k_i \), the minimum permeability \( k_{\text{min}} \), the final permeability \( k_f \), and the variation range of the samples with different dip angles under the action of the intermediate principal stress and the dip angle of the sample.

As shown in Figure 8, during loading of intermediate principal stress, the minimum permeabilities of the samples with different dip angles decrease by 0.708 \( \times 10^{-15} \) m\(^2\), 1.319 \( \times 10^{-15} \) m\(^2\), 0.764 \( \times 10^{-15} \) m\(^2\), 1.606 \( \times 10^{-15} \) m\(^2\), 0.325 \( \times 10^{-15} \) m\(^2\), and 0.628 \( \times 10^{-15} \) m\(^2\) relative to the initial permeability, with ranges of discount of 44.67%, 50.97%, 36.71%, 47.68%, 36.71%, and 37.62%, respectively. The permeability of the 75° dip angle sample showed the least decrease, whereas the permeabilities of the 15° and 45° dip angle samples had the largest decreases—4 and 4.9 times of the former, respectively. However, the ranges of discount in the permeabilities of the samples with different dip angles were not considerably different, and the difference between the smallest sample (α = 0°, 60°) and the largest sample (α = 90°) was only 14.72%. Compared with the initial permeability, the final permeability of the samples with a 0° dip angle increased by 9.78%, whereas the permeabilities of the samples with other dip angles decreased by 38.87%, 28.21%, 47.68%, 13.01%, 20.14%, and 48.81%. The final permeabilities of the samples with 0° and 60° dip angles were similar to the initial permeability, whereas those of the samples with other dip angles were largely reduced. These results indicate that except for these two angles, intermediate principal stress significantly decreases the permeability of similar-material samples with the columnar jointed rock mass. The final permeabilities of the samples with different dip angles increased by 98.40%, 24.67%, 13.44%, 0%, 37.45%, 28.01%, and 5.40% relative to the minimum permeability. In summary, the influence of intermediate principal stress on the permeability of the columnar jointed rock mass was highly significant, and the samples with dip angles of 0°, 15°, and 45° were most sensitive to changes in intermediate principal stress.

3.2.2 Relationship between Volume Velocity and Pressure Gradient under Minimum Principal Stress

3.2.2.1 Relationship between Volume Velocity and Pressure Gradient under Minimum Principal Stress. With the axial \( \sigma_1 = 6 \) MPa and transverse \( \sigma_2 = 6 \) MPa remaining constant, the minimum principal stress \( \sigma_3 \) perpendicular to the direction of the column was applied (Figure 5). The volume velocities of similar-material samples of the columnar joints
**Figure 11: Continued.**

(a) $SS0^\circ$

$y = 1.924 - 0.665 \ln x$

$R^2 = 0.9906$

(b) $SS15^\circ$

$y = 1.978 - 0.870 \ln x$

$R^2 = 0.9388$

(c) $SS30^\circ$

$y = 1.726 - 0.654 \ln x$

$R^2 = 0.9845$

(d) $SS45^\circ$

$y = 1.967 - 0.829 \ln x$

$R^2 = 0.9913$
under different pressure gradients were measured. The correlation between the volume velocity $Q$ and the pressure gradient $-dP/dL$ of similar-material samples with different dip angles under minimum principal stress is depicted in Figure 9.

As shown in Figure 9, the relationship curve between the volume velocity and pressure gradient of the similar-material samples of the columnar joint with different dip angles under minimum principal stress is approximately a straight line; good Darcy flow characteristics were exhibited. Darcy’s law function equation was used to fit the experimental data.

\[
-dP/dL = aQ,
\]

where $-dP/dL$ is the pressure gradient, $a$ is the model fitting coefficients, $Q$ is the overall volume velocity at the outlet, $\mu$ is the hydrodynamic viscosity coefficient, $k$ is the intrinsic permeability of rock, and $A$ is the flow area of the rock.

Table 2 lists the fitting results of linear Darcy’s law function and the intrinsic permeability $k$ value calculated based on the fitting results. The evaluation coefficient $R^2$ of the fitting curve under all testing conditions exceeded 0.94, indicating that the test results were in good agreement with the fitting curve. The law of variation between the volume velocity and pressure gradient of similar-material samples of the columnar jointed rock mass with different dip angles under minimum principal stress conformed to Darcy’s law.

The change in minimum principal stress caused no change in the linear flow state of the fluid for the similar-materials samples with the completely inclined columnar

Figure 11: Relationship between the intrinsic permeability $k$ and the minimum principal stress $\sigma_3$ for samples with different dip angles.
jointed rock mass. However, the slope $m$ of the linear Darcy fitting line between the volume velocity and the pressure gradient increased gradually with an increase in the minimum principal stress $\sigma_3$, and the growth exhibited a basically linear trend (Figure 10). With the $\alpha = 45^\circ$ sample as an example, when the minimum principal stress increased from 1 MPa to 6 MPa, the slope of the fitting line gradually increased from 0.633 to 2.305, reflecting a 3.64-fold increase.

3.2.2. Relationship between Intrinsic Permeability and Minimum Principal Stress. Figure 11 presents the relationship curve between inherent permeability and minimum principal stress during seepage of the similar-material samples of the columnar jointed rock mass with different dip angles. As shown in Figure 11, with an increase in the minimum principal stress, the intrinsic permeabilities of all similar-material samples of the columnar jointed rock mass exhibit a monotonically decreasing trend represented by the L-shaped type II curve.

In accordance with the change characteristics of the permeability–stress relationship curve, the following logarithmic function was used to fit the testing data:

$$k = a + b \ln \sigma_3,$$

where $k$ is the intrinsic permeability of the rock, $\sigma_3$ is the intermediate principal stress, and $a$ and $b$ are the model fitting coefficients. For all testing conditions, the fitting evaluation coefficient $R^2$ exceeded 0.94, indicating a good agreement. Therefore, the intrinsic permeability variation rule of the similar-material samples of columnar jointed rock mass under minimum principal stress can be expressed using the logarithmic function.

As shown in Figure 12, under minimum principal stress, the similar-material samples of the columnar jointed rock mass still show obvious anisotropic seepage. The specific performance was as follows: when $\sigma_3 = 1$ MPa, the initial permeabilities of the samples with different dip angles were $1.97 \times 10^{-15}$ m$^2$, $2.10 \times 10^{-15}$ m$^2$, $1.78 \times 10^{-15}$ m$^2$, $2.01 \times 10^{-15}$ m$^2$, $1.84 \times 10^{-15}$ m$^2$, $0.65 \times 10^{-15}$ m$^2$, and $0.62 \times 10^{-15}$ m$^2$. When the minimum principal stress loading was completed ($\sigma_3 = 6$ MPa), the minimum permeabilities of the samples with different dip angles were $0.79 \times 10^{-15}$ m$^2$, $0.59 \times 10^{-15}$ m$^2$, $0.63 \times 10^{-15}$ m$^2$, $0.55 \times 10^{-15}$ m$^2$, $0.47 \times 10^{-15}$ m$^2$, $0.28 \times 10^{-15}$ m$^2$, and $0.26 \times 10^{-15}$ m$^2$, which decreased by 59.56%, 71.88%, 64.85%, 72.53%, 74.30%, 57.45%, and 57.42%. The minimum principal stress significantly reduced the permeability of the columnar jointed rock mass, and the permeabilities of the samples with dip angles of $15^\circ$, $45^\circ$, and $60^\circ$ decreased the most, indicating that the columnar jointed rock mass with these three angles exhibited the highest sensitivity to changes in minimum principal stress.

Although the minimum principal stress led to decreases in the permeabilities of all similar-material samples of the columnar jointed rock masses, the trends and amplitudes of the seepage characteristics of samples varied with different dip angles under intermediate principal stress. The permeabilities of the samples with dip angles of $15^\circ$, $45^\circ$, and $60^\circ$ showed the largest reductions under minimum main stress loading; however, the final permeabilities still exceeded those of the samples with dip angles of $75^\circ$ and $90^\circ$. The final permeabilities of the samples with different dip angles, in descending order, were ranked as follows: $\alpha = 0^\circ > \alpha = 30^\circ > \alpha = 15^\circ > \alpha = 45^\circ > \alpha = 60^\circ > \alpha = 75^\circ > \alpha = 90^\circ$. Meanwhile, the minimum permeability was $0.26 \times 10^{-15}$ m$^2$ ($\alpha = 90^\circ$)—that is, 3 times worse than the maximum permeability of $0.79 \times 10^{-15}$ m$^2$ ($\alpha = 0^\circ$).

4. Conclusions

With the columnar jointed rock mass (basalt) in the dam area of the Baihetan Hydropower Station on the Jinsha River...
as the research object, similar-material model samples of columnar joints with different column dip angles \((a = 0\,^\circ, 15\,^\circ, 30\,^\circ, 45\,^\circ, 60\,^\circ, 75\,^\circ, \text{ and } 90\,^\circ)\) were prepared in accordance with the similarity principle. True triaxial seepage–stress coupling tests under different levels of intermediate principal stress, minimum principal stress, and different hydraulic pressure (0.2–0.8 MPa) were conducted for each sample with a dip angle. The nonlinear and linear flow regimes, seepage anisotropy characteristics, and variations in permeability with the dip angle of the column and different principal stresses were evaluated. Major conclusions are presented as follows:

1. In true triaxial seepage testing, the seepage of the columnar jointed rock mass exhibits obvious anisotropic characteristics. Under intermediate principal stress and minimum principal stress, the samples with different dip angles exhibit permeabilities with different levels of sensitivity to different principal stresses. The law and degree of change also vary with different principal stresses.

2. The relationship curve between the volume velocity \(Q\) and the pressure gradient \(-dP/dL\) of the similar-material samples of the columnar joints with different dip angles shows obvious nonlinear seepage characteristics under intermediate principal stress. The nonlinearity of the samples with different inclination angles, expressed using the Forchheimer equation, also varied. The fitting evaluation coefficient \(R^2\) exceeded 0.99, indicating good linear Darcy flow characteristics under minimum principal stress. All evaluation coefficients fitted using Darcy’s law were greater than 0.94.

3. The law of variation in intrinsic permeability with the intermediate principal stress of the similar-material model samples of the columnar jointed rock mass with different dip angles can be classified into two types. In the U-shaped type I curves, the permeability decreases and then increases with an increase in the intermediate principal stress. In the L-shaped type II curves, the permeability shows a monotonous decrease with an increase in the maximum principal stress. This law can be well expressed by the quadratic equation of one variable \(k = a + b\sigma_2 + c\sigma_3\). The law of variation between permeability and minimum principal stress only shows a monotonic decrease in the L-type type II curve, and the logarithmic function \(k = a + b \ln \sigma_3\) can similarly express this law of variation.

4. During the entire seepage testing process, under medium principal stress and minimum principal stress, the permeabilities of the samples with \(a = 0\,^\circ, 15\,^\circ, 30\,^\circ,\) and \(60\,^\circ\) dip angles initially decreased, increased, and decreased again. These results indicate that the permeabilities of the rock mass with dip angles of \(0\,^\circ, 15\,^\circ, 30\,^\circ,\) and \(60\,^\circ\) were most sensitive to changes in stress, and the seepage characteristics increased in complexity after the change.

**Data Availability**

All the data in this paper are obtained by experiments, and it has been presented in this manuscript.

**Conflicts of Interest**

The authors declare no conflict of interest.

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