



# Study on the Development and Distribution Rule of Tensile Shear Fracture Propagation Angle of Fractured Rock Mass Under Seepage Pressure

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**Abstract** In order to study the development and distribution rule of tensile shear fracture propagation angle of fractured rock mass under seepage pressure, the shear-fracture model of single-fractured rock mass under seepage-stress is established, and the functional relationship between fracture expansion angle and fracture angle, confining pressure and seepage pressure is derived. Then based on RFPA-Flow software, the simulation verification of the crack expansion angle expansion rule is carried out. The simulation results verified the feasibility of the fracture propagation rule obtained by theoretical analysis to some extent. (1) In the case of single-fractured rock mass under seepage pressure, the fracture expansion angle increases with the increase of the seepage pressure in the fracture at a certain fracture angle and confining pressure; (2) In the case of a certain seepage pressure and a fracture angle, as the confining pressure increases, the fracture propagation angle also increases; (3) In the case of a certain seepage pressure and confining pressure, as the fracture angle increases, the fracture propagation angle decreases; (4) The rock fracture expansion does not extend completely along the fracture propagation angle due to the influence of confining pressure, seepage pressure and fracture

angle. Generally, fractures will first develop along the direction of the fracture propagation angle, but ultimately along the direction of the maximum principal stress to form a fracture. The research results have some complementary and verifying significance for the research of rock fracture damage mechanism.

**Keywords** Fracture angle · Fracture propagation angle · Seepage pressure · Confining pressure · Tensile shear fracture

## 1 Introduction

The rock mass in mining engineering is not intact, but contains a lot of initial defects. Many mine hazards related to seepage water increase the contact degree between water and rock mass due to the existence of these initial defects, and then change the mechanical and deformation characteristics of rock mass, coupled with external construction disturbances and other factors, leading to weakening of rock mass damage until fracture instability occurs (Huang and Xu 2008; Liu et al. 2012; Yang 1995). At present, scholars at home and abroad have done a lot of research on the microcosmic mechanism and mechanical effect of water bearing rock masses (Wang 2016; Xia 2014; Wang 2012; Ballivy and Rivard 2012). It is found that in the process of mining in mining area, there are often rock hydraulics problems in which mining stress,

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in situ stress and groundwater seepage stress interact with each other (Chen 2013). Therefore, it is of great practical significance to study the stress-seepage problem of fractured rock mass for understanding the mechanism of mine water inrush and predicting the occurrence of water disaster.

In theoretical analysis, the damage and deformation of fractured rock mass under seepage-stress interaction are studied by means of meso-mechanics. Based on the initial damage and damage evolution characteristics of rock mass, the seepage-damage-fracture coupled constitutive model of fractured rock mass and the seepage tensor evolution equation of fractured rock mass are established (Zhao 2009). Yang et al. used the theory of fracture mechanics to derive the formula for calculating the stress intensity factor of multi-crack tip under the action of far-field stress and fracture water pressure. The influence of fracture spacing and fracture penetration water pressure on the fracture tip stress field was analyzed (Yang 2010). Based on the stress distribution on the fracture surface of fractured rock under the coupling of seepage field and stress field, Pu CZ proposed the criterion for high and low osmotic water pressure environment, and gave the fracture failure mechanism of fractured rock under corresponding osmotic water pressure (Pu 2014). He has found that the effect of fracture interaction on stress intensity factor is significant. The stress intensity factor reaches the maximum when the cracking angle is about  $65^\circ$ . The stress intensity factor is more sensitive to the initial fracture angle and the length of wing fracture, and less sensitive to the fracture closure (He et al. 2017). Liu studied the initial damage of the rock mass and the softness tensor of the damage evolution based on the damage mechanics of the fractured rock mass. The damage evolution equation of the progressive failure of the rock under the high seepage pressure is proposed (Liu et al. 2012). Liu et al. (1999) found that as the natural fracture angle of the rock mass increases, the initiation and expansion of the fracture gradually weaken. Based on the investigation of the distribution rule of coal seam fractures, Huang (2010) obtained the minimum fracture water pressure and the extension length of hydraulic airfoil branch fractures in hydraulic rock fracture initiation based on fracture mechanics.

In terms of numerical simulation, through numerical simulation, the longitudinal splitting failure modes caused by wing fracture, anti-wing fracture

and secondary coplanar fracture, inverted capital letter “N” failure modes and “S” failure modes are proposed respectively (Liu et al. 2017a, b). Pan et al. (2008) reproduced the development and evolution of fractures through a large number of numerical experiments, obtained the general rule of the development and evolution of fractures under specific conditions, and described the failure pattern of rock blocks. Zhou (2014) used the RFPA2D calculation software to simulate the reproduction test process. By calculating the failure process of a fractured rock under simulated uniaxial compression load, it is found that the compressive strength of the specimen with one fracture has a great relationship with the fracture inclination angle and the presence or absence of osmotic water pressure.

In physical simulation experiments, through the physical simulation, the interaction of fracture, stress field and seepage field in the rock of the floor is studied. The evolution rule of the water inrush under the fluid–solid coupling is obtained, and the monitoring of rock stress and seepage pressure is realized (Zhang et al. 2017). The indoor model experiment of one-way flow using single-fracture specimens was carried out to comprehensively study the effect of fracture surface roughness and undulation on water flow velocity. And establish a single fracture conductivity equation for laminar flow and turbulent state (Louis 1974). Li et al. (2017) through triaxial compression tests, it is found that the peak strength and residual strength of rocks are greatly reduced, brittleness is increased and mechanical properties of rocks are weakened due to the existence of seepage water pressure.

Although experts and scholars around the world have done a lot of research on the mechanism of rock fracture damage from various aspects, few studies have been done on the development and distribution of tensile-shear fracture propagation angle of fractured rock mass under seepage pressure. Based on the theory of fracture mechanics and Mohr–Coulomb strength theory, this paper further deduces the expression of fracture propagation angle under the influence of fracture water pressure. At the same time, RFPA2D software is used to simulate the development of rock fractures and pore water pressure distribution under different fracture inclination, permeability pressure and confining pressure. The numerical simulation results verify the feasibility of the theoretical

calculation. Through the above research, it is hoped that the research work on the mechanism of rock fracture damage will be further assisted.

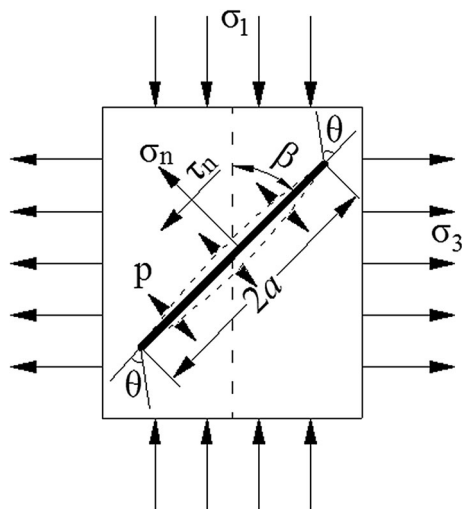
## 2 Mechanical Analysis of the Development Rule of Fracture Propagation Angle Under Seepage-Stress

### 2.1 Tension Shear Fracture Model of Single Fracture Rock Mass

In order to analyze the development rule of single-fracture rock tensile shear fracture and fracture propagation angle under the influence of seepage pressure, A tension shear model for single fractured rock mass under seepage pressure is established (see Fig. 1). Among them, the model test piece contains a fracture with a length of  $2a$  and an inclination of  $\beta$ , and  $\sigma_1$  is the vertical stress,  $\sigma_3$  is the horizontal stress,  $\sigma_n$  is the vertical stress acting on the fracture surface,  $\tau_n$  is the shear stress acting on the fracture surface,  $P$  is the seepage pressure, and  $\theta$  is the fracture propagation angle.

### 2.2 Mechanical Analysis on Tension Shear Fracture of Single Fracture Rock Mass

Without considering the fracture strength of single fractured rock mass under seepage pressure, the tensile



**Fig. 1** Tension-shear model of single fractured rock mass under seepage pressure

stress and shear stress of fracture surface in rock mechanics under tension and shear are respectively (Wang 2010):

$$\begin{cases} \sigma_n = \left(\frac{\sigma_1 + \sigma_3}{2} \cos 2\beta - \frac{\sigma_1 - \sigma_3}{2}\right) \\ \tau_n = \frac{\sigma_1 - \sigma_3}{2} \sin 2\beta \end{cases} \quad (1)$$

Considering the effect of seepage pressure on the fracture, combined with the stress expression of the rock structural surface in rock mechanics (Wang 2004), the effective stresses of single fracture surface under tension and shear are obtained as follows:

$$\begin{cases} \sigma_n = \left(\frac{\sigma_1 + \sigma_3}{2} \cos 2\beta - \frac{\sigma_1 - \sigma_3}{2} + P\right) \\ \tau_n = \frac{\sigma_1 - \sigma_3}{2} \sin 2\beta \end{cases} \quad (2)$$

According to the theory of stress intensity factors,  $K_I = \sigma_n \sqrt{\pi a}$ ,  $K_{II} = \tau_n \sqrt{\pi a}$ , and combined with the Mohr–Coulomb strength theory, there are:

$$\begin{cases} K_I = \left(\frac{\sigma_1 + \sigma_3}{2} \cos 2\beta - \frac{\sigma_1 - \sigma_3}{2} + P\right) \sqrt{\pi a} \\ K_{II} = \frac{\sigma_1 - \sigma_3}{2} \sin 2\beta \sqrt{\pi a} \end{cases} \quad (3)$$

Set  $t = \sigma_3 / \sigma_1$ , then Eq. (3) can be converted into:

$$\begin{cases} K_I = [t - (1+t) \sin^2 \beta] \sigma_1 \sqrt{\pi a} \\ K_{II} = (1+t) \sin \beta \cos \beta \sigma_1 \sqrt{\pi a} \end{cases} \quad (4)$$

According to the maximum circumferential stress criterion in the theory of fracture mechanics (Wang and Chen 2009), the maximum direction of the circumferential normal stress  $\sigma_\theta$  is the direction in which the fracture propagates, and the expression of the circumferential stress is:

$$\sigma_\theta = \frac{1}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left[ K_I \cos^2 \frac{\theta}{2} - \frac{3}{2} K_{II} \sin \theta \right] \quad (5)$$

The conditions for obtaining extreme value of circumferential stress are:  $\frac{\partial \sigma_\theta}{\partial \theta} = 0$ . Then, the derivative of (5) is obtained and reduced to:

$$K_I \sin \theta + K_{II} (3 \cos \theta - 1) = 0 \quad (6)$$

The Eqs. (4) and (6) of the simultaneous equations can be used to obtain the relationship between the fracture propagation angle and the fracture angle, the variable  $t$ , and seepage pressure:

$$\frac{(1+t) \sin^2 \beta - \frac{P}{\sigma_1} - t}{(1+t) \sin \beta \cos \beta} = \frac{3 \cos \theta - 1}{\sin \theta} \quad (7)$$

### 2.3 Developmental Rule of Fracture Propagation Angle in Single Fractured Rock Mass

According to the functional relationship between the variables in Eq. (7), this paper studies the relationship between the fracture propagation angle and the fracture angle, confining pressure and seepage pressure in two steps.

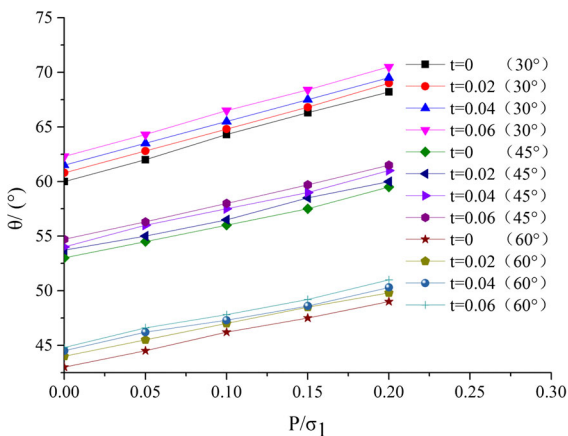
In the first step, the values of  $t$  are taken as 0, 0.02, 0.04, and 0.06, respectively. The values of  $\beta$  are taken as 30°, 45°, and 60°, respectively. Substituting the two sets of data into Eq. (7), the distribution of the fracture propagation angle under different seepage pressure (The seepage water pressure  $P$  here is expressed in  $\frac{P}{\sigma_1}$ ) is calculated (see Fig. 2).

In the second step, the values of  $t$  are 0, 0.02, 0.04, and 0.06, respectively. The values of  $\frac{P}{\sigma_1}$  are 0, 0.05, 0.1, 0.15, and 0.2, respectively. Substituting into Eq. (7), the distribution of fracture propagation angles at different fracture angles is calculated (see Fig. 3).

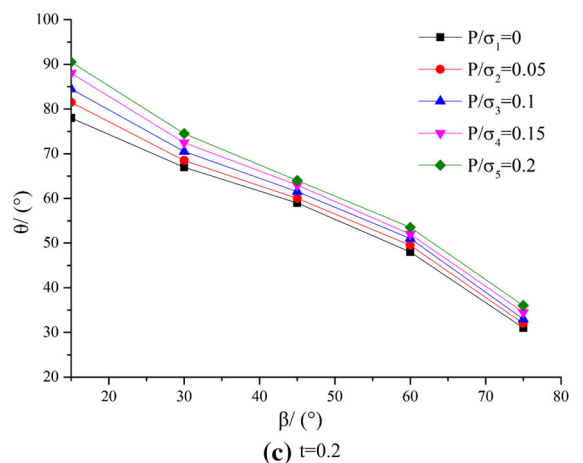
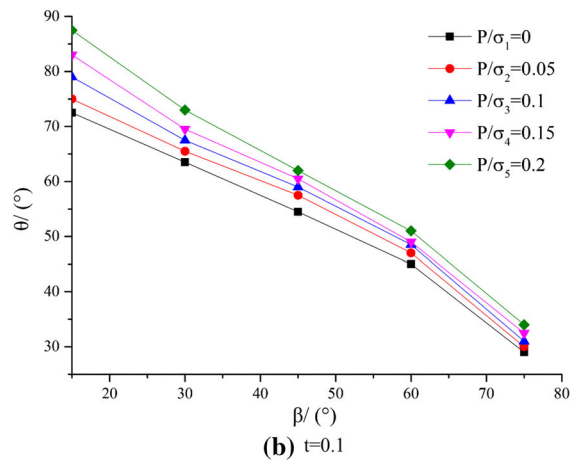
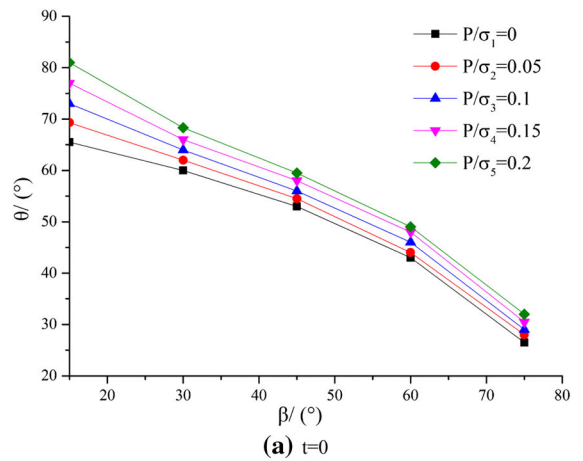
From the calculation results in Fig. 2 can be drawn.

When  $\beta$  is 30°, the maximum value of the fracture propagation angle appears at  $\frac{P}{\sigma_1} = 0.2$ . And if the value of the  $t$  is different, the maximum value of the fracture propagation angle is different. When  $t = 0$ , the maximum value of the fracture propagation angle is 68.2°. When  $t = 0.06$ , the maximum value of the fracture propagation angle is 70.5°.

When  $\beta$  is 45°, the development rule of the fracture propagation angle is similar to that when  $\beta$  is 30°. When  $t = 0$ , the maximum value of the fracture



**Fig. 2** Distribution of fracture propagation angle under the influence of seepage pressure



**Fig. 3** Distribution of fracture propagation angle under the influence of fracture angle

propagation angle is  $59.5^\circ$ . When  $t = 0.06$ , the maximum value of the fracture propagation angle is  $61.5^\circ$ .

When  $\beta$  is  $60^\circ$ , the development rule of the fracture propagation angle is similar to that when  $\beta$  is  $30^\circ$  and  $45^\circ$ . When  $t = 0$ , the maximum value of the fracture propagation angle is  $49^\circ$ . When  $t = 0.06$ , the maximum value of the fracture propagation angle is  $51^\circ$ .

In summary, the following conclusions can be drawn.

① When the fracture angle and the variable  $t$  (i.e. confining pressure) remain unchanged, with the increase of seepage pressure in the fracture, the fracture propagation angle increases, and its growth trend is approximately in line with the growth trend of the first-order function.

② When the seepage pressure and fracture angle remain unchanged, the fracture propagation angle increases with the increase of the variable  $t$  (i.e. confining pressure).

From the calculation results in Fig. 3 can be drawn.

When  $t = 0$ , the maximum value of the fracture propagation angle appears at the position of  $\beta = 0$ . And if the value of  $\frac{p}{\sigma_1}$  is different, the maximum value of the fracture propagation angle is different. When  $\frac{p}{\sigma_1} = 0$ , the maximum value of the fracture propagation angle is  $65.5^\circ$ . When  $\frac{p}{\sigma_1} = 0.1$ , the maximum value of the fracture propagation angle is  $73^\circ$ . When  $\frac{p}{\sigma_1} = 0.2$ , the maximum value of the fracture propagation angle is  $81^\circ$ .

When  $t = 0.1$ , the development rule of the fracture propagation angle is similar to that when  $t$  is 0. When  $\frac{p}{\sigma_1} = 0$ , the maximum value of the fracture propagation angle is  $72.5^\circ$ . When  $\frac{p}{\sigma_1} = 0.1$ , the maximum value of the fracture propagation angle is  $79^\circ$ . When  $\frac{p}{\sigma_1} = 0.2$ , the maximum value of the fracture propagation angle is  $87.5^\circ$ .

When  $t = 0.2$ , the development rule of the fracture propagation angle is similar to that when  $t$  is 0 and 0.1. When  $\frac{p}{\sigma_1} = 0$ , the maximum value of the fracture propagation angle is  $78^\circ$ . When  $\frac{p}{\sigma_1} = 0.1$ , the maximum value of the fracture propagation angle is  $84.5^\circ$ . When  $\frac{p}{\sigma_1} = 0.2$ , the maximum value of the fracture propagation angle is  $90.5^\circ$ .

In summary, the following conclusions can be drawn.

In the case where the seepage pressure and the variable  $t$  (i.e., confining pressure) remain unchanged, as the fracture angle increases, the fracture propagation angle decreases. Moreover, as  $\beta$  increases, the rate at which the fracture propagation angle becomes smaller tends to decrease first and then increase.

### 3 Numerical Simulation of the Development Rule of Fracture Propagation Angle Under Seepage-Stress

#### 3.1 Introduction to RFPA Software

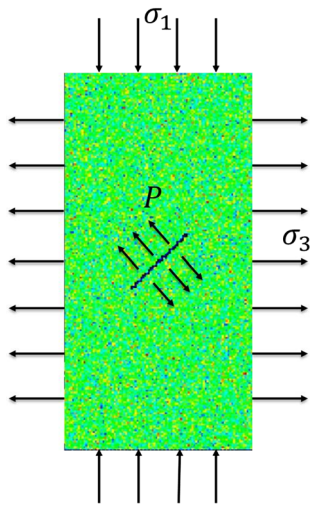
RFPA<sup>2D</sup> analysis software is a numerical technology tool which can simulate and reproduce the progressive failure process of rock medium by finite element method. It includes two functions: stress analysis and failure analysis. The software can be divided into several versions, such as rock movement, seepage, and gas, depending on the actual demand. The seepage edition of RFPA<sup>2D</sup> software mainly includes four functions: stress analysis, seepage analysis, failure analysis and coupling analysis. Therefore, the seepage plate of RFPA<sup>2D</sup> software is used to simulate the evolution rule of fracture propagation angle under stress-seepage coupling.

#### 3.2 Establishment of Numerical Model

In order to verify the feasibility of the development rule of fracture propagation angle under seepage-stress action proposed in theoretical analysis. Using the RFPA numerical simulation software, a triaxial tensile permeability model of a single fracture specimen with a height (y-direction) of 100 mm, a width (x-direction) of 50 mm, a fracture length of 20 mm and a width of 1 mm was established (see Fig. 4). The mechanical parameters of the model specimens are shown in Table 1, the seepage parameter of the model specimens are shown in Table 2 (Song 2017; Men 2015; Tian 2017).

#### 3.3 Numerical Simulation Results and Analysis

(1) When the fracture angle is  $45^\circ$  and the confining pressure is  $-0.8$  MPa (Minus sign represents direction), the evolution rule of fracture propagation angle



**Fig. 4** Triaxial tensile permeability model for single fracture specimens

under different seepage pressure is obtained (see Fig. 5).

The numerical simulations shown in this section are from left to right: the initial fracture expansion shear stress map, the initial fracture expansion pore water pressure map, the shear stress map when the fracture is formed, and the pore water pressure map when the fracture is formed.

It can be seen from the evolution diagram (Fig. 5) of fracture propagation angle under the influence of seepage pressure.

Under certain conditions of fracture angle and confining pressure, when the seepage pressure is 0.4 MPa, the fracture propagation angle is only 67°. When the seepage pressure is 0.6 MPa, the fracture propagation angle reaches 71°. When the seepage pressure is 0.8 MPa, the fracture propagation angle is further increases to 75°. Therefore, under certain conditions of fracture angle and confining pressure, with the increase of seepage pressure, the fracture propagation angle tends to increase. For every increase of seepage pressure of 0.4 MPa, the fracture propagation angle increases by about 4°, which conforms to the rule of development of the first-order function.

It can be seen from the rule of fracture evolution in Fig. 5 that rock fracture propagation does not follow the direction of fracture propagation angle completely, but first develops along the direction of fracture propagation angle, then the angle is gradually reduced, and finally form a fracture along the direction of the maximum principal stress.

(2) The evolution rule of fracture propagation angle under different confining pressures when the seepage pressure is 0.4 MPa and the fracture angle is 45°.

It can be seen from the evolution diagram (Fig. 6) of fracture propagation angle under different confining pressures.

Under certain conditions of fracture angle and seepage pressure, when confining pressure is 0, that is to say, it is uniaxial compression, and the fracture propagation angle is only 45°. When confining

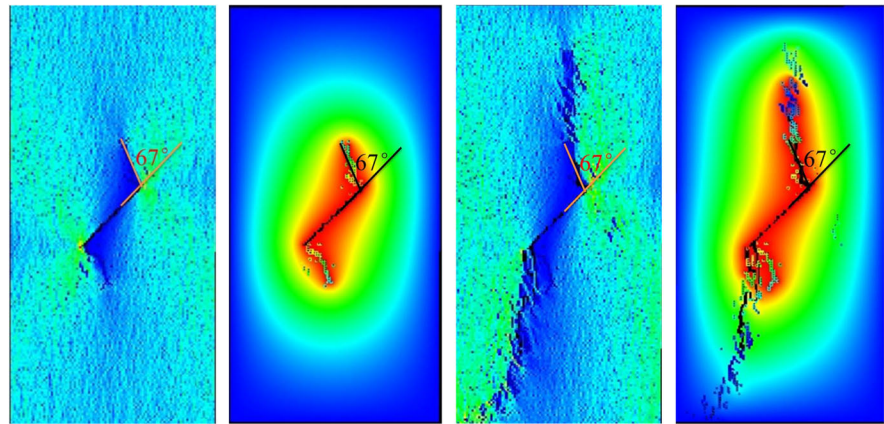
**Table 1** Failure characteristic parameter of the model

Parameter	Value	Parameter	Value
Internal friction angle	37°	Residual strength percentage	0.1
Poisson ratio	0.25	Percentage of residual Poisson’s ratio	1.1
Coefficient of pressure variation	200	Homogenization coefficient	3
Coefficient of tension	1.5	Uniaxial compressive strength average	200 MPa

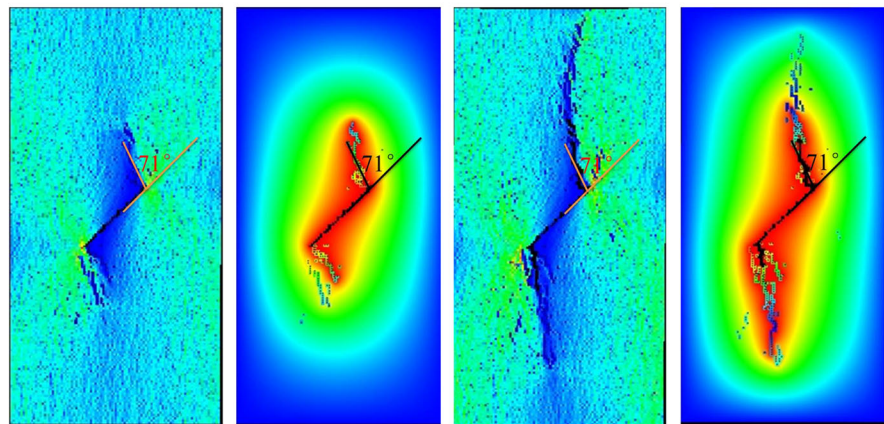
**Table 2** Seepage parameter of the model

	Horizontal hydraulic conductivity (m/day)	Coefficient of vertical permeability (m/day)	Porosity	Coefficient of pore pressure	Damage mutation coefficient	Separation coefficient	Coupling coefficient
Homogeneous degree	100	100	100	100	1000	1000	1000
Average value	0.000864	0.000864	0.1	1	5	100	0.1

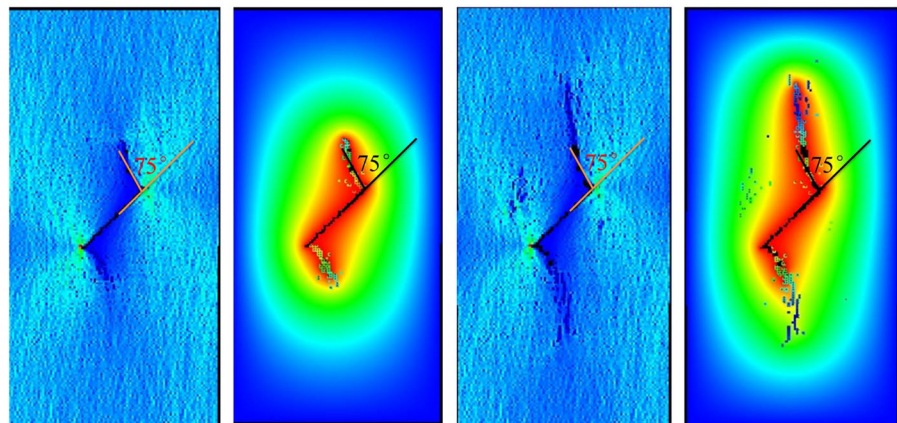
**Fig. 5** Evolution diagram of fracture propagation angle under Influences of seepage pressure



(a) The seepage pressure is 0.4MPa



(b) The seepage pressure is 0.6MPa

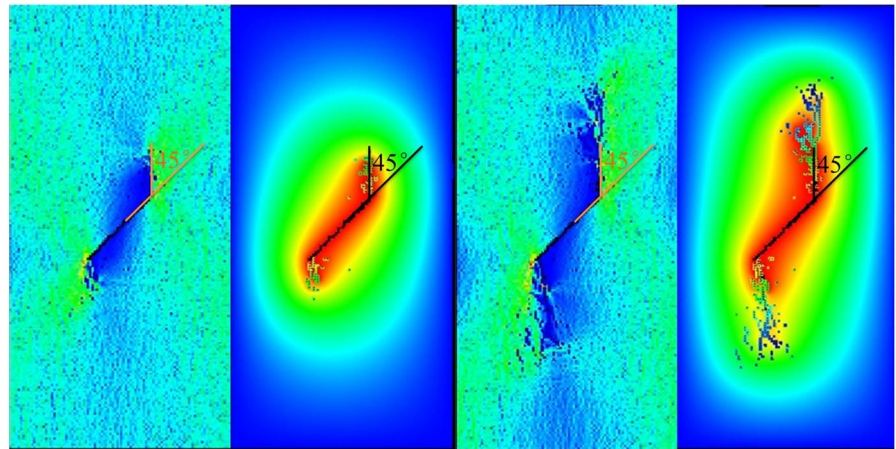


(c) The seepage pressure is 0.8MPa

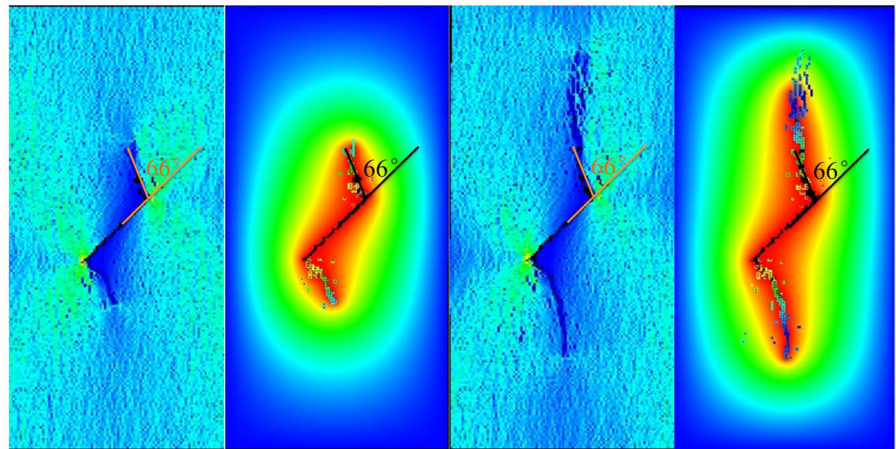
pressure increases to 0.6 MPa (Consider only the value of confining pressure, not the direction of confining pressure), the fracture expansion angle reaches 66°, and the fracture propagation angle

increases obviously, which indicates that confining pressure has a great influence on the fracture growth. When confining pressure increases to 1.2 MPa (Consider only the value of confining pressure, not the

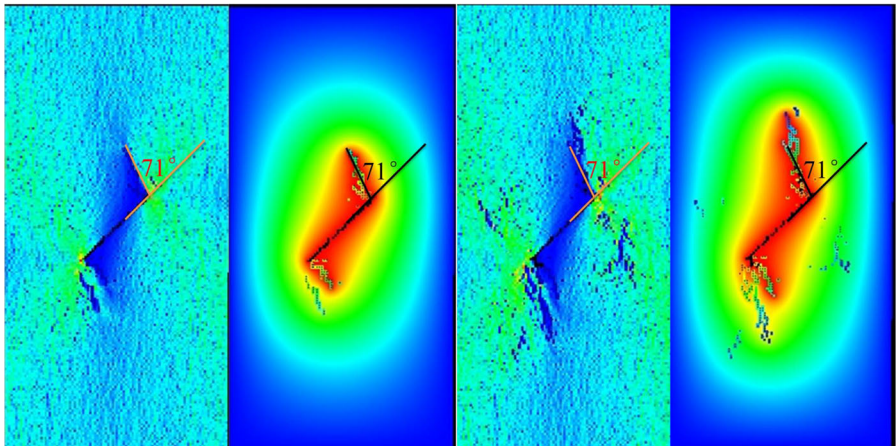
**Fig. 6** Evolution diagram of fracture propagation angle under different confining pressures



(a) The confining pressures is 0MPa



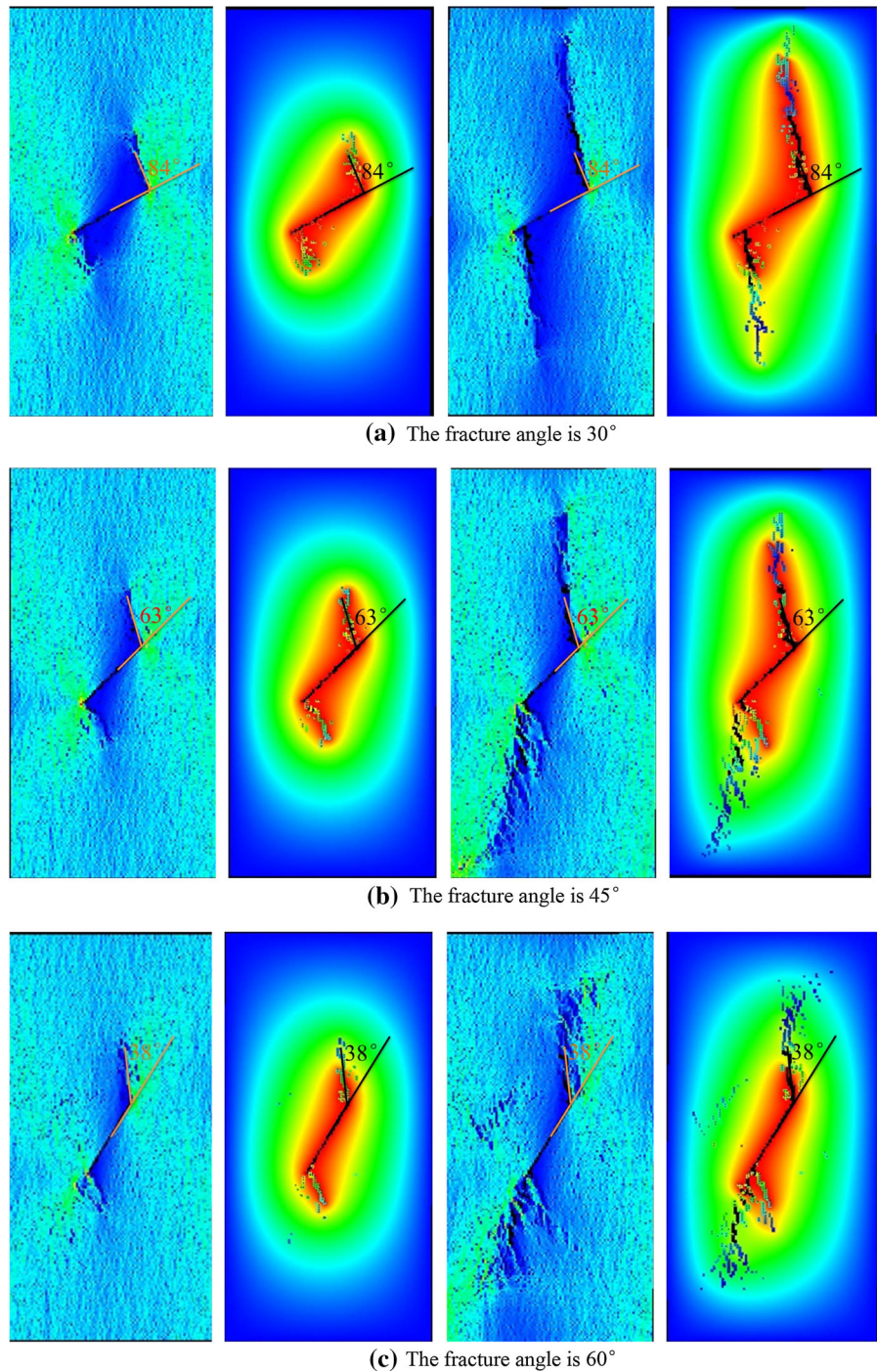
(b) The confining pressures is -0.6MPa



(c) The confining pressures is -1.2MPa



**Fig. 7** Evolution diagram of fracture propagation angle under the influence of different fracture angles



direction of confining pressure), the fracture propagation angle reaches 71°. Therefore, under the condition that the fracture angle and the seepage pressure remain unchanged, as the confining pressure increases, the fracture propagation angle also increases.

It can be seen from the rule of fracture evolution in Fig. 5 that when rock is not subjected to confining pressure, the fracture extension angle develops along the direction of the maximum principal stress, and the final fracture is still developing along the direction of

the fracture expansion angle. When rock is subjected to confining pressure, the angle of fracture propagation angle increases and deviates from the direction of maximum principal stress, but the direction of final fracture formation is still along the direction of maximum principal stress.

(3) When confining pressure is—2 MPa and seepage pressure is 0.4 MPa, the evolution of fracture propagation angle under different fracture angles are studied.

According to the evolution diagram (Fig. 7) of fracture propagation angle under the influence of different fracture angles, it can be seen that under the condition that the seepage pressure and confining pressure remain unchanged, when the fracture angle is  $30^\circ$ , the fracture propagation angle is  $84^\circ$ , when the fracture angle increases to  $45^\circ$ , the fracture extension angle decreases to  $63^\circ$ , and when the fracture angle is  $60^\circ$ , the fracture extension angle continues to decrease to  $38^\circ$ . Thus, we can conclude that under certain conditions of seepage pressure and confining pressure, the fracture propagation angle decreases with the increase of fracture angle.

It can be seen from the rule of fracture evolution in Fig. 7 that with the increase of fracture angle, the direction of fracture propagation angle gradually approaches the direction of maximum principal stress. That is to say, the larger the fracture angle, the more the fracture propagation direction will be consistent with the fracture propagation angle direction.

Through numerical simulation, not only the rules of fracture propagation angle development proposed in theoretical analysis are verified, but also the basic rules of fracture propagation process are summarized. The basic rules of fracture propagation process are basically consistent with those proposed by many previous researchers (Li 2008; Wang 2010), indirectly proving the applicability of these rules.

## 4 Conclusions

In this paper, a triaxial tension mechanical model of rock mass with single fracture under seepage pressure is constructed based on the fracture mode of rock fracture. The functional relationship between the fracture propagation angle and the fracture angle, confining pressure and seepage pressure is deduced. Then, based on RFP-Flow software, the simulation

verification of the crack expansion angle expansion rule is carried out. These conclusions can be drawn:

(1) The fracture propagation of the single-fractured rock mass under the action of shearing takes into account the influence of the seepage pressure on the fracture propagation angle. It is found that the seepage water pressure exacerbates the fracture initiation of the compression shear fracture, when the fracture angle and confining pressure remain unchanged, the fracture propagation angle increases with the increase of seepage pressure in the fracture.

(2) When the seepage pressure and fracture angle remain unchanged, the fracture propagation angle increases with the increase of confining pressure. When the seepage pressure and confining pressure remain unchanged, the fracture propagation angle decreases with the increase of fracture angle.

(3) Rock fracture propagation is not completely along the direction of fracture propagation angle due to confining pressure, seepage pressure and fracture angle. In general, the fracture first develops along the direction of the fracture propagation angle, but eventually forms a fracture crack along the direction of the maximum principal stress.

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