Experimental study on visualization of seepage flow and grout diffusion and seepage reduction patterns in rough single fissure

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Abstract

The study of fissure seepage and grouting diffusion, seepage reduction law is of great significance for the prevention and control of water damage in fissured rock bodies. To this end, a visualization test model based on the morphology of real rock fissures was prepared in bulk using 3D scanning and 3D printing technology, and tests were carried out to realize the visualization of seepage flow in a single fissure, grouting with different water-cement ratios, and seepage flow after the fissure grouting was consolidated and filled. The test results show that: compared with grouting diffusion, the seepage of water injection into the fissure is different in activity and coverage; the rough single fissure seepage shows nonlinear flow characteristics, and is a composite flow form of laminar and turbulent flow; the grouting into the fissure has the effect of climbing and swooping, and the diffusion rate and filling rate of the grout are obviously different under different water-cement ratio conditions; after the grout is filled and consolidated in the fissure, the permeability coefficient of the fissure is greatly reduced, and the seepage performance is significantly different. After the slurry is filled and consolidated in the fissure, the permeability coefficient is greatly reduced, and the seepage flow is nonlinear, which conforms to the Forchheimer's equation, and with the decrease of the water-cement ratio of the cement slurry, the coefficient of the linear term decreases, and the coefficient of the nonlinear term increases and accounts for a larger proportion in the binomial.

Introduction

Fissures in geotechnical bodies affect various engineering and construction activities of human beings. The study of fissures is the basis for ensuring the safe construction of engineering. Among them, the study of fissure seepage characteristics, grout diffusion and seepage reduction law is of great significance in the extraction of fossil energy such as oil and natural gas, underground sequestration of carbon dioxide, underground transportation of pollutants, and prevention and control of geologic disasters (Wang et al. 2014; Li et al. 2000; Xu et al 2003; Xue et al. 2003; Min et al. 2004).

The study of seepage through fissures was initially based on Darcy's law, which was restricted to laminar motion at lower flow velocities. Later, the cubic law was introduced to establish the relationship between flow rate and slit width (Snow et al. 1965), which is also only applicable to the study of parallel smooth fissures. In order to generalize the cubic law, the fissure model was reconstructed to take the elements of roughness, fissure opening and filling into account, and the concepts of mechanical slit width and equivalent hydraulic opening were introduced, which in turn modified and extended the cubic law (Xun et al. 2003; Lomize 1951; Su et al 1995; Louis C 1974; Xiong et al. 2011; Cui et al. 2020). With further research, it was found that the fissure seepage no longer showed linear variation at faster flow rates. The binomial nonlinear equation derived by Forchheimer through the study of gas flow in porous coal samples based on a large amount of experimental data has been recognized and applied by many subsequent scholars (Guan R et al. 2018; Yin et al 2017).
In order to carry out an in-depth study of rough fissure seepage, some scholars directly fracture the standard specimen fissure model of artificial fracturing for testing, and some of the artificially created fissures with roughened surfaces of parallel plates for testing, in addition to numerical simulation means of three-dimensional fissure reconstruction is also used for the study (Zhu et al. 2023; Wang 2002; Wang et al. 2016; Wang 2022; Shi et al. 2023). However, the models constructed by these researches have the defects of specificity, artificiality, randomness, uncontrollable roughness, non-replicability, etc. The fissures obtained by numerical simulation are difficult to simulate the real seepage due to the complexity of parameter setting and determination of boundary conditions. In recent years, 3D printing technology combined with the field of geotechnical engineering can be used to simulate natural and real fissures with small discrete, high credibility and reusable characteristics (Wang et al. 2023). Li and Wang et al. (2022, 2021) utilized 3D printing of specific fissure models to study their fissure seepage patterns under different openings, different JRCs, and different normal stresses, and explored the relationship between the linear and nonlinear terms in the Forchheimer equation and their relationship. Sun et al. (2022) used oil storage in an underground cavern as a background, and used 3D printing technology to fabricate transparent fissures with different roughnesses to visualize the multi-phase seepage in a single fissure. Huang et al. (2021), on the other hand, carried out seepage characterization under different conditions on a printed 3D fracture network model. 3D printed fracture models for the study of seepage patterns in fractures have their unique advantages and characteristics.

Grouting of fractured geotechnical body can reduce its permeability, increase its strength and improve the safety of underground engineering construction. Hao and GOTHALL R et al. (2002, 2009) investigated the effect of slurry on fissure deformation and its cleavage effect during grouting through model tests, and derived the formula for the change of fissure opening and the formula for the expansion pressure. Sui et al. (2015) used a transparent model to visualize the motion-diffusion process of slurry injected into a three-dimensional rock fissure. Liu et al. (2017) used two kinds of quick-setting slurries as grouting materials, established a slurry diffusion model considering the time-varying viscosity of slurry under dynamic water environment, and verified the validity of the numerical modeling method by means of indoor testing of the model. Hirokazu (2018) proposed a radial flow model of parallel-plate slurry that is valuable for the intelligent construction of grouting. The research on fissure grouting tends to focus on the effect of fissure changes on slurry diffusion, and there is still a lack of testing on the filling effect and seepage barrier characteristics after fissure grouting.

In summary, the visualization and analytical description of the seepage process of the rough fissure is insufficient, and the research on the examination of the effect of slurry filling and the law of resisting seepage after slurry filling needs to be further carried out.

In this paper, the natural fissure was scanned in three dimensions, reconstructed and modeled, and a transparent single fissure model was 3D printed with photosensitive resin as the raw material, and the seepage law of this fissure model was investigated on the basis of visualization. Subsequently, ordinary silicate cement slurry with different water-cement ratios was injected into it to analyze the diffusion process of cement slurry with different ratios in the fissure. After the slurry solidified and filled the
cracks, the effect of grouting and the seepage law of the filled cracks were investigated. This study has certain reference value for the fine analysis of the slurring process in the fissure and the detection of the grouting effect.

**Materials and methods**

**Model construction**

In this study, a core specimen was selected from the No. 3 tuff stratum of the Taiyuan Formation of the Wanfu Coal Mine in Shandong, China. A standard specimen with a diameter of 50 mm and a length of 100 mm was cut out using a coring machine, and the top and bottom surfaces of the specimen were polished and dissected to ensure a certain degree of flatness. The prepared specimen was ruptured by applying pressure along the center longitudinal direction with the circular loading head of WAW-1000D microcomputer-controlled electro-hydraulic servo universal testing machine. A complete fracture surface of this ruptured rock cylinder was selected for the study (Fig. 1).

![Figure 1 Fissure specimen preparation (a) Standard chert specimen (b) Specimen after fracturing (c) Selected fissure surfaces from the test block](image)

In order to obtain the morphological characteristics of the complete fissure surface, a 3D structural scanner (Einscan Pro 2X, with a scanning accuracy of up to 0.05mm) was used to lay scratch and capture the surface morphology, and editing and processing were carried out through the self-contained software. The processed fissure surface in STL format was imported into the 3D software for modeling, and the established model was 166mm long, 54mm wide and 56mm high, in which the fissure was 120mm long and 30mm wide, and the fissure seam width was set to 1mm. buffer grooves were laid at both ends of the fissure, which had the role of buffer and adjustment, and could convert the liquid from the pipeline flow to the fissure flow.

The model was sliced using the slicing software (layering thickness of 0.01mm), and the sliced data were printed by importing them into a light-curing 3D printer (model LD-003) with photosensitive resin as the raw material for layering, and then the desired test model was obtained after a simple post-processing (Fig. 2).

**Fracture roughness analysis**

Fracture seepage research is essential to the study of its fracture roughness, currently used to characterize the fracture roughness of the main methods are absolute roughness method (bump height method), relative roughness method, fractal dimension method and nodal roughness characterization method (JRC), this paper adopts the JRC method for the model of fracture roughness characterization. JRC is the first Norwegian scholar Barton(1974) was initially used to effectively describe the roughness, and later its 10 roughness curves drawn according to the JRC classification were widely recognized by the International Rock Mechanics. Association.Tse et al (1979) proposed that the relationship between
the JRC and the average surface gradient modulus $Z_s$ can be used to quantitatively describe the fissure roughness, and its calculation formula is as follows:

$$JRC = 32.2 + 32.47 \log Z_s$$

1

$$Z_s = \left[ \frac{1}{(N_x-1)(N_y-1)} (a+b) \right]^{1/2}$$

2

$$a = \frac{1}{\Delta x^2} \sum_{i=1}^{N_x-1} \sum_{j=1}^{N_y-1} \frac{(z_{i+1,j+1} - z_{i,j+1})^2 + (z_{i+1,j} - z_{i,j})^2}{2}$$

3

$$b = \frac{1}{\Delta y^2} \sum_{j=1}^{N_y-1} \sum_{i=1}^{N_x-1} \frac{(z_{i+1,j+1} - z_{i+1,j})^2 + (z_{i,j+1} - z_{i,j})^2}{2}$$

4

In the formula:

A point in the fissure region is the coordinate origin, and the fissure surface is gridded. $N_x$ and $N_y$ are the number of sampling points in the x-axis and y-axis directions, respectively; $\Delta x$ and $\Delta y$ are the intervals of sampling points in the x-axis and y-axis directions, respectively; $z_i$ and $z_{i+1}$ are the z-axis direction coordinates of the i and i + 1 fissure discrete points, respectively; and $i$ and $j$ are the ordinal numbers of the fine-viewing planes along the x-axis and y-axis directions, respectively.

For the cleavage surface constructed in this test, the lower left end point of the cleavage surface was set as the coordinate origin at 3.74mm downward, and a coordinate system was constructed to grid it, with the spacing of each neighboring measurement point set at 1mm, 121 measurement points along the X-axis, 31 measurement points along the Y-axis, and a total of 3,751 measurement points, and 3,600 grid cells were delineated. Therefore, $N_x$ and $N_y$ are 121 and 31, respectively, and $\Delta x$ and $\Delta y$ are 1 mm, and the resulting fracture parameters are shown in Table 1.
Table 1
Morphological parameters of fissure specimens

<table>
<thead>
<tr>
<th>Length L/mm</th>
<th>Width B/mm</th>
<th>Minimum height of rough undulation ( Z_{\text{min}} )/mm</th>
<th>Maximum height of rough undulation ( Z_{\text{max}} )/mm</th>
<th>Mean value of rough undulation height ( Z )/mm</th>
<th>JRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>30</td>
<td>0.68</td>
<td>9.57</td>
<td>4.00</td>
<td>18.7</td>
</tr>
</tbody>
</table>

Seepage test design

Test equipment

The instruments used in the experiment are HK-400 syringe pump (injection flow rate up to 1500 ml/h, blocking pressure 40–150 KPa), high-power water injection pump (maximum output water pressure value of 2.5 MPa, rated maximum flow rate of 30 mm/min, rated operating voltage 220 V), pressure transmitter (range of 10 KPa, 100 KPa, 1 MPa, respectively), Date taker 85 series 3 data collector, computer, fissure model, smart phone, hose, adapter, etc. (Fig. 3)

The experimental process is controlled by a syringe pump equipped with a syringe through a program to inject liquid according to different flow gradients, the liquid is injected into the 3D printed fissure model and the pressure transmitter through a hose, and different flow rates are controlled according to the experimental program, and the data collection is performed in the Date taker. In addition the fissure model is connected to a large syringe pump, which can be connected to a computer for program control and real-time recording of flow and pressure changes. The whole experimental process can be video-recorded and photo-collected by the cell phone on the stand.

Test program

This test is mainly divided into 3 parts, the first part is the seepage study of the fissure model, the second part is the study of the fissure grouting process, and the third part is the study of seepage resistance and seepage pattern of the conduction fissure after the grouting consolidation of the fissure model.

Fissure seepage: The fissure model has two ports, A and B. If water is injected into one port, water will come out of the other port, and the experiment was conducted by injecting water into both ports sequentially. During the experiment, the pressure data were collected by controlling the flow rate of different gradients, there were 12 flow rate gradients, 1.67-25 ml/min, the test time of each gradient was 20s, and the frequency of pressure data collection was 1 time per second. In order to facilitate the observation of the water body in the fissure seepage diffusion process, put a small amount of red dye in the water, the water body from the fissure model side of the inlet into the buffer tank, through the fissure by the other side of the buffer tank after the end of the port at the end of the outflow for collection.
Grouting diffusion: The experiment used five different water-cement ratio slurries, which were injected into the model by a syringe pump, with water-cement ratios of 0.75:1, 1:1, 1.25:1, 1.5:1, and 2:1, respectively. The flow rate of the injected slurry was controlled to be 200 ml/h, and the change of pressure at the two ends of the fissure was recorded by a paperless recorder that receives signals from a pressure transmitter.

Research on seepage resistance and seepage law after slurry consolidation: For the fracture model injected with different water-cement ratio slurries, in order to control the variables of the experiment, each proportion was left to solidify for 7d, and water injection could be carried out only after it was completely solidified. At the beginning of the rated power syringe pump for its water injection, the injected water body into a small amount of red dye, to observe the seepage process, and collect its pressure change data. Subsequently, a high-power water pressure-volume control box was used, and the same 12 flow gradients (1.67-25 ml/min) were laid out for its water injection and percolation.

This experiment was conducted in a small scale, which inevitably affects the experimental parameters due to the effect of pipe seepage. For this reason, an equal gradient of flow was set up specifically for the pipe seepage, and the pipe pressure was measured. Two groups were deployed and their average values were taken. The pressure in the fissure is equal to the pressure difference between the two ends of the injection monitoring pressure minus the seepage pressure of the pipe.

Ensure that all air bubbles are discharged as far as possible during the test, so as not to affect the experiment. In each operation to ensure that the pipeline position head unchanged, to reduce human error.

**Results and discussion**

**Fracture seepage**

**Fissure seepage process**

A smartphone was used to take photos of the whole process of fissure seepage, with the liquid entering into the fissure as the starting time, and the photos were intercepted and analyzed every 10s, for a total of 93s.

From the flow of stained water in Fig. 4, it can be seen that the water flow through the fissure is initially driven along the fissure grooves, and a protruding front will be formed along the direction of the water flow in the flow process, and the morphology and position of the front will be changed along with the undulating state of the fissure surface, and it will be preferentially flowed to the low-lying part of the fissure. Part of the fissure convex place, the liquid failed to flow through, but with the overall advance of the water body, the convex place is also gradually covered by the water, with a certain lag, and in the end of the fissure convex place of the water flow failed to flow through, the main reason is that the water
body has already arrived at the end of the buffer tank, the overall driving force of the water body is weakened.

The water body does not completely fill the entire fissure at lower flow rates, and voids occur where the fissure surface is more undulating.

Figure 4 Fissure seepage process

Seepage patterns and analysis of results

Twelve different flow gradients were used to inject water into the model for seepage, and the pressure changes caused by water injection in different ports of A and B were recorded, and the real-time curves obtained are shown in Fig. 5. Under each flow gradient, the pressure initially increased sharply and gradually stabilized in the latter half of the flow gradient. According to each flow gradient, the stabilized pressure characterization corresponding to the second half was taken respectively, and its permeability coefficient was initially calculated by Darcy's law.

The coefficient of permeability is a parameter index that characterizes the ability of water to pass through a geotechnical body, and the reasonable calculation and use of the coefficient of permeability to carry out research on the infiltration capacity of the geotechnical body is a commonly used means of calculating the following formulas:

\[ K = \frac{Q}{AJ} = \frac{Q \rho g L}{A \Delta P} \]

Where \( Q \) is the flow rate, \( m^3/s \); \( J \) is the hydraulic gradient; \( \rho \) is the density of water, \( kg/m^3 \); \( L \) is the length of the fissure channel, \( m \); \( A \) is the cross-sectional area of the channel, \( m^2 \); and \( \Delta P \) is the difference in pressure between the two ports of the fissure, \( Pa \).

As shown in Fig. 6, with the change of hydraulic gradient, the permeability coefficient \( K \) gradually decreases, and its variation range is 0.02 ~ 0.12 \( m/s \). The relationship between \( K \) and \( J \) is characterized by the curve, and the curves by different ports can be fitted by the power function (the correlation coefficient \( R^2 > 9.1 \)), which has a better fitting effect, and the better the fitting effect is with the increase of \( J \). The relationship between \( K \) and \( J \) is characterized by the curve, which is characterized by the power function (the correlation coefficient \( R^2 > 9.1 \)). Since \( K \) is no longer linear at different pressure gradients, and the seepage is not only laminar, the theoretical analysis of the experiment by Darcy's law is not perfect.

Figure 6 Infiltration coefficient \( K \) versus hydraulic gradient \( J \)

According to previous studies, it is known that for nonlinear seepage, Forchheimer's equation can better describe the non-Darcy motion law in the fracture with the equation:
Where A is the coefficient of the linear term (related to the viscous force of the cleft itself) and B is the coefficient of the nonlinear term (related to the inertial force of the cleft itself)

Each flow gradient corresponds to a seepage pressure, and all the flow and pressure data are presented in a graph (Fig. 7).

It can be seen that the fitting characterization of the relationship between flow and pressure of seepage using the binomial equation is very effective, and the correlation coefficients, $R^2$, can reach 99% with a high degree of confidence.

Fluid seepage in the fissure, due to the fissure surface has a certain roughness, its ups and downs change unevenly. Therefore it has a certain pattern in different gradients. In the lower flow gradient, the flow rate is very slow, the viscous force in the fissure occupies the dominant position, the secondary term $BQ^2$ becomes very small and negligible, and the seepage in the fissure at this time can be characterized by Darcy's law. As the seepage flow rate increases, its seepage velocity increases, the viscous force decreases, the inertial force gradually increases, and the inertial term dominates.

For the ideal laminar motion, the nonlinear term coefficient B in the equation is zero only the linear term remains, in line with Darcy's equation of motion. When the coefficient of the linear term in the equation is very small or even zero, there are only nonlinear terms in the equation, which is turbulent. According to the above image analysis, the relationship of P-Q is analyzed by the nonlinear seepage equation, and its viscous term and inertia term occupy a large proportion, so it can be considered that the seepage in this fissure is in the laminar and turbulent flow mixing with each other in common motion.

At present, most scholars mainly use the critical Reynolds number to distinguish laminar and turbulent flows from each other. But the size of the critical Reynolds number and the fluid channel collision, the smoothness of the pipe wall, the degree of external disturbance and other factors, can not simply apply the classical model of the critical Reynolds number of laminar and turbulent flow boundaries, need to be based on the specific flow model to make the corresponding decision. Its calculation formula:

$$Re = \frac{\rho v d}{\mu}$$

Re is the Reynolds number; $\rho$ is the fluid density, kg/m$^3$; $d$ is the characteristic length of the flow field, m; $\mu$ is the dynamic viscosity, N s m$^{-2}$; Combining the rift structure used in this test, the flow rate Q of the overwater section, and the characteristic length of the flow field used as the equivalent hydraulic opening eh, the formula for Reynolds number becomes:
A is the area of the fissure overwater section, m$^2$; w is the width of the fissure seam, m.

In the same fissure, the seepage flow Q is the same in different sections of the overwater section, the more complex the undulation of the fissure in the overwater section, the longer the width of the seam, the smaller the Reynolds number. It can be seen that the seepage state of water in different sections of the rift is different. Combined with the above water body in the process of fissure seepage in different areas of the flow variability, it can be seen in the fluid in the rough fissure seepage process has a strong active, seepage state is constantly changing. It can be further explained that in the process of fissure seepage appears in the laminar flow and turbulent flow combined with the form of composite flow movement.

**Grout diffusion and consolidation seepage**

**Grouting diffusion process**

The injection is a constant flow injection, with a constant rate of 200ml/h. The whole process of the grouting experiment was video-recorded, taking the injection of cement slurry with a water-cement ratio of 1:1 as an example, and the results of the video recording were intercepted with pictures, and one picture was intercepted every 10s until the grouting was completed and stopped, which took a total time of 78s (Fig. 8).

According to the picture information, it can be seen that the slurry replaces the water inside the fissure during the injection process, and the slurry moves slowly in the initial section of the fissure because the slurry needs to withstand the resistance of the whole fissure water at the beginning. As the injection proceeds, the slurry gradually moves faster in the fissure, and the slurry movement tends to stabilize in the middle section of the fissure. In the middle section of the fracture, the slurry movement tends to stabilize, and the speed becomes faster when the slurry reaches the exit of the fracture.

Slurry in the transport process of its frontal morphology and smooth plate-like elliptical transport is different, with the undulation of the fissure, its frontal morphology will continue to change, and the tip of the front will be transported toward the undulating low-lying fissure surface. The fronts will appear to be concave when flowing through the high undulations. However, no matter how the fronts change, the slurry will gradually spread forward with the peak line, and can spread the entire fissure is complete.

**Analysis of the grouting process**

A constant injection flow rate of 200 ml/h was used to inject ordinary silicate cement slurry into the same five fissure models obtained by 3D printing with water-cement ratios of 0.75:1, 1:1, 1.25:1, 1.5:1, and 2:1, respectively, and the pressure changes were recorded during the experiments(Fig. 9).
As analyzed in Fig. 9, with the grouting, the pressure inside the fissure will change gradually, which can be roughly divided into two stages, one is the rising stage, and the other is the plummeting stage. For the plummeting stage, the main reason is that this experiment is based on the actual engineering grouting, and the grouting is stopped when the slurry reaches the exit of the fissure, and at this time, the pressure inside the model will be quickly released. In the pressure rise stage, the slurry drive extrusion of water body so that the pressure inside the fissure increases, but this process is not completely linear incremental increase, more to step jitter rise, due to the slurry in the water-filled fissure transport, fissure surface rough and uneven, when the slurry flow through the concave surface of the fissure surface, the slurry will have a gravitationally downward dive driving force, at this time out of the measuring point of the pressure rises slowly, when the slurry flow through the fissure face When the slurry flows through the convex part of the fracture surface, the slurry will have a climbing process, at this time the pressure will increase faster. This pressure fluctuation caused by the pitching and climbing effects of the rough surface slurry is especially obvious in the slurry injection process with a water-cement ratio of 2:1. Overall, the pressure fluctuates and changes as the slurry is transported due to the effect of the undulation of the rough fissure surface, but, as the grouting process continues, the pressure is generally an increasing process, and the rate of increase becomes faster and faster.

According to the curve analysis, when slurry with different water-cement ratios is injected, the fracture pressure increases at different rates within the same time, in which the faster the pressure increases with a water-cement ratio of 0.75:1, and the rate of pressure increase decreases with the increase of water-cement ratio. In addition, in Fig. 9 can also be based on the peak out time to know the speed of the slit injection process, in which the water-cement ratio of 0.75:1 of the slurry injection speed is the fastest, with the water-cement ratio of the larger the time used for the injection of the slit instead of increasing. After analysis, it can be seen that: this experiment is a fixed-flow grouting, the injection process to ensure that the flow rate is always maintained at 200ml/h, in the slurry with a larger proportion of cement, the accumulation of cement particles makes the fissure channel narrower, but the flow rate of the slurry is unchanged, the cement slurry will be in the narrow channel under the performance of the stronger active, the pressure within the fissure will increase the faster, therefore, the slurry with a small water-cement ratio in the narrow channel of the transportation of its front running will be faster.

Seepage study after slurry fill consolidation

As the ordinary cement slurry without any additives has water precipitation, and the slurry will be precipitated so that the filling in the fissure will produce voids. Due to the undulation of the fissure, the water precipitation and precipitation of the slurry in the fissure is more complicated, the study of the infiltration path and infiltration law of the fissure after the slurry filling and consolidation, and master the infiltration performance of the fissure after the grouting and consolidation, it is of great significance for the study of the seepage barrier of the fissure grouting, the detection and evaluation of the grouting effect and the guidance of the practical engineering grouting application.
In this experiment, a high-power syringe pump is utilized, which can realize the fixed-flow injection of seepage. The five slurry-filled fissure models were placed for 7d, and the seepage test study was carried out on them after they were completely solidified and molded, and the same 12 flow rate gradients were used to collect the pressure change data in different time periods.

**Seepage path**

As shown in Fig. 10, the water body is enrolled into a small amount of red ink, and then the liquid is injected into the fissure model through a syringe pump, and its main infiltration path can be reflected. In the figure, the water body does not present a faceted whole cross-section seepage in the slurry-filled fissure, but seeps through tiny conductive branch channels. At the beginning stage, the buffer tank is filled with a main channel, and then two branches appear in the middle of the fissure, which converge at the end of the fissure, and the area covered by the water body at the end of the fissure increases in size.

The cement-filled fissure model with a water-cement ratio of 1:1 is divided into 3 sections, each fissure is 4 cm long, and the filling conditions of the fissure entrances and exits as well as the middle two sections are observed in a total of 4 cross-sections (Fig. 11), and it can be found that: according to the situation shown in Figs. a-d, the cement slurry is very unevenly filled in it, and it shows a law of gradual decrease of the cement's filling rate from the entrance to the exit; in Fig. a, it is the entrance cross-section, and the overall filling condition is better. Figure a is the inlet cross-section, the overall filling of the cross-section is good, but in the cross-section of the high degree of undulation of the voids will appear, these voids for the main channel of water seepage; in Figure b, the overall filling of the cracks is good, in the left end of the large voids channel; in Figure c can be seen that the filling rate of the cracks is obviously reduced, the voids appeared in the cracks in the middle and upper part of the face of the large area of the distribution of the segments; in the outlet cross-section d, the degree of filling of the cracks is poor, the distribution of voids further expanded, and the distribution of voids is very small, and the filling rate is very small, and the distribution of voids is very small. The distribution of voids is further expanded, and the overall upper and lower stratification of voids and cement particles is obvious.

Combined with the fissure seepage path diagram and the fissure cross-section diagram, it can be seen that the ordinary cement slurry in this fissure model is extremely uneven filling, unfilled to the site will appear voids, mainly distributed in the raised high point of the fissure surface, these voids are inter-conducting, is the main flow channel of the water flow. Water flow in the second half of the distribution of the fissure is expanded, the cross-section of the filling degree is poor, is the more active part of the water seepage.

The factors affecting the filling effect of ordinary cement slurry in rough fissures are mainly divided into two major parts: the first part is mainly reflected in the grouting process, which is related to the means of grouting and the morphology of the fissure surface. In the process of grouting, the slurry is pushed forward from the entrance, and different precipitation accumulation phenomena will occur at the same time when it is continuously transported forward, so that the crack channel becomes narrower, and if the control of the slurry flow rate is unchanged, this narrow part of the slurry runs faster, but the filling rate of
the crack behind will be reduced. The second part of the slurry itself is related to the precipitation of water, the slurry itself will precipitate water up and down the stratification, but by the influence of the degree of undulation of the fracture, the precipitation of the slurry is not a uniform area, in the undulation of different places of different precipitation, the undulation of the higher the precipitation of water is more obvious, the more likely to produce a void.

**Study of infiltration patterns**

The collected data will be sorted and analyzed, according to the pressure and flow rate under each gradient, the relationship between the permeability coefficient $K$ and $J$ of the gradient in which it is located can be calculated by Eq. 5 as shown in Fig. 13, which shows that the permeability coefficient is changing with the change of the hydraulic gradient, and the overall trend is decreasing, embodying the characteristics of the non-Darcy seepage flow. When the hydraulic gradient $J$ is 0-500, the permeability coefficient varies from 0 to 0.0007m/s. Comparing it with the non-grouted seepage before the fissure, it can be seen that: in the range of the same flow rate gradient, the permeability of the grouted filled fissure with different water-ash ratios shrinks by 100–1000 times.

The use of power functions to $K$-$J$ curve fitting has a good effect, the coefficients and exponents of the fit and correlation coefficients are shown in Table 3, and their correlation can be greater than 0.979, with a high degree of confidence. Under the same hydraulic gradient, the smaller the water-cement ratio, the smaller the permeability coefficient obtained from the model after slurry injection. In addition, the power function coefficients obtained from the fitting show a positive correlation with the water-cement ratio.

Curve fitting of the relationship between $-\nabla P$ and $Q$ for filled fissures with different water-cement ratios has a nonlinear shape and conforms to the binomial equation (Fig. 12, and the specific fitting coefficients are shown in Table 2). The correlations are all greater than 0.996, which is a very good fitting effect, and the Forchheimer equation can well describe the relationship between the two variables.

<table>
<thead>
<tr>
<th>Water-cement ratio</th>
<th>Coefficient A</th>
<th>Coefficient B</th>
<th>Correlation $R^2$</th>
<th>B/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:1</td>
<td>841.99</td>
<td>10002</td>
<td>0.997</td>
<td>11.88</td>
</tr>
<tr>
<td>1.5:1</td>
<td>747.85</td>
<td>18238</td>
<td>0.996</td>
<td>24.39</td>
</tr>
<tr>
<td>1.25:1</td>
<td>603.76</td>
<td>22063</td>
<td>0.996</td>
<td>36.54</td>
</tr>
<tr>
<td>1:1</td>
<td>442.22</td>
<td>26266</td>
<td>0.997</td>
<td>59.40</td>
</tr>
<tr>
<td>0.75:1</td>
<td>327.56</td>
<td>33386</td>
<td>0.996</td>
<td>101.92</td>
</tr>
</tbody>
</table>
Table 3
Individual coefficients obtained using power function fitting

<table>
<thead>
<tr>
<th>Water-cement ratio</th>
<th>Power function coefficient</th>
<th>Exponents of power functions</th>
<th>Correlation $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2:1</td>
<td>0.0009</td>
<td>-0.449</td>
<td>0.979</td>
</tr>
<tr>
<td>1.5:1</td>
<td>0.0008</td>
<td>-0.495</td>
<td>0.991</td>
</tr>
<tr>
<td>1.25:1</td>
<td>0.0007</td>
<td>-0.485</td>
<td>0.986</td>
</tr>
<tr>
<td>1:1</td>
<td>0.0006</td>
<td>-0.487</td>
<td>0.986</td>
</tr>
<tr>
<td>0.75:1</td>
<td>0.0005</td>
<td>-0.481</td>
<td>0.983</td>
</tr>
</tbody>
</table>

It can be seen that the modeled seepage in the fissure after grouting consolidation is non-Darcy nonlinear seepage, and its seepage state is not only affected by viscous force, but also inertia force accounts for an important part. From the Forchheimer equation, it can be seen that the linear term coefficient $A$ and the nonlinear term coefficient $B$ are related to the characteristics of the fissure itself, and have nothing to do with the fluid condition in the fissure, $A$ is dominated by the viscous force in the fluid flow process, and $B$ is dominated by the inertia force in the fluid flow process, and the inertia force is the main factor mainly influencing the fluid to show the non-Darcy movement in the non-Darcy seepage. From the curve in Fig. 12, it can be seen that at the same flow rate, the smaller the water-cement ratio is, the greater the pressure it is under. The coefficients $A$ and $B$ obtained from the binomial fitting of $-\nabla P$ and $Q$ are shown in Table 2. The linear term coefficient $A$, the nonlinear term coefficient $B$ and the water-cement ratio show positive and negative correlation, respectively (Figs. 14), so that the ratio of $B$ to $A$ in the binomial equation increases with the reduction of the water-cement ratio, which is gradually increased from the original 12 times to 102 times. The linear term coefficient $A$ is related to the over-watering capacity of the fracture section, the smaller $A$ is, the smaller the conduction channel formed by the filling of cement slurry is, and the worse the permeability of the water body is. The smaller the water-cement ratio is, the larger the nonlinear term coefficient $B$ is, the heavier the inertia term is in the binomial, and the smaller the fissure channel is, but the larger the role of inertia force in the seepage.

Conclusions

Based on the natural fissure, the fissure reconstruction is carried out by 3D scanning, and the simulated real fissure model is 3D printed for visualization test to study its fissure seepage law, and on this basis, it is grouted and filled with different water-cement ratios by controlling different water-cement ratios using common silicate cement slurry, and the grouting process is briefly analyzed, and the seepage law of the fissure model is analyzed and investigated after the grouting and consolidation. The main conclusions can be drawn from the study:

(1) During the process of water injection and grouting in the fissure, the liquid flow front will change with the undulation of the fissure, and at low flow rate, due to the difference in the nature of the liquid itself, the cement slurry is less active than the water, but the coverage of the fissure is large.
(2) Rough single fissure seepage has obvious nonlinearity, which can be better described by Forchheimer equation, the fluid has strong activity in rough fissure seepage process, and the seepage process can be considered as a compound flow movement combining laminar and turbulent flow.

(3) During the grouting process, the flow of slurry in the fissure will have the effect of climbing and swooping, so that the pressure rise process shows a step change. Under the fixed flow rate, the slurry runs faster in the slurry with small water-cement ratio due to the filling effect.

(4) The slurry filling and consolidation in the fissure is extremely uneven, and the overall filling effect shows a gradual deterioration from the inlet to the outlet. The flow of water body in the filled fissure has obvious difference, and the flow area is large and active in the latter half of the fissure.

(5) The permeability coefficient of the slurry-filled and consolidated fissure is greatly reduced, and the permeability pressure with the change of flow rate also shows nonlinear change, and the nonlinear seepage law can be better described by the Forchheimer equation in the same way. The linear term coefficient and nonlinear term coefficient are positively and negatively correlated with the water-cement ratio. Therefore, as the water-cement ratio decreases, the linear term coefficient decreases, the nonlinear term coefficient increases and accounts for a larger proportion in the binomial.

Declarations

Conflict of interest

The authors declare that they have no conflict of interest to this work.

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Author Contribution

CT: Conceptualization, Methodology, Validation, Software, Data Processing, Writing-Review and Editing. ZQ: Methodology, Review and Editing, Obtaining Funding. BW: Review and Editing, Supervision.

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Data availability
Data will be made available on request.

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Figures

Figure 1

Fissure specimen preparation (a) Standard chert specimen (b) Specimen after fracturing (c) Selected fissure surfaces from the test block
Figure 2

3D printed fissure model fabrication process
Figure 3

Test system

Figure 4
Fissure seepage process

Figure 5

Pressure variation of fissure seepage
Figure 6

Infiltration coefficient $K$ versus hydraulic gradient $J$

$K_1 = 0.0262J^{-0.302}$
$\ R^2 = 0.914$

$K_2 = 0.0222J^{-0.303}$
$\ R^2 = 0.9235$
Figure 7

\( \nabla P \) versus flow rate \( Q \)

\[
\begin{align*}
\nabla P_1 &= 27.627Q^2 + 16.083Q \\
R^2 &= 0.9987
\end{align*}
\]

\[
\begin{align*}
\nabla P_2 &= 35.413Q^2 + 19.112Q \\
R^2 &= 0.9984
\end{align*}
\]
Figure 8
Grouting diffusion process (with water-cement ratio of 1:1 as an example)

Figure 9
Pressure data of grouting process
Figure 10

Seepage process after consolidation of fissure grout filling (modeled with 1:1 water-cement ratio)

Figure 11

Cross-section of filled fissure (model with 1:1 water-cement ratio as an example, where: (a) Cross-section of fissure inlet (b) Cross-section of fissure at 4 cm (c) Cross-section of fissure at 8 cm (d) Cross-section of fissure outlet)
Figure 12

$\nabla P$ vs. $Q$ for seepage after grouting consolidation of fissure models
Figure 13
K vs. J for seepage after consolidation of fissure grouting

Figure 14
(a) Relationship between coefficient A and water-cement ratio  
(b) Relationship between coefficient B and water-cement ratio