Study on fracture and seepage characteristics of rock mass with high water pressure caused by unloading

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Abstract: Research on the damage and seepage characteristics of unloading rock with high water pressure can help to further understand the mechanism of water inrush in deep mine and to take effective measures to prevent water inrush. In this paper, the finite element software RFPA2D-Flow was used to study the failure and seepage characteristics of unloading rock coupled with high water pressure and high stress. The effects of different water pressure on the failure of unloading rock and the law of seepage were investigated. The results show that the form of unloading rock failure without water pressure is brittle; however, the failure form of unloading rock with water pressure is obviously ductile failure, and the fracture is mainly concentrated at the bottom of the rock sample with high water pressure. During unloading, the seepage coefficient of rock increased with the increase of unloading amount until sudden jump occurs, and the failure form and permeability law of the rock with different water pressure were basically the same, but the larger the water pressure difference, the smaller the effective unloading capacity is needed when the permeability coefficient suddenly jumps, this shows that the larger the water pressure difference is, the more likely the rock mass will be damaged by water inrush under unloading condition.

1 Introduction

From the perspective of the nature of mechanics, the excavation and support of underground engineering belong to a category of alternating loading and unloading mechanics. In many cases, the unloading rock is simultaneously affected by groundwater seepage pressure. Most roof and floor water inrush failures in underground mining are caused by water pressure and unloading.

Chen and Li [1-2] conducted unloading test research on rock under high confining pressure and high water pressure. The analysis found that the degree of unloading damage after the rock reached the peak strength was greater than that before the peak. High water pressure reduces the strength of the rock. Yu [3] conducted a permeability test study on the full stress-strain process of sandstone, and analyzed the characteristics of the permeability of

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the sample with its brittleness and ductility during the full stress-strain process and the relationship between the permeability and the axial strain and volume strain. Liu [4] took raw coal as the research object and carried out post-peak confining pressure unloading test. The study found that when the axial pressure after the peak is unchanged and the confining pressure is unloaded, the coal sample permeability becomes larger and larger. The lower the axial pressure after the peak, the greater the influence of the confining pressure on the permeability. Yu [5] conducted a seepage-stress coupled three-axis test study on fractured sandstone and siltstone, and revealed its permeability law. Zhang [6] analyzed the influence of different unloading rates on the strength of rock samples through 2D elastic-plastic cellular automata numerical test and unloading confining pressure test. Guo [7] adopted the COMSOL software to establish the Darcy-and-non-Darcy-and-free-flow equation before and after the fault over-break in the stages of aquifer, fault and working face, thus obtaining the fault water inrush and current flow mechanism under the effect of stress and water pressure. Zhang [8] adopted the FLAC 3D numerical software to investigate the formation and evolution of water-inrush channel advancing with workface in high water pressure mining.

So, in order to be consistent with the actual, in this paper, considering the influence of water pressure difference on confining pressure unloading rock, RFPA2D-flow software is used to analyze and study the strength characteristics and failure evolution of confining pressure unloading rock with different water pressure difference.

2 Principles of Mechanics

The seepage of unloaded rock mass essentially means that the rock is subjected to stress and water pressure. And the cracks in the rock stratum are generated, expanded and penetrated until the rock stratum is unstable and damaged. It is a typical fluid-solid coupling process. The porous media deforms under the fluid load, which in turn affects the distribution and magnitude of the flow field load.

When simulating the fluid - solid coupling problem of rock, the rock is regarded as porous medium. The flow of fluid in the porous medium is based Darcy's Law [9] and meets Biot's fluid-solid coupling equation [10]. The classic basic equation of seepage coupling theory is:

Equilibrium equation:

$$G\nabla^2 u_j - (\lambda + G) \frac{\partial \varepsilon_v}{\partial x_j} - \frac{\partial p}{\partial x_j} + f_j = 0 \quad (1)$$

Geometric equation:

$$\begin{cases} \varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \\ \varepsilon_v = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} \end{cases} \quad (2)$$

Constitutive equation:

$$\sigma'_{ij} = \sigma_{ij} - \alpha p \delta_{ij} = \lambda \delta_{ij} \varepsilon_v + 2G \varepsilon_{ij} \quad (3)$$

Seepage equation:

$$k \nabla^2 p = \frac{1}{S} \frac{\partial P}{\partial t} - \frac{\partial \varepsilon_v}{\partial t} \quad (4)$$

Seepage and stress coupling equation:

$$k(\sigma, p) = \xi k_0 e^{-\beta \left(\frac{\sigma_{ij} - ap}{3} \right)}$$

(5)

In the formula, λ and G are Lamé coefficient and shear modulus respectively; ρ is the medium density; σ_{ij} and σ'_{ij} are total stress and effective stress respectively; x_j , u_j and f_j are coordinates, displacement and volume forces in the direction of j ; ε_{ij} and ε_v are total strain and volumetric strain; δ is the Kronecker constant; k is the permeability coefficient; S is the water storage coefficient; ξ , β , and a are the permeability coefficient jump ratio, coupling coefficient, and pore water pressure coefficient, respectively.

3 Numerical Analysis Model

RFPA2D-flow simulation software was used to carry out loading and unloading seepage tests on rock with water pressure. Figure 1 shows the two-dimensional plane stress thin plate model. The model is 50 mm wide and 80 mm high. The model is divided into 100×160 units. The physical and mechanical parameters of the model are shown in Table 1.

Fig. 1. The schematic diagram of model

Table 1. Mechanical parameters of model

parameter	Elastic Modulus /GPa	Poisson's ratio μ	Compressive strength /MPa	Tensile strength /MPa	Residual compressive strength /MPa	Permeability coefficient K_0 m/d	Water pressure coefficient α	Coupling coefficient β
value	10	0.22	100	10	1	0.2	0.6	0.2

The bottom boundary of the model was imposed with a displacement constraint in the vertical direction, an axial pressure p_1 was applied on the top, and a confining pressure p_2 was applied on all sides, and upper water pressures p_3 and lower water pressures p_4 are applied on the top and bottom boundaries of the model, respectively. In the process of stress-seepage coupling calculation, in order to make the rock unit better realize the coupling of seepage field and stress field, the equivalent permeability coefficient was calculated according to the stress and pore water pressure of the model unit at the end

of each cycle, and then the permeability coefficient was reassigned to each element of the model. It should connect the evolution of pores and fractures in rock with permeability coefficient, so that the seepage field and stress field interact with each other [11]. Considering that if the confining pressure of the rock is released after the peak, the stress has exceeded the yield strength of the rock, and the specimen is in a state of failure. Mohr-Coulomb strength criterion was used to simulate the unloading of seepage rock before the peak [12]. The simulation steps were as follows:

- 1) First apply axial pressure p_1 and confining pressure p_2 at the same time, and kept them equal at all times. After loading to a predetermined pressure step by step, apply certain pore water pressures p_4 and p_3 at the bottom and upper boundaries of the model to realize rock seepage simulation.
- 2) Kept the confining pressure p_2 unchanged, and used displacement control to carry out axial loading on the rock model. The loading displacement increment was $\Delta S= 0.005$ mm, until the axial pressure value p_1 reached a certain state before rock failure. That was the critical unloading point. The critical value of the unloading stress should be much greater than the compressive strength under uniaxial compression, and less than the compressive strength of the three-axis test under the corresponding confining pressure [13]. The starting point of unloading in this simulation was taken as 75% of the maximum strength of three-axis compression.
- 3) Kept the axial pressure p_1 unchanged, and gradually removed the confining pressure p_2 . Each unloading stage $p= 0.2$ MPa, until the model was damaged.

Table 2. Numerical simulation scheme of different water pressures

Model	Confining pressure p_2 /MPa	upper water pressure p_3 /MPa	lower water pressure p_4 /MPa	Water pressure difference Δp /MPa
1			6	2
2	15	4	8	4
3			10	6

First, the pre-peak unloading of rocks with or without water pressure was simulated. The rock at a depth of 800 m was selected, and its gravity stress was approximately 20MPa. The confining pressure was 0.6-0.8 times of the gravity stress. In this simulation, the confining pressure was 15MPa. The simulation process of unloading rock with water pressure was similar to that without water pressure. On the basis of the model without water pressure, pore water pressure p_3 and p_4 were applied to the upper and lower boundaries of the model, which were respectively 8MPa and 10MPa. In order to explore the failure process of confining pressure unloading rocks with different water pressure differences, the following simulation schemes were made, as shown in Table 2.

4 Results Analyses

- (1) Analysis of high water pressure
- 1) The comparative analyses of acoustic emission and fracture mode of rock with or without water pressure

Fig. 2. AE and axial stress and fracture mode of unloading rock without water pressure

Fig. 3. AE and axial stress fracture mode of unloading rock with water pressure

By comparing and analyzing Figures 2 and 3, it could be seen that the number of acoustic emissions reached the maximum when the unloading model without water pressure was at step 80, and almost no acoustic emission occurred before this. The ultimate fracture mode of the rock was brittle failure. The fracture started from the lower left corner to the upper right. The model with water pressure is different from the model without water pressure. Acoustic emission occurred before the maximum number of acoustic emissions in the unloading model with water pressure. The initial damage was earlier than the model without water pressure. Because the water pressure at the bottom boundary of the model was greater than that at the top boundary, the failure of the model mainly occurred in the lower part of the model.

2) Permeability coefficient and Seepage vector

Figures 4 and 5 are the permeability coefficient change curve and seepage vector diagram of the unloading rock with water pressure, respectively. During the loading process, the primary pores and micro-fractures gradually closed and the permeability coefficient of rock decreased. During the unloading stage, the permeability coefficient increased and even abruptly changed, because of the continuous initiation, expansion and acceleration of rock micro-fractures. The seepage path became increasingly obvious, and the seepage vectors

were concentrated around the fracture zone.

Fig. 4. permeability coefficient curve of unloading rock with water pressure

Fig. 5. Seepage vector in the process of unloading rock with water pressure

(2) Influence analyses of different water pressure

According to the numerical simulation calculation results of confining pressure unloading rock with different water pressure differences, the strength characteristics and failure evolution of confining pressure unloading rocks with different water pressure differences are analyzed from three perspectives, including the models of rock fracture, the changes of axial stress and acoustic emission and permeability coefficient during the experiment, relationship between unloading and permeability coefficient.

1) The Failure forms and seepage vectors of rock with different water pressure

Fig. 6. The failure forms of unloading rock with different water pressure

Fig. 7. Seepage vectors of unloading rock with different water pressure

Figures 6 and 7 are the final fracture and seepage vector of rock specimens with different water pressure differences. It can be seen from Figure 6 that with the increase of water pressure difference, the range and degree of rock fracture increase continuously. The seepage vector distribution of $\Delta p=2\text{Mpa}$ in Figure 7 is relatively uniform, indicating that the fracture is not too large. With the increase of water pressure difference, the more seepage vectors are generated near the fracture zone. This is in accordance with the law of optimizing the seepage path, that is, the velocity of macro-fractures is larger than that of micro-fractures [14].

2) The changes of rock acoustic emission and permeability coefficient

Fig. 8. AE and axial stress of unloading rock with different pore water pressure

Fig. 9. Permeability coefficient of unloading rock with different pore water pressure

Figures 8 and 9 are the AE and axial stress and permeability coefficient of rock specimens with different water pressure differences. It can be seen from Figure 8: during the initial loading stage, the rock with different water pressure difference has no acoustic emission, and the rock has not been damaged; as the calculation proceeds, small failure points and acoustic emission appear; when the acoustic emission reaches the maximum, it indicates that the rock has been greatly damaged. When the water pressure difference is 2MPa, 4MPa and 6MPa, and the corresponding load step is 117, 97 and 95, the acoustic emission number reaches its maximum value. It shows that the number of running steps to make rock failure decreases with the increase of water pressure difference. It can be seen from the change process of permeability coefficient in Figure 9 that rock failure modes with different pressure differences are basically same: during the loading process, the permeability decreases; in the unloading stage, the permeability increases continuously and even jumps.

3) Influence of unloading rate

Fig. 10. The relationship between unloading rate and permeability coefficient

To further describe the relationship between unloading volume and permeability coefficient, the unloading ratio of effective stress is introduced. It is the ratio of the difference between the initial stress and the effective stress corresponding to a load step in the unloading process and the initial stress, which is:

$$\eta = \frac{\sigma_0 - \sigma_i}{\sigma_0} \tag{6}$$

In the formula, η is the unloading ratio of effective stress; σ_0 is the initial stress; σ_i is the stress value corresponding to a load step in the unloading process. Figure 10 shows the relationship between the permeability coefficient and the unloading when the water pressure difference is 2MPa, 4MPa, and 6MPa. In the unloading elastic stage, the permeability coefficient increases little and changes little. When entering the plastic stage, the reduction of confining pressure increases the rock fracture and the brittleness of the rock. The deformation of rock changes from compacting deformation to dilating deformation. Percolation transitioned from the percolation of compressed pores to the percolation of shear fractures. The permeability coefficient increased greatly. The penetration of unloading rock with different water pressure differences is also quite different: When the water pressure difference is 2MPa, 4MPa, 6MPa, and the corresponding unloading capacity is 68.15%, 50.66%, 45.58%, the permeability has obviously increased. It shows that with the increase of water pressure difference, the unloading quantity to make rock failure becomes smaller and smaller. In addition, when the p_4 is 6MPa, 8MPa, 10MPa, the permeability coefficient is basically 0.0178 m/d at the initial stage of unloading, and the permeability coefficient after failure is 0.149 m/d, 0.1512 m/d, 0.2343 m/d, respectively. It is 8.37 times, 8.51 times, 13.16 times the original. It indicates that with the increase of water pressure difference, the change of permeability coefficient increases with the failure of rock. It shows that the permeability has changed greatly after rock failure. The water flow channel is pores composed of compacted particles, which are transformed into continuous cracks formed by shear failure.

5 Conclusions

According to the comparative analysis of the simulation results, the following conclusions can be obtained:
(1) The unloading rock without water pressure was brittle failure, while the unloading rock with water pressure was obviously ductile failure and its cracks first break through at the bottom of the sample with higher osmotic pressure.

(2) With the increase of water pressure difference, the extent and degree of rock fracture increase. The increase of water pressure difference makes the seepage path gradually obvious, and a larger seepage vector is generated near the fracture zone.

(3) The rock failure modes under different water pressure differences are basically identical: in the loading process, the permeability of rock decreases, and in the unloading stage, the permeability increases and even jumps.

(4) When the water pressure difference is 2MPa, 4MPa, 6MPa, and the corresponding unloading volume is 68.15%, 50.66%, 45.58%, the permeability of the rock has increased significantly. It shows that the strength of the rock decreases with the increase of the water pressure difference. The amount of unloading when the rock fails is getting smaller and smaller the permeability coefficient of rock failure is 8.37 times, 8.51 times, 13.16 times of the original. It shows that with the increase of water pressure difference, the change of permeability coefficient during rock failure increases.

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