SIMULATION STUDY ON STRESS-SEEPAGE COUPLING OF COAL

by

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Mining significantly affects the mechanical properties and structure of coal seams and increases the risk of disasters such as coal and gas outburst. Gas extraction is the key technology of disaster prevention and resource utilization. In this study, a damage elastoplastic constitutive model was developed, and the stress-strain change of rock was simulated by finite element program. Through the simulation of drilling gas extraction, it is found that the gas pressure increases with the increase of the distance from the center of the borehole, and the pressure drop decreases. These findings have practical significance for the prevention and control of gas disasters.

Key words: *stress-seepage coupling, numerical simulation, gas, coal, pore-fracture model*

Introduction

The coal and gas outbursts caused by the destruction of gas containing coal pose a serious threat to the safety of miners. Therefore, understanding the changes in gas pressure during coalbed methane drainage is crucial for the efficient and safe utilization of energy [1]. Based on experimental research, scholars have established various permeability models to reveal the permeation law of gas in coal seams [2-4]. Although the analysis of stress seepage coupling theory is relatively mature, its application in numerical simulation still needs to be strengthened. On the basis of previous research, this article conducts stress seepage coupling simulation of coal and rock mass, verifies the rationality of the force field, and analyzes the law of gas pressure affected by drilling.

Elastic plastic damage mechanics model

The Drucker Prager yield criterion is widely used to describe the plastic characteristics of rock materials. From the perspectives of elastic-plastic mechanics and damage theory, a plastic yield function based on considering damage effects is established [5]:

$$f^{DP}(\boldsymbol{\sigma},\bar{\varepsilon}^p,D)=\sqrt{J_2(s(\boldsymbol{\sigma}))}+\eta\, p(\boldsymbol{\sigma})-(1-D)\xi c(\bar{\varepsilon}^p) \tag{1}$$

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where $J_2 = 1/2\boldsymbol{s}$ and $\boldsymbol{s}$ is the second invariant of deviatoric stress, $\boldsymbol{s} = \boldsymbol{\sigma} - p(\boldsymbol{\sigma})\boldsymbol{I}$ – the stress partial tensor, $\boldsymbol{I} = \delta_{ij}e_i \otimes e_j$ – the second-order tensor, δ_{ij} – the Kronecker symbol, $p = 1/3tr[\boldsymbol{\sigma}]$ – the hydrostatic pressure, $c(\bar{\varepsilon}^p)$ – the internal cohesion considering damage, and D – the damage variable. Here, η and ξ are material parameters:

$$\eta = \frac{6\sin\theta}{\sqrt{3}(3-\sin\theta)}, \quad \xi = \frac{6\cos\theta}{\sqrt{3}(3-\sin\theta)} \tag{2}$$

where θ is the internal friction angle. Describing the evolution equation of damage variables using Weibull distribution:

$$D = 1 - \exp\left[-\left(\frac{\bar{\varepsilon}^p}{\lambda}\right)^\kappa\right] \tag{3}$$

where κ and λ are the shape damage evolution parameters and scale damage evolution parameters, respectively, and $\bar{\varepsilon}^p$ – the equivalent plastic strain.

Pore-fracture model

The coal structure can be generalized as coal matrix blocks with different sizes and fracture structures with tortuosity. Define ϕ as the absolute porosity of coal, $\phi = \phi_m + \phi_f$, with subscripts m and f representing matrix and fractures, respectively. According to fractal theory [6], the expression for the fracture porosity affected by changes in effective pressure can be derived:

$$\phi_{f0}(P_{\text{effr}}, P_1) = \phi_0 \left\{1 - C_0 \left[\frac{3\pi\left(1-\nu^2\right)P_{\text{effr}}}{4\left(1-D\right)E}\right]^\beta \left(1 - \frac{P_{\text{effr}}}{P_1}\zeta\right)\right\}^3 \tag{4}$$

where $C_0 \geq 4$ and ϕ_0 – the porosity of the coal body, β – the rough element distribution parameter with $\beta \in (0, 1)$, E and ν are the elastic modulus and Poisson's ratio, P_{effr} and P_1 are the radial effective pressure and overlying rock pressure, and ζ – defined as the pressure influencing factor. The porosity of cracks ϕ_f can be determined:

$$\phi_f = \frac{\phi_{f0}(P_{\text{effr}}, P_1) - \varepsilon_s + \varepsilon_v}{1 + \varepsilon_v} \tag{5}$$

where $\varepsilon_s = \varepsilon_L p_0/p_0 + p_L$ is the gas adsorption strain is, ε_L – the Langmuir volume strain, and p_L – Langmuir pressure constant. The matrix porosity [7]:

$$\phi_m = \frac{\phi_{m0} + \alpha(M - M_0)}{1 + M - M_0} \tag{6}$$

where α is the Biot coefficient of coal matrix, $M = \varepsilon_V(D) + P_g/K_s - \varepsilon_s$, $M_0 = \varepsilon_{Vm} + P_{g0}/K_s - \varepsilon_L p_0/p_0 + p_L$, and K_s is the bulk modulus of coal skeleton.

Diffusion-seepage coupling equation

The diffusion seepage coupling module combines Fick's diffusion law, Darcy's seepage law and gas continuity equation. For dual-porosity media, adsorbed gas exists in coal matrix pores and fissures. Taking the total volume of gas-bearing coal as 1, the mass of coal rock skeleton is $\rho_c(1 - \phi_m - \phi_f)$, and the mass of adsorbed gas is given:

$$m_{ad} = \rho_{ga}\rho_c(1 - \phi_m - \phi_f)\frac{V_L b P_g}{1 + bP_g} \tag{7}$$

where ρ_{ga} and ρ_c are the coalbed methane density and coal density, respectively. Assuming that the diffusion process of coalbed methane in the matrix can be described by fick diffusion, the derivation of eq. (7) with respect to time, t, combined with the mass conservation equation is given:

$$\frac{\partial(m_{ad})}{\partial t}=\nabla[D_f\nabla(m_{ad})]-m_g \tag{8}$$

where m_g is the gas-flow density/mass source term for the diffusion process of the dual pore system. The gas phase continuity equation in the seepage system can be expressed:

$$\frac{\partial}{\partial t}\left[\rho_g\left(\phi_m+\phi_f\right)\right]+\nabla\left[\rho_g\left(\phi_m+\phi_f\right)\vec{\boldsymbol{v}}_g\right]=Q_g+m_g \tag{9}$$

$$\left(\phi_m+\phi_f\right)\vec{\boldsymbol{v}}_{rg}=-\frac{k}{\mu_g}(\nabla P_g+\rho_g\mathbf{g}) \tag{10}$$

$$\vec{\boldsymbol{v}}_{rg}=\vec{\boldsymbol{v}}_g-\vec{\boldsymbol{v}}_s \tag{11}$$

where $\vec{\boldsymbol{v}}_g$ is the velocity of rock skeleton movement, ρ_g – the gas density, $\vec{\boldsymbol{v}}_g$ – the real velocity of gas, $\vec{\boldsymbol{v}}_{rg}$ – the relative velocity of gas to the coal skeleton, Q_g – the source/sink of gas, and k is coal seam permeability. With help of eqs. (8) and (9) and , the gas phase continuity equation is obtained:

$$\frac{\partial}{\partial t}\left[\rho_g\left(\phi_m+\phi_f\right)+m_{ad}\right]+\nabla\left[\rho_g\left(\phi_m+\phi_f\right)\vec{\boldsymbol{v}}_g\right]-\nabla[D_f\nabla(m_{ad})]=Q_g \tag{12}$$

According to the Galerkin method, an equivalent integral weak form is established, and the weight function is taken as the element shape function $w^{\mathrm{T}}=\mathbf{H}^{(\mathrm{m})\mathrm{T}}$, $\overline{w}^{\mathrm{T}}=\mathbf{H}^{\mathrm{s(m)T}}=\mathbf{H}^{(\mathrm{m})\mathrm{T}}$. The finite element format of the diffusion seepage coupling equation:

$$\begin{aligned}&\int_{\Omega}\mathbf{H}^{(\mathrm{m})\mathrm{T}}\left[\left(\phi_m+\phi_f\right)\frac{M_g}{ZRT}+\frac{\left(1-\phi_m-\phi_f\right)\rho_{ga}\rho_c V_L b}{(1+bP_g)^2}\right]\frac{\partial P_g}{\partial t}\mathrm{d}V+\int_{\Omega}\mathbf{B}^{(\mathrm{m})\mathrm{T}}\left[\frac{\rho_g}{\mu_g}\left(k\nabla P_g\right)\right]\mathrm{d}V=\\&=\int_{\Omega}\mathbf{H}^{(\mathrm{m})\mathrm{T}}Q_g\,\mathrm{d}V+\int_{S_q}\mathbf{H}^{\mathrm{S(m)T}}\overline{q}_g\mathrm{d}s+\int_{\Omega}\mathbf{H}^{(\mathrm{m})\mathrm{T}}\left\{\nabla\left[D_f\frac{\left(1-\phi_m-\phi_f\right)\rho_{ga}\rho_c V_L b}{(1+bP_g)^2}\left(\nabla P_g\right)\right]\right\}\mathrm{d}V-\\&-\int_{\Omega}\mathbf{H}^{(\mathrm{m})\mathrm{T}}\rho_g\left(\phi_m+\phi_f\right)\frac{\partial\varepsilon_v}{\partial t}\mathrm{d}V-\int_{\Omega}\mathbf{B}^{(\mathrm{m})\mathrm{T}}\left[\frac{\rho_g^2}{\mu_g}\nabla\left(k\mathbf{g}\right)\right]\mathrm{d}V\end{aligned} \tag{13}$$

In eq. (13), the first item on the left is the storage coefficient of gas pressure (including adsorption term and seepage term). The second item is the gas pressure conduction coefficient. The first and second items on the right are the gas mass sources/sinks in the system and on the surface, respectively. The third item on the right is the change of adsorbed gas mass flux caused by pressure gradient. The fourth item is the change of mass flux caused by solid deformation. The fifth term is the correction term of gravity effect on seepage effect.

Validation of elastoplastic damage model

According to the uniaxial- and triaxial-compression tests of rock [5], combined with the damage elastoplastic constitutive model established in this paper, the ADINA program is redeveloped and simulated. The test data of rock samples are shown in tab. 1.

Table 1. Basic parameters of rock samples

Simulation parameters	Values	Simulation parameters	Values
Young's modulus, E [GPa]	24.54	Density, ρ_c [kgm^{-3}]	2.932
Poisson ratio, v	0.24	Internal cohesion, c [MPa]	24.12
Angle of internal friction, ϕ [°]	32.57	Internal cohesion at obvious damage, c_r [kPa]	95.75

As shown in fig. 1, there is a positive correlation between the axial pressure and confining pressure that rocks experience during failure. With the application of confining pressure, the stress-strain curve calculated by the damage model is more in line with the experimental curve. Therefore, it can be considered that the elastoplastic damage constitutive model developed in this article can to some extent reflect the mechanical and deformation characteristics of rocks.

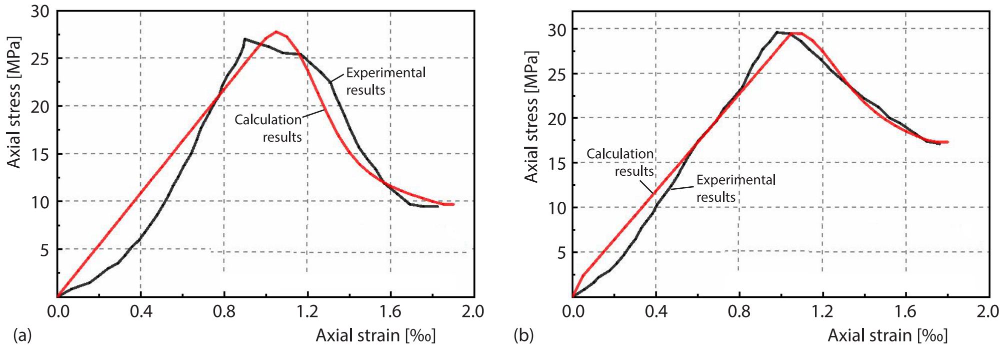

Figure 1. Comparison of the experimental data and the calculation results of the elastoplastic damage constitutive model under various confining pressures; (a) P_c = 0 MPa and (b) P_c = 2 Mpa

Simulation of drilling gas extraction conditions

The 3-D numerical simulation is used to verify the correctness of the established coupled diffusion-seepage model for gas-containing coal. Taking the actual situation of Xinzhuangzi Coal Mine [8, 9] as an example, the influence of drilling on gas pressure in coal seam is studied. The numerical simulation parameters are shown in tab. 2.

Table 2. Property parameters of simulation model

Simulation parameters	Values	Simulation parameters	Values
Young 's modulus of coal, E [GPa]	2.4	Gas pressure, P_g [MPa]	1.8
Poisson ratio of coal, v	0.29	Coal 's density, ρ_c [kgm^{-3}]	1450
Internal cohesion, ϕ [°]	20	Standard atmospheric pressure, P_0 [MPa]	0.1

As shown in fig. 2(a), based on the symmetry of the model, take a 1/4 model with dimensions of 5 m × 5 m × 1.8 m and a drilling radius of 0.037 m. The overlying rock pressure is P_z = –12.8 MPa, and the geostress is σ_x = –5.23 MPa, and σ_y = –5.23 MPa (negative sign indicates that the coal seam is under pressure). The boundary conditions of the seepage field: BC and CD are given gas pressure boundary conditions, AB and DE are free air pressure boundary conditions, and the AE edge of the wellbore is subjected to standard atmospheric pressure. The boundary conditions of the solid deformation field are the BC and CD edges are subjected to horizontal geostress, the AE edge is a free boundary, the AB edge has fixed displacement in the

Y-direction and free displacement in the *X*-direction, and the DE edge has fixed displacement in the *X*-direction and free displacement in the *Y*-direction.

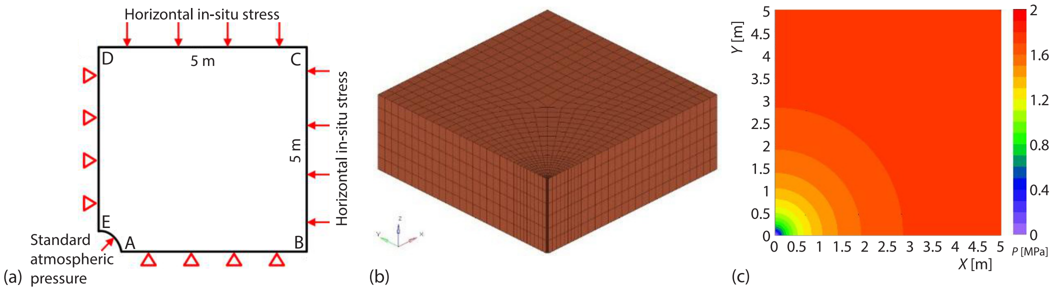

Figure 2. Schematic diagram of 1/4 model of Xinzhuangzi coal mine; (a) schematic diagram of mechanical model, (b) grid division diagram, (c) pressure distribution in coal seam

Figure 2(c) shows the distribution pattern of coal seam gas pressure after the formation of boreholes in gas bearing coal seams. As shown in the figure, after the formation of the wellbore, there is a significant change in the gas pressure of the reservoir around the wellbore. According to fig. 3(a), it can be seen that after drilling holes in gas bearing coal seams, the gas pressure around the holes immediately decreases. As the distance from the gas center increases, the gas pressure also increases. Closer is the center of the borehole, lower the gas pressure. From fig. 3(b) shows that as the distance from the center of the borehole increases, the pressure drop decreases and the magnitude of the decrease also decreases until it reaches 0.

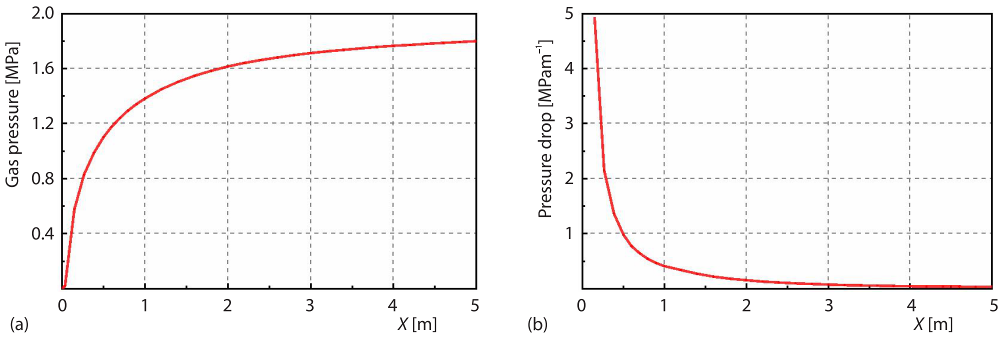

Figure 3. The influence of drilling center distance on gas pressure (a) and gas pressure drop (b)

Conclusion

We have established an elastoplastic damage constitutive model based on the Drucker-Prager yield criterion. Introduce the pore fracture model into the diffusion seepage coupling equation. A model for simulating gas extraction through drilling was independently developed based on the established equation, and it was found that the gas pressure around the borehole immediately decreased after the formation of the borehole. The closer to the center of the borehole, the closer the gas pressure is to 0, and the greater the gas pressure drop. As the distance from the center of the borehole increases, the gas pressure increases and the gas pressure drop approaches zero. The rate of decrease in gas pressure drop decreases as the distance from the center of the borehole increases.

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Nomenclature

D – damage variable, [–]
E – elastic modulus, [GPa]
K_s – bulk modulus of coal skeleton [GPa]
k – coal seam permeability, [mD]
m_{ad} – mass of adsorbed gas, [kgm^{-3}]
P_g – gas pressure, [MPa]
p_L – Langmuir pressure constant, [MPa^{-1}]
Q_g – source/sink of gas, [kgm^{-3}s^{-1}]
$\vec{v}_s$ – velocity of rock skeleton movement, [ms^{-1}]
$\vec{v}_{rg}$ – gas relative velocity, [ms^{-1}]
$\vec{v}_g$ – real velocity of gas, [ms^{-1}]

Greek letters

α – Biot coefficient of coal matrix, [–]
δ_{ij} – Kronecker symbol, [–]
ε_L – Langmuir volume strain, [–]
$\bar{\varepsilon}^p$ – equivalent plastic strain, [–]
η – material parameters of D-P criterion, [–]
θ – internal friction angle, [°]
κ – shape damage evolution parameters, [–]
λ – scale damage evolution parameters, [–]
ν – Poisson 's ratio, [–]
ξ – material parameters of D-P criterion, [–]
ρ_c – coal density, [kgm^{-3}]
ρ_g – density of free gas, [kgm^{-3}]
ρ_{ga} – density of coalbed methane, [kgm^{-3}]
ϕ – absolute porosity, [–]
ϕ_f – fracture porosity, [–]
ϕ_m – matrix porosity, [–]

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