Experimental Study on the Influence of Hydromechanical Boundary Conditions on Shear-Flow Coupling Characteristics of Granite Joints

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The instability of jointed rock mass is usually the shear process of the rock mass along discontinuities under the influence of groundwater flow. By conducting laboratory tests and numerical experiments on the shear-flow coupling of rock joints under constant normal stiffness (CNS) and constant normal stress (CNL) boundary conditions, the influence of normal boundary conditions and seepage pressure on the shear mechanical and flow characteristics of joints were investigated. The test results were as follows: The joint shear stiffness, peak, and residual shear strength under the CNS boundary condition were predominantly larger than those under the CNL boundary condition. Overall, these parameters were positively correlated with the initial normal stress $\sigma_n$. When $\sigma_n > 2$ MPa, the postpeak shear stress of the CNS boundary condition showed a sharp decrease, whereas that of the CNL boundary condition changed from a slowly decreasing type ($\sigma_n = 4$ MPa, 6 MPa) to a sharply decreasing type at $\sigma_n = 8$ MPa. The peak dilation rate under the CNS boundary condition at all levels of normal stress was lower than that of CNL, and the strain softening in postpeak of the latter was more remarkable. In the process of joint shear, the hydraulic aperture displayed a four-stage variation law of "steady-sudden increase-slow increase-basically stable." Moreover, the hydraulic aperture under the CNS boundary condition was always lower than that under the CNL boundary condition. The seepage pressure increased from 0.5 MPa to 1.5 MPa, and the average hydraulic aperture in the stable stage under normal stress at all levels increased from 0.146 mm to 0.187 mm. In addition, the average peak shear stress and average shear stiffness decreased by 0.9 MPa and 0.83 GPa/m, respectively. We also established a numerical model of a real rough three-dimensional joint, compiled a calculation program for the shear-flow process of a joint under CNS boundary conditions, and visualized the flow channel inside the joint. The seepage flow bypassed the area where the joints contacted each other, forming obvious flow channels. The flow rate increased at the intersection of the flow channels.

1. Introduction

The instability of rock slopes and caverns surrounding rocks is typically triggered by rainfall or groundwater seepage, which is essentially a shear-flow coupling process of loaded rock along the discontinuity under the action of water flow. Therefore, for most jointed rock instability problems, this can be attributed to the effect of hydromechanical boundary conditions on the coupling shear-flow characteristics of the joints. Current researches are focused on the response of the deformation and flow characteristics of joints to normal stress $\sigma_n$ and seepage pressure $P$. They predominantly concentrate on the variation law of hydraulic conductivity and flow rate of joints during the shearing process of joints under constant normal stress (CNL) boundary conditions, as well as the refinement and modification of the cubic law [1–5]. Shen et al. [6] established the relationship between normal stress and joint contact area based on laboratory test data.
and showed that flow rate decreased with increasing contact area. The results of Ahola et al. [7] demonstrated that an increase in normal stress leads to a decrease in hydraulic conductivity. Lee and Cho [8] and Esaki et al. [9] observed that the hydraulic conductivity of joint decreases with increasing normal load and increases with increasing shear displacement, whereas Fang et al. [10] concluded that the hydraulic conductivity of the joint gradually decreases with shear displacement under high normal stress. Yang et al. [11] observed that joint hydraulic conductivity is more sensitive to shear stress than normal stress. Xiong et al. [12] conducted laboratory and numerical shear-flow coupling tests to establish the relationship between hydraulic conductivity and mechanical aperture. Zhou et al. [13] considered the dilation effect caused by normal stress and shear stress and derived a theoretical analytical equation for fracture permeability in the shear process. Shen et al. [14] concluded that the fracture transmissivity increases continuously with

<table>
<thead>
<tr>
<th>Test groups</th>
<th>Normal stiffness (GPa·m⁻¹)</th>
<th>Initial normal stress (MPa)</th>
<th>Seepage pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0</td>
<td>2, 4, 6, 8</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>2, 4, 6, 8</td>
<td>1</td>
</tr>
<tr>
<td>II</td>
<td>1.8</td>
<td>2, 4, 6, 8</td>
<td>0.5, 1, 1.5</td>
</tr>
</tbody>
</table>

Table 1: Joint shear-flow coupling test protocol.

<table>
<thead>
<tr>
<th>Material type</th>
<th>ρ (kg·m⁻³)</th>
<th>σₙ (MPa)</th>
<th>σₛ (MPa)</th>
<th>φₛ (°)</th>
<th>E (GPa)</th>
<th>v</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite</td>
<td>2.63 × 10³</td>
<td>146.3</td>
<td>7.0</td>
<td>27.1</td>
<td>17.6</td>
<td>0.18</td>
</tr>
<tr>
<td>UHPC</td>
<td>2.32 × 10³</td>
<td>145.6</td>
<td>9.1</td>
<td>30.4</td>
<td>14.7</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 2: Physical and mechanical parameters of the granite and UHPC.

Figure 1: Granite joint using splitting method.

Figure 2: Rock joint shear-flow coupling test system.
shear displacement before the peak shear strength and is essentially constant after the peak shear strength when the effective normal stress is greater than 10 MPa.

With advancements in research, researchers have conducted numerous studies on the shear mechanics and deformation characteristics of joints under constant normal stiffness (CNS) boundary conditions [15–18]. Cui et al. [19] demonstrated that the shear strength, peak normal stress, and peak normal displacement of joints under CNL boundary conditions were significantly lower than those under CNS, which is consistent with the experimental results derived by Indraratna et al. [20, 21]. Direct shear tests under both CNS and CNL normal boundary conditions have also been carried out [22–24], and the results demonstrated that CNS boundary conditions increased the shear strength of the joints. In addition, the peak and residual shear stress increased significantly with an increase in the initial normal stress. With regard to the shear-flow coupling characteristics of joints under CNS boundary conditions, Olsson and Barton [25] indicated that hydraulic conductivity decreases with increasing normal stiffness, but the highest seepage pressure imposed by the test can only reach 0.04 MPa. Chiba et al. [26] also studied the variation law of hydraulic characteristics. However, the shear
displacement of this test system could only reach 3 mm, which does not reflect the flow behavior of the entire joint shear process. Li et al. [27] carried out the shear-flow coupling test under CNS and CNL conditions and studied the variation law of the flow rate of the joint with the contact area during the shear process. Most studies on the effect of seepage pressure on the shear-flow coupling characteristics of joints have focused on the effect of seepage pressure on the seepage characteristics and normal deformation characteristics of joints [28–31].

Cao et al. [32] conducted a shear-flow coupling test on sawtooth joints to study the variation in the flow rate and hydraulic aperture with seepage pressure. Rong et al. [33] displayed that the hydraulic gradient increases with an increase in the flow rate. Di et al. [34] concluded that hydraulic conductivity is positively correlated with seepage pressure and the particle size of the joint material. Zhang et al. [35] demonstrated that the greater the seepage pressure, the greater the flow velocity, and proposed an improved relationship between the flow rate and hydraulic aperture. Some scholars have reported that the normal deformation of the joint increases with an increase in seepage pressure [36, 37]. However, Xia et al. [38] concluded that the normal deformation of the joint decreases with an increase in seepage pressure under CNS boundary conditions.

In summary, existing studies on the coupled shear-flow characteristics of joints have mostly discussed the flow characteristics of joints under CNS or CNL conditions and have predominantly focused on the effects of normal load and seepage pressure on flow rate, hydraulic conductivity, and other seepage characteristics. Unfortunately, less attention has been paid to the variation of mechanical characteristics such as shear stiffness, shear stress, and hydraulic aperture of joints under the action of seepage pressure and different normal boundary conditions. Moreover, the law of the influence of seepage pressure on the dilation effect of joints under CNS boundary conditions is still controversial. Based on these deficiencies, laboratory tests on the coupled shear-flow of granite joints were carried out with normal stiffness $K_n$, initial normal stress $\sigma_{n0}$, and seepage pressure $P$ as variables. It was combined with numerical experiments to reveal the influence law of hydromechanic boundary conditions on the mechanical characteristics of joints, such as shear stiffness, shear stress, and hydraulic aperture.

2. Experimental Protocol and Methods

2.1. Test Protocol. The background of this study is based on water-sealed storage caverns; relevant parameters of granite are set according to the engineering geological and hydrogeological conditions of the water-sealed storage caverns. In this study, normal stiffness, initial normal stress, and seepage pressure were utilized as variables to investigate the effects of hydromechanic boundary conditions on the coupled shear-flow characteristics of granite joints. The initial normal stress is determined according to the circumferential stress and joint production of the cavern chamber of a water-sealed storage cavern, and the seepage water pressure is determined according to the groundwater environment in which the cavern storage is located [39]. $K_n$ is equivalent to the elastic foundation coefficient of the granite rock at the small deformation stage, which was calculated as 1.8 GPa/m according to the literature [40]. The seepage pressure was set to 1 MPa, and the initial normal stresses were applied to 2 MPa, 4 MPa, 6 MPa, and 8 MPa, respectively. Subsequently, the shear-flow coupling tests of granite joints under CNS and CNL conditions were carried out, corresponding to test group I in Table 1. Group I was designed
to investigate the influence of normal boundary conditions on the shear-flow coupling characteristics of granite joints. To explore the response of hydromechanical characteristics to seepage pressure, three levels of seepage pressure (0.5 MPa, 1.0 MPa, and 1.5 MPa) were set. For each level of seepage pressure, joint shear-flow coupling tests (CNS boundary condition) were conducted under normal stresses of 2 MPa, 4 MPa, 6 MPa, and 8 MPa, as shown in test group II in Table 1.

2.2. Specimen Preparation. The effect of normal boundary conditions on the coupled shear-flow characteristics of joints was investigated based on real rough three-dimensional granite joints. The joint samples were made by cutting and grinding in situ granite and then splitting it (Figure 1).

A noncontact 3D scanner was used to scan the surface morphology of the joints, and the point cloud data of the joint surfaces were accurately obtained and processed. The joint roughness coefficient JRC was used to evaluate the joint roughness, which was calculated using Equations (1) and (2) regarding the literature [41].

$$JRC = \frac{1}{m} \sum_{i=1}^{m} \text{JRC}_i = \frac{1}{m} \sum_{i=1}^{m} (32.2 + 32.47 \log_{10} Z_2), \quad (1)$$

$$Z_2 = \sqrt{\frac{1}{L} \int_{x=0}^{x=L} \left( \frac{dy}{dx} \right)^2 dx}. \quad (2)$$

Afterward, JRC of the granite joint was calculated, and joint specimens with $JRC = 4$ were selected for the shear-flow coupling test.

Although we prepared a large number of granite joint specimens by splitting, enough specimens could not be produced with the same roughness. Accordingly, the joint specimen with $JRC = 4$ was selected as the template from the split specimens, and the real 3D joints of granite were replicated using UHPC (ultra-high-performance concrete) material.

Subsequently, these replicated UHPC specimens were used to carry out the test group II in Table 1 to explore the influence of seepage pressure on the shear-flow coupling characteristics of joints. The basic physical and mechanical parameters of the granite [42] and UHPC samples were tested: density $\rho$, uniaxial compressive strength $\sigma_c$, tensile strength $\sigma_t$, basic friction angle $\phi_0$, elastic modulus $E$, and Poisson’s ratio $\nu$. The values of each parameter are listed in Table 2. It was found that the physical and mechanical properties of the two materials were relatively consistent. Therefore, UHPC could be used to simulate the granite material for the test that followed.
The servo-controlled rock joint shear-flow coupling test system shown in Figure 2 was utilized to perform joint shear-flow coupling tests under CNL and CNS boundary conditions.

The test was composed of the following steps.

1. In specimen placement, the sample was placed in the shear-flow box according to the marked shear direction, and sealant was applied on the corresponding part of the inside of the shear box.

2. In the application of normal stress and lateral pressure, the normal load was applied to the set value at a rate of 0.1 kN/s, followed by the application of oil pressure greater than the seepage pressure to the lateral window of the shear-flow box.

3. In exerting seepage pressure, seepage pressure was applied to the test target value at a loading rate of 0.05 MPa/s.

4. In shear loading, the joints were sheared at a rate of 0.5 mm/min and terminated when the shear displacement reached 15 mm.

3. Results and Analysis

3.1. Influence of Mechanical Boundary Conditions on Shear-Flow Coupling Characteristics of Joints

![Figure 10: Relationship between the peak dilation rate and initial normal stress.](image1)

![Figure 11: Curves of hydraulic aperture with shear displacement.](image2)

![Figure 12: Variation of peak shear stress with normal stress.](image3)

![Figure 13: Variation of shear stiffness with initial normal stress.](image4)
3.1.1. Analysis of Shear Mechanical Characteristics of Joints.

Figure 3 displays the variation curves of shear stress $\tau$ with shear displacement $\delta_h$ for the joints, both under the CNL and CNS boundary conditions. It can be observed from the figure that the shear stress increased rapidly with the shear displacement to the peak shear stress and then dropped to the residual shear stress. When the initial normal stress $\sigma_{n0}$ was 2 MPa, the residual shear stress under both boundary conditions approached the peak value. Interestingly, the postpeak shear stress of the CNS boundary condition displayed a sharp decrease when $\sigma_{n0} > 2$ MPa, while the postpeak shear curves of the CNL boundary condition changed from a slowly decreasing type ($\sigma_{n0} = 4$ MPa and 6 MPa) to a sharply decreasing type ($\sigma_{n0} = 8$ MPa). In addition, the peak and residual shear stresses under both boundary conditions increased with increasing in the initial normal stress. As $\sigma_{n0}$ increased from 2 MPa to 8 MPa, the peak shear stresses under CNS and CNL boundary conditions increased by 9.62 MPa and 10.19 MPa, respectively. In addition, the residual shear stresses increased by 4.49 MPa and 4 MPa, respectively. The normal load increased with dilation under the CNS boundary condition, which increased the shear resistance of the joint. This resulted in the peak and residual shear stresses under the CNS boundary condition being larger than those under the CNL boundary condition. Notably, the impact of the boundary condition on the residual shear stress was more obvious.

The slope of the prepeak linear stage of $\tau - \delta_h$ is defined as the shear stiffness $k_s$ of the joint. It can be seen from the relationship of $k_s - \sigma_{n0}$ (Figure 4) that when $\sigma_{n0}$ increased...
from 2 MPa to 8 MPa, the shear stiffness under CNS and CNL conditions increased by 2.58 GPa/m and 3.71 GPa/m, respectively. It was found that the shear stiffness of joints under the CNS boundary condition was always greater than that under CNL. After the peak shear displacement, $\tau - \delta_h$ curves exhibited a strain-softening phenomenon. As defined in Equation (3), the shear stress drop coefficient $S_c$ represented the development of shear stress after peak shear displacement:

$$S_c = \frac{\tau_p - \tau_r}{\tau_p},$$  \hspace{1cm} (3) 

where $\tau_p$ is the peak shear stress and $\tau_r$ is the residual shear stress. When $S_c = 0$ and 1, the joint exhibited ideal plasticity and ideal brittle shear behavior, respectively. The strain-softening behavior of the joint was characterized by $S_c$ between 0 and 1.

The variation in the drop coefficient with the initial normal stress under the two boundary conditions is shown in Figure 5. In general, the softening coefficient increased with an increase in the initial normal stress. As $\sigma_{n0}$ increased from 2 to 8 MPa, $S_c$ under the CNS and CNL conditions increased by 0.527 and 0.226, respectively. In addition, it was found that $S_c$ for the CNS boundary condition was

![Figure 15: Curves of hydraulic aperture with shear displacement.](image-url)
always smaller than that for the CNL condition, indicating that the strain-softening phenomenon was more significant in the CNL boundary condition as compared to CNS.

Based on the evolution curves of shear stress path with normal stress under CNS boundary conditions (Figure 6), normal stress continuously increased with shear displacement. At the same time, the shear stress showed the phenomenon of “increase rapidly-drop-stability” ($\sigma_n > 2 \text{MPa}$) or “increase rapidly-increase slowly” ($\sigma_n = 2 \text{MPa}$) with normal stress.

By linear fitting of $\tau_p$ and $\tau_r$ with normal stress, the shear peak and residual friction angle under CNS boundary conditions were 53.7° and 35.3°, respectively, and the friction angle was reduced by 34.3%. Similarly, the relationships of $\tau_p - \sigma_{n0}$ and $\tau_r - \sigma_{n0}$ under CNL boundary conditions were linearly fitted (Figure 7), and the peak and residual friction angle were 52° and 33.4°, respectively. This indicated that both the peak and residual friction angles for the CNL boundary condition were lower than those for CNS condition.
3.1.2. Analysis of Influence on Joint Dilation Characteristics.

Figure 8 displays the relationship between normal and shear displacements under CNS and CNL boundary conditions. The joints gradually closed under normal stress during the initial shear phase for both boundary conditions, resulting in shear shrinkage. Subsequently, the joint exhibited dilation behavior as the shear displacement continued to increase. The smaller the initial normal stress, the more obvious the dilation phenomenon. With the continuous development of the shear displacement, the dilation effect gradually weakened, and the dilation curves turned flat. Furthermore, it was clearly observed throughout the shearing process that the normal displacements for the CNS condition were always smaller than those for CNL, and this difference became apparent as the initial normal stress increased. Taking $\delta_{v-15}$ as an example ($\delta_{v-15}$ was the normal displacement when $\delta_{h} = 15$ mm), the difference of $\delta_{v-15}$ under the two boundary conditions increased from

(a) $P = 0.5$ MPa ($A_v = 18.67\%$)

(b) $P = 1.0$ MPa ($A_v = 21.62\%$)

(c) $P = 1.5$ MPa ($A_v = 17.35\%$)

Figure 17: Failure condition of the joint when the initial normal stress is 8 MPa.
showed three stages of shear displacement curve (Figure 9). The dilation rate \( \lambda \) the joint entered the dilation stage with a rapid increase in sponded to the joint shear shrinkage stage. Subsequently, the joint entered the stage of normal displacement increased rapidly, and the hydraulic aperture entered the stage of slow increase-basically stable. (Figure 11), the hydraulic aperture under the two boundary conditions displayed a stable phenomenon with an increase in shear displacement owing to the insignificant dilation effect of the joints. Subsequently, the normal displacement increased rapidly, and the hydraulic aperture entered the stage of "sudden increase" at approximately the peak shear displacement. The joint dilation effect began to diminish with the development of the shear displacement; that is, the aperture displayed a phenomenon of "slow increase."

The joint dilation effect gradually disappeared when the shear displacement developed to a certain extent. Thus, the hydraulic aperture shows a state of "basically stable." Furthermore, it can be clearly observed from the figure that the hydraulic aperture under the two boundary conditions decreased with increase in the initial normal stress, and the hydraulic aperture under the CNS condition was always lower than that under CNL. The greater the initial normal stress, the stronger the influence of the normal stiffness boundary condition on the hydraulic aperture \( e_{15} \) (\( e_{15} \) was the hydraulic aperture when \( \delta = 15 \text{ mm} \)). With the initial normal stress increasing from 2 MPa to 8 MPa, the difference in \( e_{15} \) increased from 0.001 mm to 0.180 mm under the two boundary conditions. It should be noted that under CNL boundary conditions, the curve appears abnormal when \( \sigma_{n0} = 8 \text{ MPa} \). For this abnormal phenomenon, we believe that although the hydraulic aperture is closely related to the normal displacement in the shear-flow coupling process, the granite joints with the same JRC prepared by splitting cannot guarantee the complete consistency of their morphology. As a result, the seepage channel is blocked to varying degrees in the shear process, so the hydraulic aperture calculated by the cubic law is abnormal.

3.2. Influence of Seepage Pressure Boundary Conditions on Joint Shear-Flow Coupling Characteristics

3.2.1. Analysis of Influence on Shear Mechanical Characteristics. Figure 12 shows the relationship between peak shear stress and normal stress under three level seepage pressure, which was 0 MPa, 1 MPa, and 1.5 MPa, respectively. The average peak shear stress decreased from 6.0 MPa to 4.5 MPa when the seepage pressure increased from 0.5 MPa to 1.5 MPa, which was a reduction of 25%. Meanwhile, the peak shear stress decreased most obviously when \( P = 1.5 \text{ MPa} \). Therefore, it can be considered that the weakening effect of seepage pressure on shear strength will be strengthened with an increase in seepage pressure. As shown in Figure 13, it displayed a decreasing trend for the peak friction angle of the joint owing to the increase in seepage pressure. The peak friction angle decreased from 48.5° to 39.7° with the increase of seepage pressure from 0.5 MPa to 1.5 MPa, which was a reduction of 18.1%. This phenomenon also explained, to some extent, the increase in seepage pressure leading to a decrease in the friction angle which affected the peak shear strength of the joint.

Based on the relationship between joint shear stiffness and the initial normal stress under different seepage pressures (Figure 13), joint shear stiffness decreased with the
increase in seepage pressure. This was because the seepage pressure reduced the effective normal stress of the joint surface and the lubrication effect of seepage on the joint surface. The average shear stiffness under four-stage initial normal stress decreased from 3.92 GPa/m to 3.09 GPa/m with the increase of seepage pressure from 0.5 MPa to 1.5 MPa. Notably, the shear stiffness decreased most significantly under the condition of $\sigma_n = 2$ MPa and $P = 1.5$ MPa.

### 3.2.2. Analysis of Influence on Joint Dilation Characteristics.
Based on the relationship between normal displacement and shear displacement under different seepage pressures (Figure 14), normal displacement under the three level seepage pressures showed a consistent feature. That is, the normal displacement decreased, owing to the shear shrinkage behavior of joints in the early stage of shear, but the decrease was small; subsequently, the normal displacement increased slowly, with gradual weakening of the amplitude. In Figure 14, the normal displacement curve was rough and fluctuant. We analyses that during the shearing process, joint asperities will be sheared off and damaged to form the fragments. During the staggered movement of the joint, the dilation of the fragments will lead to a small increase in the normal displacement, and the fragment will be easily crushed and destroyed or transported to cause a small decrease in the normal displacement. At the same time, the role of seepage pressure intensifies the transfer of fragments.

In addition, the dilation effect of the joint also increased with increasing seepage pressure, which is the same as that of Yin and Chen [37]. Incorporating the normal displacement when the shear displacement was 15 mm as an example, the average normal displacement under the four-stage initial normal stress increased from 1.03 mm to 1.78 mm with an increase in the seepage pressure from 0.5 MPa to 1.5 MPa.
3.2.3. Analysis of Influence on Hydraulic Aperture. Figure 15 displays the variation curves of the hydraulic aperture with shear displacement under different seepage pressures. Overall, the hydraulic aperture under different seepage pressures shows relatively consistent characteristics, that is, it showed four changing rules of "steady-sudden increase-slow increase-basically stable."

It can be clearly observed from Figure 15 that the joint hydraulic aperture increased with an increase in seepage pressure. Taking the hydraulic aperture \( e_{h-15} \) at shear displacement of 15 mm as the stable hydraulic aperture, the average value (under initial normal stress at four levels) of \( e_{h-15} \) increased from 0.146 mm to 0.187 mm with an increase in the seepage pressure from 0.5 MPa to 1.5 MPa. This was because the seepage pressure enhanced the dilation effect of the joint surface.

3.3. Variation Law of Joint Morphology under Shear-Flow Coupling. MATLAB programming was used to binarize the joint surface image after shearing, to study the failure characteristics of the joint surface under shear-flow coupling. The shear failure zone was defined as white and the rest as black. The ratio of the shear area to the total area of the joints was defined as the shear area ratio \( A_s \), which represented the degree of joint failure. Figures 16 and 17 display the failure and binary images of the joint surfaces when the initial normal stresses are 2 MPa and 8 MPa, respectively, under different seepage pressures. It should be noted that the failure condition refers to the final failure state when the shear displacement reaches 15 mm.

Based on the wear morphology characteristics of the joint surface post shear, it can be observed that the zones of wear-out failure occur at the high asperities of the joint surface. Therefore, it can be considered that high asperities play a key role in the shear process. The binary images also indicate that the failure degree of the joint surface increased with an increase in the initial normal stress. The average \( A_s \) (under different water pressures) of joint surface increased from 7.59% to 19.21% when initial normal stress increased from 2 MPa to 8 MPa. In addition, seepage pressure affected the wear area of the joint surface to a certain extent. Taking the wear of joint surface \( (\sigma_n = 2 \text{ MPa}) \) as an example, the seepage pressure increased from 0.5 MPa to 1.5 MPa, and the proportion of wear area decreases from 8.77% to 6.22%. In other words, the wear area demonstrates a decreasing trend with an increase in seepage pressure. Interestingly, this characteristic was not obvious when \( \sigma_n = 8 \text{ MPa} \). In fact, this rule was not controlled by seepage pressure alone, but the result of two factors: seepage pressure reduced the effective normal stress; nevertheless, the applied normal stiffness increased the normal stress owing to joint dilation. It is worth noting that the factors affecting the joint morphology are not limited to normal stress and osmotic water pressure on the joint surface morphology was analyzed.

3.4. Numerical Experimental Study on Seepage Path Evolution in Joint Shear Process

3.4.1. Introduction to Numerical Simulation. Based on the 3DEC simulation software, a rough three-dimensional
A single joint model with JRC = 4 was constructed. Typical hydromechanic conditions ($\sigma_{\text{n}} = 6$ MPa, $P = 1.5$ MPa) were set to carry out the shear-flow coupling numerical experiment under CNS boundary conditions to visually reflect the seepage path and hydraulic aperture distribution of the joint in the shear process, which could complement the laboratory tests.

The size of the numerical model was consistent with that of the sample used in the laboratory test, consisting of upper and lower blocks and a joint plane. The size of the two rock blocks was $200 \times 100 \times 50$ mm, and the joint length was 200 mm. The numerical model is shown in Figure 18. The CNS boundary condition was applied to the upper surface of the model. The left side of the upper block was a constant shear rate boundary with a rate of 0.001 mm/min, and the lower block remained fixed. Seepage pressure was applied on the left side of the model, and the right side was considered as the zero-water pressure boundary. Figure 19 displays
the joint geometric model and cloud diagram of seepage pressure distribution.

In this numerical experiment, the M-C constitutive model was used for the blocks, and the continuous yield joint model (C-Y model) was selected for the joint. The model parameters were determined based on laboratory tests. The parameters required for the block constitutive model were density \( \rho \), elastic modulus \( E \), Poisson’s ratio \( \nu \), tensile strength \( \sigma_t \), cohesion \( c \), and internal friction angle \( \varphi \). The values of each parameter are listed in Table 3. The mechanical parameters in the C-Y model included shear stiffness \( k_s \), normal stiffness \( k_n \), normal stiffness index \( e_n \), shear stiffness index \( e_s \), roughness parameter \( R \), initial friction angle \( \varphi(i)m \), basic friction angle \( \varphi_b \), initial hydraulic aperture \( a_{\text{zero}} \), maximum hydraulic aperture \( a_{\text{max}} \), and residual hydraulic aperture \( a_{\text{res}} \). The determination method for each parameter was as given by Gao et al. [44]. They can be determined by referring to the test results of the variation range of equivalent hydraulic aperture under the condition of constant normal stiffness and normal stress of 6 MPa in Figure 15, and the values of each parameter are listed in Table 4. The hydraulic parameters which included the bulk modulus of water, density of water, and the viscosity coefficient of water were \( 2 \times 10^9 \) Pa, \( 1000 \) kg m\(^{-3} \), and \( 1 \times 10^{-3} \) Pa s, respectively.

3.5. Analysis of Numerical Experimental Results. For an improved description of the seepage law on the joint surface, we demonstrate the distribution of the apparent dip angle of the joint asperities (Figure 20). The distribution of the hydraulic aperture during the shear process is demonstrated in Figure 21. As shown in Figure 21(a), owing to the climbing and interlocking action of the joint when \( \delta_h = 3 \) mm, the back shear surface detached and formed several cavities, resulting in a large hydraulic aperture being distributed in the cavity position of the back shear surface. With the further development of shear displacement, the joint surface continued to dilate, and the hydraulic aperture increased accordingly. Subsequently, the shear behavior entered the residual stage, and the dilation effect weakened. By comparing Figures 20 and 21(b), it can be seen that the asperities with large undulant asperities of the joint surface play a major role in dilation in the residual stage, and most of the contact surfaces were detached to form several cavities. This resulted in a uniform distribution of the hydraulic aperture on the entire joint surface, except for a smaller hydraulic aperture at the position of steeper asperities on the shear surface (Figure 21(b)).

Figure 22 shows the evolution law of seepage pressure and seepage path of the joint surface during the shear process. It can be observed that the seepage pressure of the joint surface gradually decreased along the shear direction when \( \delta_h = 0 \) (Figure 22(a)). At the same time, because the initial hydraulic aperture was set, water flowed along the entire joint surface, but the flow rate was small. When the shear displacement changed to 3 mm, water flowed in the cavity regions where the contact surfaces separated from each other, and seepage channels were gradually formed (Figure 22(b)). As the shearing continued, the large dilation caused most of the asperities to separate when \( \delta_h = 9 \) mm (Figure 22(c)), and the water flowed almost along the entire joint surface. However, because of the joint contact with each other at undulant asperities with large sizes, seepage bypassed these contact regions. As a result, dominant seepage channels were formed, and a larger flow rate appeared at the intersection of the seepage channels.

4. Conclusions

(1) The peak and residual shear stresses under the CNS and CNL boundary conditions increased with an increase in the initial normal stress. In addition, the peak and residual shear stresses under the CNS boundary conditions were greater than those under the CNL boundary conditions. When the initial normal stress increased from 2 MPa to 8 MPa, the shear stiffness under CNS and CNL boundary conditions increased by 2.58 GPa/m and 3.71 GPa/m, respectively. The shear stiffness under the CNS boundary condition was always greater than that under CNL. In general, the larger the initial normal stress, the more obvious the drop extent of the post-peak shear stress. Compared to the CNS boundary condition, the drop phenomenon of shear stress under CNL condition was more significant.

(2) The normal displacement of the joint under the CNS boundary condition was always lower than that under CNL. The dilation rate displayed three stages of “increase rapidly-drop-stability” with the ratio of shear displacement to peak shear displacement. When the initial normal stress increased from 2 MPa to 8 MPa, the peak dilation rate under CNS and CNL boundary conditions decreased by 57.5% and 44.4%, respectively. In addition, the peak dilation rate under CNS boundary conditions was always lower than that under CNL.

(3) The seepage pressure increased from 0.5 MPa to 1.5 MPa, the average peak shear stress at all levels of initial normal stress decreased from 6.0 MPa to 5.1 MPa, the peak friction angle decreased from 48° to 39.8°, and the average shear stiffness decreased from 3.92 GPa/m to 3.09 GPa/m under the four initial normal stresses. In the shear process, the hydraulic aperture increased with the increase in seepage pressure, experiencing a four-stage change rule of “steady-sudden increase-slow increase-basically stable,” and the hydraulic aperture under the CNS boundary condition was always lower than that under CNL.

(4) The initial normal stress increased from 2 MPa to 8 MPa, and the proportion of average wear area at all levels of seepage pressure of joints increased from 7.59% to 19.21%. The influence of seepage pressure on the wear failure of the joint surface was controlled by two factors: the seepage pressure reduced the effective normal stress; nevertheless, the applied
normal stiffness increased the normal stress owing to joint dilation

(5) The numerical experimental results demonstrated that seepage flows along the entire joint surface before joint shear. The maximum hydraulic aperture was distributed at the joint cavity regions with the development of shear displacement, and seepage channels were gradually formed. When the shear entered the residual stage, a uniform distribution of the hydraulic aperture was observed on the entire joint surface, except for a smaller hydraulic aperture at the position of steeper asperities on the shear surface. The seepage bypassed the contact regions of the fluctuant asperities with large sizes, forming obvious dominant seepage channels on the joint surface. A higher flow rate with larger magnitude appeared at the intersection of the seepage channels

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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