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Seepage-Stress-Damage Coupled Model of Coal Under Geo-Stress Influence

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Abstract: In the seepage-stress-damage coupled process, the mechanical properties and seepage characteristics of coal are distinctly different between pre-peak stage and post-peak stage. This difference is mainly caused by damage of coal. Therefore, in the process of seepage and stress analysis of coal under the influence of excavation or mining, we need to consider the weakening of mechanical properties and the development of fractures of damaged coal. Based on this understanding, this paper analyzes the influence of damage on mechanics and seepage behavior of coal. A coupled model is established to analyze the seepage-stress-damage coupled process of coal. This model implemented into COMSOL and MATLAB software to realize the numerical solving. Two examples are adopted to verify the correctness of the model and some useful conclusions are obtained. The numerical model establishes the relationship between microcosmic damage evolution and macroscopical fracture and simulates the whole process of coal from microcosmic damage to macroscopical fracture, and the dynamic simulation of fluid flow in this process. It provides a numerical tool for further research on the seepage-stress-damage analysis.

Keywords: Permeability, porosity, gas pressure, damage, coupled model.

1 Introduction

Coal usually occurs in deep geo-stress and gas coupled environment. When it is affected by external factors such as mining disturbance, the initiation, expansion and coalescence of microcracks will emerge in coal, and the coal will be damaged and fractured [Wold, Connell and Choi (2008); Cao and Zhou (2015); Xue, Gao and Liu (2015); Salmi, Nazem and Karakus (2016); Newman, Agioutantis and Leon (2017)]. Damage causes the degradation of coal mechanical performance, and significantly changes the seepage performance [Durucan and Edwards (1986); Xue, Ranjith, Gao et al. (2017); Domingues,

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Baptista and Diogo (2017)]. In addition, the coal mechanical properties and permeability changes will affect the behavior of fluid seepage in coal, and then affect the distribution of effective stress and pore pressure in coal. In turn, coal stress and pore pressure changes will lead to changes in effective stress, which leads to the further development of the internal damage of coal. This mutual influence is seepage-stress-damage coupled influence [Zhu and Tang (2004); Li, Yang, Liang et al. (2011); Xue, Zhu, Zhang et al. (2016); Cao, Du, Xu et al. (2017)].

The excavation process of underground coal seam is a dynamic process comprised of a series of coupled effects and interactions such as coal deformation, gas flow, coal damage and the evolution of porosity and permeability. The tunnel excavation has been studied comprehensively. Cao et al. [Cao, Li, Tao et al. (2016)] explored the dynamic unloading excavation process by PFC after verifications against the theoretical results and studied the characteristics of unloading waveform under high initial stress under various ratios of horizontal and vertical in situ stresses. Zhang et al. [Zhang, Xu, Wang et al. (2016)] developed a coupled elastoplastic damage model for brittle rocks and deduced the constitutive relationships under three different loading conditions: damage, plastic and coupled plastic damage. Ren et al. [Ren, Zuo, Xie et al. (2014)] presented an updated method for finding the optimal shape of an underground excavation using the latest bi-directional evolutionary structural optimization techniques and discussed its engineering application through illustrated examples. However, the coal mass is a special rock material. It has a strong adsorption and heterogeneity characteristics, unlike sandstone, granite, marble and other rock materials. A fewer publications are available to account for the coupled effects with adsorption and heterogeneity characteristics.

Considering the heterogeneity of mechanical parameters of coal material, a seepage-stress-damage coupled model is established for analyzing the fracture evolution of coal. The numerical solution of the model is achieved through finite element software and the correctness of the model is verified by an example.

2 Coupled seepage-stress-damage model

2.1 Parameter assignment method of coal based on statistical distribution

Coal is a mixture including different mineral particles, cementation, pore fissure defects and so on. Therefore, the properties distribution of different mesoscopic elements is usually nonuniform in coal material. The heterogeneity of coal materials is very important for simulating the localized fracture phenomenon of coal. In this paper, the statistical mathematics method is used to describe the heterogeneity of physical and mechanical parameters of coal materials.

In order to describe the heterogeneity of coal materials, it is assumed that coal is consisted of a large number of microscopic elements. Assuming that the mechanical properties of these units obey Weibull distribution, the distribution can be defined according to the following density distribution function.

$$f(u)=\frac{m}{u_0}(u/u_0)^{m-1}\exp[-(u/u_0)^m] \tag{1}$$

Where u satisfies the numerical value of the Weibull distribution function, u_0 is a parameter related to the average value of all the unit parameters, and the shape parameter m gives the shape of the distribution density function.

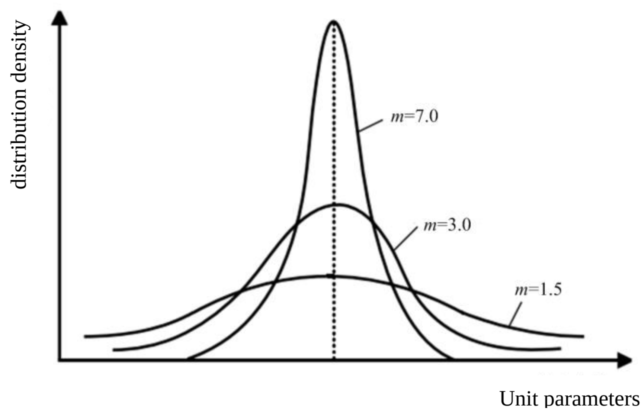


Figure 1: Distribution of mechanical properties in coal

Fig. 1 gives the distribution of the mechanical properties of microscopic elements of coal material under different homogenization coefficients. According to the basic properties of the Weibull distribution, the greater the parameter m, the better the uniformity of the material unit, and vice versa. Therefore u_0 and m are called the distribution parameters of materials. Using the Eq. (1), the inhomogeneous parameters of the coal materials can be generated in the numerical calculation. These parameters are closer to the true sample parameters in the laboratory test.

2.2 Deformable control equation

According to the theory of porous elasticity, the unit of coal satisfies the following equilibrium equation

$$\frac{\partial\sigma_{ij}}{\partial x_j}+f_i=0 \tag{2}$$

where σ_{ij} is the total stress component of the coal body unit; f_i is the body stress in the direction i; x_j is the direction coordinates in the direction j.

The coal is regarded as a porous medium, and the coal element satisfies the constitutive equation. It can be expressed by stress, strain and pore pressure as follows

$$\varepsilon_{ij} = \frac{1}{2G}\sigma_{ij} - (\frac{1}{6G} - \frac{1}{9K})\sigma_{kk}\delta_{ij} \tag{3}$$

where G is the shear modulus of coal, μ is the Poisson's ratio of coal, δ_{ij} is the symbol of Kronecker, α is the Biot coefficient of coal, $\alpha = 1 - K / K_m$; K_m is the bulk modulus of coal matrix, K is the volume modulus of coal, ε_{ij} is the component of strain tensor, and σ_{ij} is the component of stress tensor.

The following geometric equations are obtained according to the continuous deformation condition:

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{4}$$

After the coal adsorb gas, the adsorption expansion strain can be expressed

$$\varepsilon_s = \varepsilon_L \frac{p}{p + p_L} \tag{5}$$

where ε_L and p_L are the Langmuir strain constant and the Langmuir pressure constant, respectively.

The stress equilibrium equation can be expressed by displacement, pore pressure and adsorption expansion

$$Gu_{i,jj} + \frac{G}{1-2\mu}u_{j,ji} - \alpha p_{,i} - K\varepsilon_{s,i} + f_i = 0 \tag{6}$$

2.3 Gas seepage equation

The seepage of gas follows the law of conservation of mass.

$$\frac{\partial m}{\partial t} + \nabla(\rho_g \vec{q}_g) = Q_s \tag{7}$$

where m is the unit volume for the gas in the coal; ρ_g is the gas density; $\vec{q}_g$ is the Darcy velocity; Q_m is the source or sink; t is the time variable. The mass of the gas m is composed of free term and adsorption term, which can be expressed as:

$$m = \rho_g \phi + \rho_{ga}\rho_c \frac{V_L p}{p + p_L} \tag{8}$$

where ρ_{ga} is the gas density under the standard condition; ρ_c is the density of the coal; V_L is the Langmuir volume constant; ϕ is the porosity of the coal; p_L is the Langmuir volume constant.

Under the function of pressure gradient, the gas seepage equation in the fractured medium is as follows

$$\vec{q}_g = -\frac{k}{\mu}\nabla p \tag{9}$$

where μ_f is the coefficient of dynamic viscosity; k is the permeability of the gas.

Because of the compressibility of the gas, the relation between the gas density and the pressure is:

$$\rho_g = \frac{M_g p}{RT} \tag{10}$$

The continuity equation of gas seepage can be obtained as

$$\frac{M_g}{RT}\frac{\partial}{\partial t}(\frac{\phi p^2}{p_a}) - \frac{M_g k}{RT\mu_f}\nabla[p(\nabla p + \frac{M_g g}{RT}\nabla z)] = Q_m \tag{11}$$

2.4 Permeability model of coal

The basic skeleton of coal is deformed under the affection of gas pressure, which changes the porosity of coal, and affects the seepage of gas in coal. The coal is subjected to the double action of external stress and pore pressure. According to the principle of Terzaghi effective stress, the following equation can be obtained

$$\sigma_{ij}^{'} = \sigma_{ij} - \alpha p \delta_{ij} \tag{12}$$

where $\sigma_{ij}^{'}$ is the effective stress, σ_{ij} is the total stress, α is the Biot coefficient of the coal, p is the pore pressure, and δ_{ij} is the Kronecker symbol.

The coal body is regarded as the porous medium. The volume of the coal V is the summation of pore V_p and matrix V_s, so the porosity is defined as $\phi = V_p / V$. The volume deformation of the coal matrix consists of two parts: the effective stress and the matrix adsorption. Therefore, the volumetric strain and the fracture strain of the coal can be expressed as

$$\frac{\mathrm{d}V}{V} = -\frac{1}{K}(\bar{\sigma} - \alpha p) + \varepsilon_s \tag{13}$$

$$\frac{\mathrm{d}V_p}{V_p} = -\frac{1}{K_p}(\bar{\sigma} - \beta p) + \varepsilon_s \tag{14}$$

where $\bar{\sigma}$ is the average stress; K is the bulk modulus of coal; K_p is the bulk modulus of fractures; coal; α is the Biot coefficient of coal, $\alpha = 1 - K / K_m$; β is the Biot coefficient of coal fracture, $\beta = 1 - K_p / K_m$. ε_s is the adsorption deformation of coal, $\varepsilon_s = \varepsilon_{\max}\frac{p}{p + p_L}$; $\varepsilon_{\max}$ is the maximum adsorption amount of deformation,

p_L is the gas pressure when expansion deformation reaches half the maximum deformation.

The change rate of porosity is as follows:

$$\mathrm{d}\phi = \mathrm{d}\left(\frac{V_p}{V}\right) = \frac{V_p}{V}\left(\frac{\mathrm{d}V_p}{V_p} - \frac{\mathrm{d}V}{V}\right) \tag{15}$$

Then the following equation can be obtained:

$$\frac{\phi}{\phi_0} = \exp\left\{(\frac{1}{K} - \frac{1}{K_p})[(\sigma - \sigma_0) - (p - p_0)]\right\} \tag{16}$$

The permeability of the coal body is related to the porosity, which can be expressed by the Kozeny-Carman equation:

$$k = \frac{\phi^3}{CS^2(1-\phi)^2} \tag{17}$$

where ϕ is the porosity, C is the KC constant, which is associated with fracture tortuosity; S is the fracture surface area of porous medium per unit volume.

In the elastic stage, when the coal body deforms under the effect of external force, C and S are regarded as constants. And for coal seam, $\phi \ll 1$, permeability can be expressed as cubic law

$$\frac{k}{k_0} = (\frac{\phi}{\phi_0})^3 \tag{18}$$

The permeability of coal can be expressed as

$$\frac{k}{k_0} = \exp\left\{3(\frac{1}{K} - \frac{1}{K_p})[(\sigma - \sigma_0) - (p - p_0)]\right\} \tag{19}$$

Eq. (19) can be obtained after finishing transposition

$$k = k_0 e^{-3c_f(\sigma_e - \sigma_{e0})} \tag{20}$$

where k_0 is the initial permeability of coal, c_f is the compression coefficient of fracture, $c_f = \frac{1}{K_p} - \frac{1}{K}$; K is the volume modulus of coal; K_p is the volume modulus of coal fractures, and σ_e is the effective stress.

Considering the adsorption of coal, the volumetric strain of coal under the effect of pore pressure can be expressed as:

$$\varepsilon_v = -\frac{1}{K}(\sigma - \alpha p) + \varepsilon_s \tag{21}$$

The porosity of coal can be expressed in strain forms

$$\phi = \frac{1}{1+S}[(1+S_0)\phi_0 + \alpha(S - S_0)] \tag{22}$$

where, $S = \varepsilon_v + \frac{p}{K_s} - \varepsilon_s$, $S_0 = \varepsilon_{v0} + \frac{p_0}{K_s} - \varepsilon_{s0}$.

The expression of permeability can be derived as

$$\frac{k}{k_0} = (\frac{\phi}{\phi_0})^3 = \left\{ \frac{1}{1+S}[(1+S_0) + \frac{\alpha}{\phi_0}(S - S_0)] \right\}^3 \tag{23}$$

Eqs. (19) and (20) are permeability models in stress form, Eq. (23) is permeability model in strain form, both of which can effectively evaluate the permeability evolution characteristics of coal seam. According to the theory of elastic porous media, these two kinds of permeability models can be deduced and verified by each other.

2.5 Analysis of damage theory

The maximum tensile stress criterion is used to determine the tensile damage of coal, and the Mohr-Coulomb criterion is used to determine the shear damage of coal, as shown in Fig. 2.

$$\begin{aligned} F_1 &= \sigma_1 - f_t = 0 \\ F_2 &= -\sigma_3 + \sigma_1((1+\sin\phi)/(1-\sin\phi)) - f_c = 0 \end{aligned} \tag{24}$$

where σ_1 and σ_3 are the maximum principal stress and the minimum principal stress of coal units; f_t and f_c are uniaxial tensile strength and uniaxial compressive strength of coal unit, respectively.

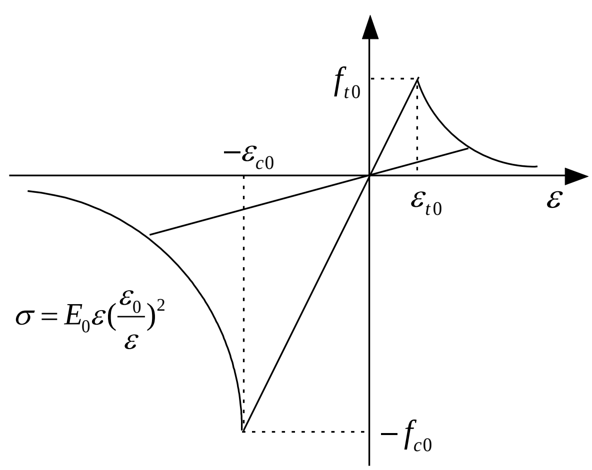


Figure 2: The constitutive law of coal under uniaxial stress condition

Based on the strain, the damage variable of coal units can be expressed using the following expression:

$$D=\begin{cases} 0 & F_1<0, F_2<0 \\ 1-\left|\dfrac{\varepsilon_{t0}}{\varepsilon_t}\right|^2 & F_1=0, \mathrm{d}F_1>0 \\ 1-\left|\dfrac{\varepsilon_{c0}}{\varepsilon_c}\right|^2 & F_2=0, \mathrm{d}F_2>0 \end{cases} \tag{25}$$

where ε_t and ε_c are the maximum principal strain and the minimum principal strain; ε_{t0} and ε_{c0} are the ultimate strain corresponding to tensile damage and shear damage, respectively. Under three-dimensional stress state, ε_t and ε_c are the equivalent principal strain of tension state and compression state, which can be expressed as

$$\begin{aligned} &\varepsilon_t=\sqrt{\langle\varepsilon_1\rangle^2+\langle\varepsilon_2\rangle^2+\langle\varepsilon_3\rangle^2} \\ &\varepsilon_c=\min\{\varepsilon_1,\varepsilon_2,\varepsilon_3\} \end{aligned} \tag{26}$$

where $\varepsilon_1, \varepsilon_2$ and ε_3 are the maximum principal strain; $\langle\varepsilon\rangle$ is the symbolic function, when $x \geq 0$, its value is x, when $x<0$, its value is 0.

According to the elastic damage theory, the elastic modulus of coal under damage state can be expressed as follows:

$$E=(1-D)E_0 \tag{27}$$

where, E_0 is the elastic modulus of undamaged state, E is the elastic modulus of the unit in the damaged state.

When the coal is damaged, the effect of the coal damage on the permeability can be described as

$$k=k_0 e^{-3c_f\lambda D(\sigma_e-\sigma_{e0})} \tag{28}$$

where k_0 is the initial permeability, c_f is the compression coefficient of the coal fracture, λ is the influence coefficient of damage to permeability, and σ_e is the effective stress.

2.6 Numerical realization of computational model

In this paper, a coupled seepage-stress-damage model for coal is proposed, which regards damage as a process. One of the most effective methods to solve the problem of fluid-solid coupled problem is to analyze it by using the multi-physical field coupled software COMSOL Multiphsics. In this paper, COMSOL Multiphsics and MATLAB are used to achieve the coupled solution of solid field, fluid field and damage field. The calculation process is shown in Fig. 3.

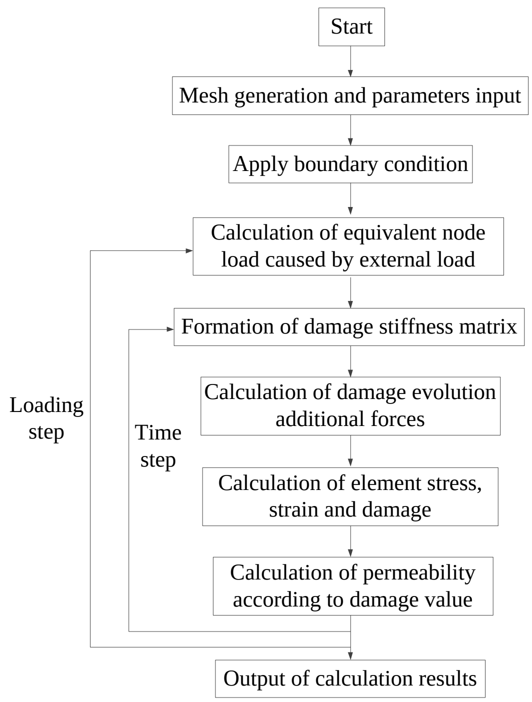


Figure 3: Flowchart for computational procedure of the approach

3 Numerical simulation of coupled process of coal

3.1 Example I: compression seepage coupled process of fractured coal

First, we use the proposed model to carry out the compression seepage coupled numerical simulation test of standard coal samples, and compare the numerical simulation results with the existing test results to verify the effectiveness of this model in simulating the deformation, fracture and seepage behavior of coal.

The basic model of numerical experiments is shown in Fig. 4. The size of the simulated coal sample is 50 mm×100 mm. In order to characterize the heterogeneity of coal materials, it is assumed that the initial mechanical parameters and seepage parameters of coal meet the Weibull distribution. The initial attribute parameters of each mesoscopic unit are generated by Monte-Carlo stochastic simulation method. The spatial distribution of the initial elastic modulus of coal is shown in Fig. 5. The mechanical parameters and percolation parameters used in the calculation are shown in Tab. 1. Similar with the conventional triaxial loading process, a constant confining pressure is applied on the left and right boundaries of the model, the bottom boundary is fixed. The axial load increment ($\Delta F = 50\text{N}/\text{step}$) is applied on the top boundary to control the loading until the sample completely loses the bearing capacity. The seepage behavior in numerical experiments is simulated by steady state seepage model. The left and right boundary of the sample is impermeable, and the upper and lower boundary is applied constant gas pressure. The lower boundary is atmospheric pressure p_2 and the pressure difference is $\Delta p = p_1 - p_2$. The numerical simulation is consistent with the conventional coal gas seepage test in the laboratory.

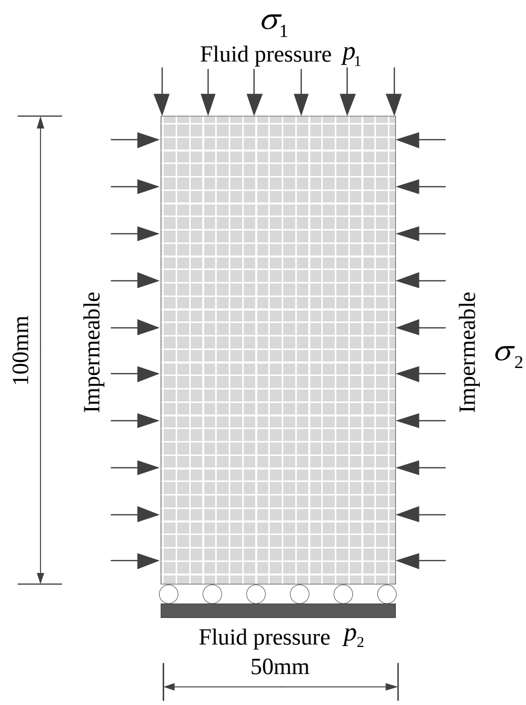


Figure 4: Calculation model of coal specimen under loading

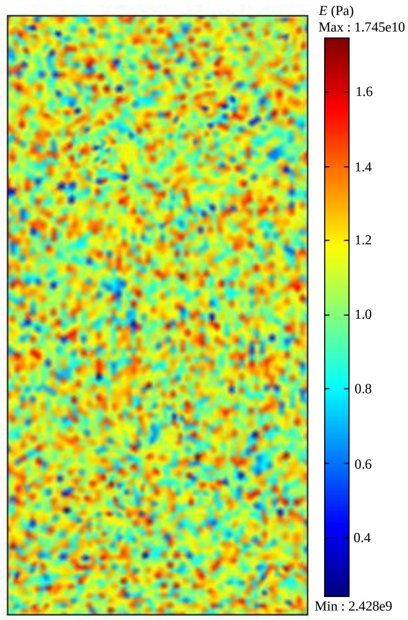


Figure 5: Heterogeneous properties of coal medium

Table 1: Material parameters for numerical tests of coal under loading

Parameter	Value
Uniaxial compressive strength of coal S_c / MPa	60
Uniaxial tensile strength of coal S_t / MPa	6
Homogenization coefficient m	6
Initial permeability of coal k_0 / m^2	1×10^{-18}
Initial porosity of coal ϕ_0	0.08
Gas dynamic viscosity μ_f / Pa·s	1.84×10^{-5}
Young's modulus of coal E / GPa	37.5
Poisson ratio of coal ν	0.33

In order to investigate the damage, fracture and permeability evolution law of coal specimen during axial loading process, the homogeneous degree coefficient of initial elastic modulus distribution of coal specimen is $m=6$. During the loading process, the specimen is subjected to the confining pressure $\sigma_2=2\text{MPa}$ and gas pressure $p_1=2\text{MPa}$. Fig. 6 shows the damage distribution of coal during the loading process. The positive value of the color bar indicates the shear failure and the negative value indicates the tensile failure.

The whole loading process of coal samples can be divided into four stages: linear elastic stage, plastic deformation stage, stress drop stage and residual strength stage. Each stage is related to the deformation of coal and the initiation and development of internal cracks. The crack initiation of coal can be seen from the figures. In the initial loading process, a random distribution of damage points is found inside the specimen. Then, with the loading of stress, the random distribution of the damage zone continues to expand and converge. The failure of coal is mainly shear failure. Finally, a macroscopic fracture zone, which is composed of massive fracture units, is formed. This macroscopic fracture zone is consistent with phenomena observed in a large number of coal mechanics experiments. Therefore, the seepage-stress-damage coupled model can be used to simulate the failure process of coal under compression conditions.

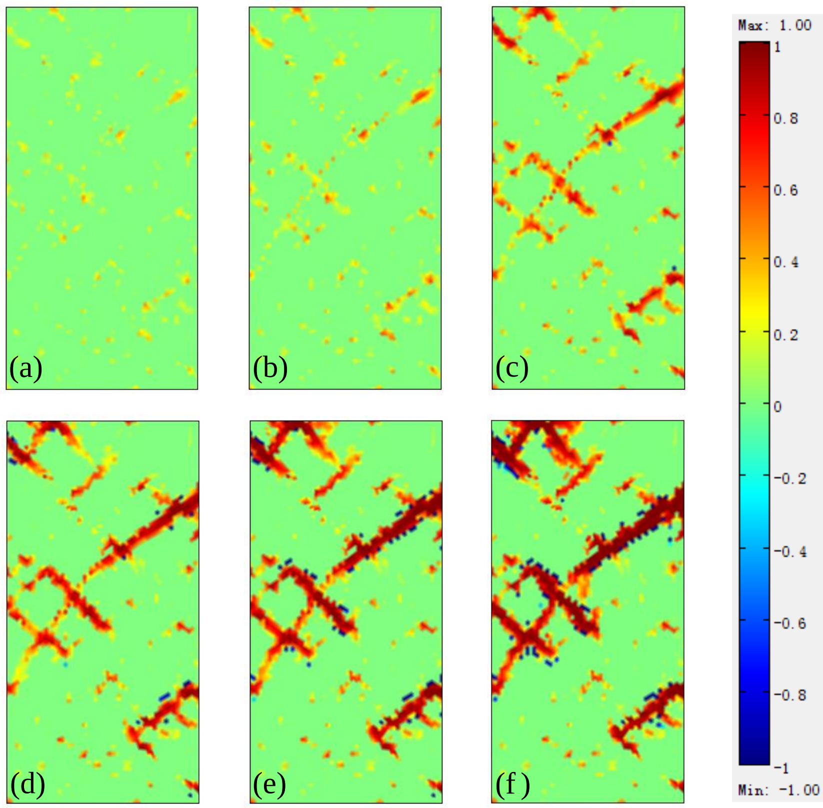


Figure 6: The fracture evolution process of coal specimen during the loading process

Fig. 7 is the permeability distribution during the loading process. It can be seen that the damage and destruction of coal resulted in the increase of permeability. However, because there was no obvious breakthrough in coal in the initial stage, the macroscopic flow behavior of the coal sample was not violent. Gas gas flows rapidly in the macroscopic shear zone, while the area outside the shear zone is comparatively slow due to the smaller permeability coefficient.

Fig. 8 gives a cloud map of the vectorial field distribution after the specimen is destroyed.

The size of the arrow indicates the velocity of the flow field. It can be seen that the gas flow is mainly along the high permeability region, that is, the damaged region, and the flow in the low permeability region is slow. The damage of coal resulted in a large increase in permeability. The numerical simulation simulated the change of coal sample from the random distribution of mesoscopic damage to macroscopic fracture throug self organization evolution process and the local characteristics in the evolution of seepage field. These effectively prove the validity of the simulation model of fracture process and corresponding seepage behavior of coal.

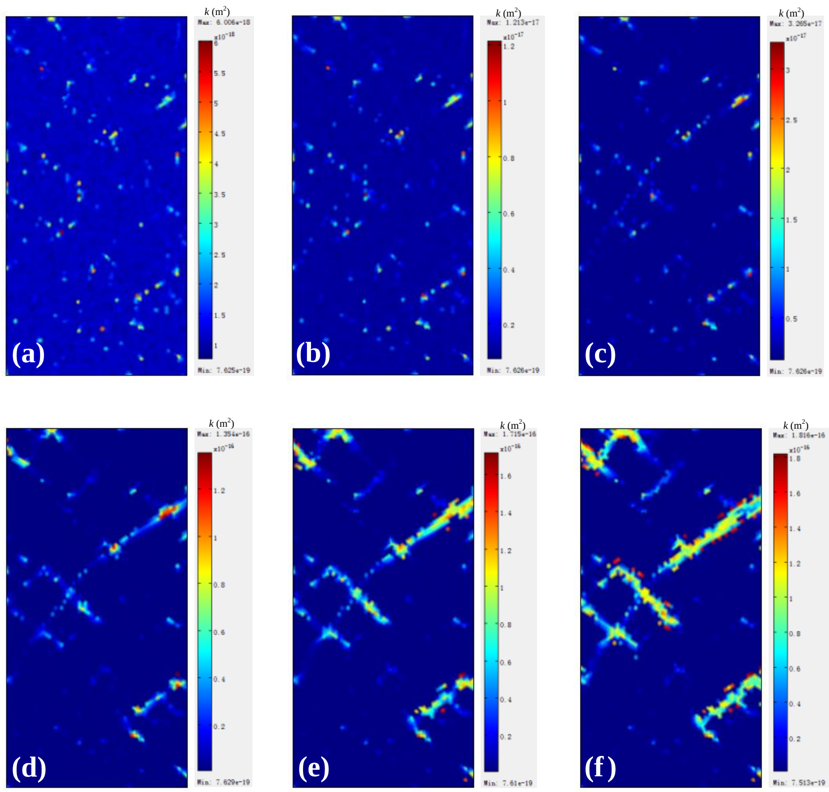


Figure 7: The permeability evolution process of coal specimen during the loading process

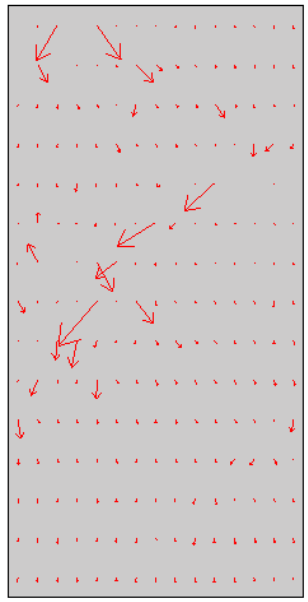
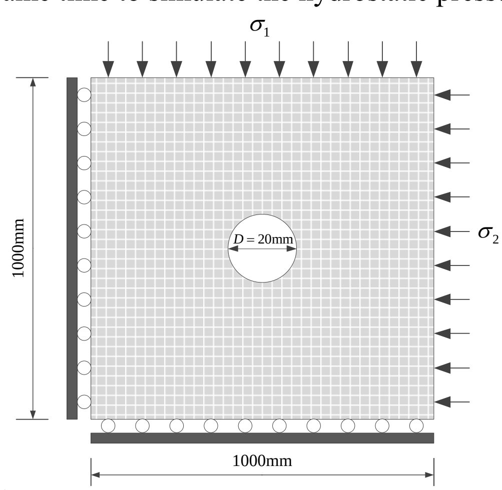


Figure 8: Distribution of flow vector in coal specimen

3.2 Example II: numerical simulation of failure process of coal with hole

The model is used to simulate numerical compression experiment of square coal with circular hole. The parameters in Tab. 1 are still used in this calculation. The size of the coal is 1000 mm×1000 mm, the circular hole is located at the center of the coal and the diameter is 20 mm. The schematic diagram of the model is shown in Fig. 9. The stress loading mode of coal is biaxial compression. The vertical stress and horizontal stress are increased uniformly at the same time to simulate the hydrostatic pressure loading method,



$\sigma_1 = \sigma_2$.

Figure 9: Calculation model of coal specimen with circular hole under loading process

The crack propagation of the coal during the loading process is shown in Fig. 10. It can be seen that under the action of horizontal and vertical stresses, the coal are subjected to the action of hydrostatic pressure. According to the elastic mechanics theory, when the hole size is far smaller than the size of the elastic model and the hole distance is far away from the boundary of model, the stress concentration will appear around the hole under the function of uniform stress. The analytical solution of coal is $\sigma_\rho = q(1-\frac{r^2}{\rho^2})$, $\sigma_\varphi = q(1+\frac{r^2}{\rho^2})$. σ_ρ and σ_φ are the main stresses in two directions.

According to the Mohr-Coulomb criterion, it is known that the coal reached the damage strength firstly at the edge of the hole. In the numerical simulation results, the damage first appears around the circular hole. Due to the heterogeneity of the mechanical parameters of the coal units, some units on the edge of the hole first reach the criterion of failure criterion and destroy.

The random distribution of the material properties of the coal leads to the random occurrence of the damage point in the coal. Subsequently, due to the failure of these units, the bearing capacity was further reduced and the damage was further developed, and obvious crack expansion appeared. It can be seen that under the action of confining pressure, the coal have been subjected to pressure shear failure. Due to the randomness of the mechanical properties distribution of coal, the number and direction of the cracks are also random distribution. This is consistent with the failure characteristics of the coal test in laboratory and it verifies the correctness of the numerical model.

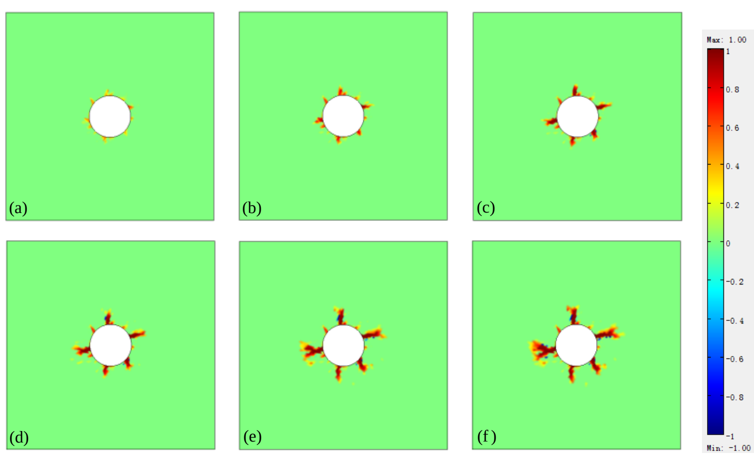


Figure 10: The fracture evolution process of coal specimen during the loading process

4 Conclusions

Based on the damage mechanics, elastic mechanics and seepage mechanics theory, we consider the effect of damage on the mechanical property and seepage characteristic of coal, and establish the seepage-stress-damage coupled model of coal in the representative elementary volume (REV) level. The numerical model is solved through the finite element software COMSOL combined with MATLAB.

The numerical model establishes the relationship between microcosmic damage evolution and macroscopical fracture and simulates the whole process of coal from microcosmic damage to macroscopical fracture, and the dynamic simulation of fluid flow in this process.

The compression seepage coupled numerical experiment is conducted in this paper and the numerical results show that in the initial loading process, a random distribution of damage points is found inside the specimen. Then, with the loading of stress, the random distribution of the damage zone continues to expand and converge, finally forming a macroscopic fracture zone. These effectively prove the validity of the simulation model of fracture process and corresponding seepage behavior of coal.

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