STUDY ON THE DAMAGE EVOLUTION AND WATER LOSS OF AQUIFER UNDER COAL MINING

by

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In this study, a stress-damage-seepage coupling model is established to explore the water inrush mechanism of mining workface. The laws of water loss in aquifers, damage evolution and seepage distributions of overlying strata are analyzed in the process of mining. The stress concentration phenomenon is obvious at both ends of goaf. The damage zone presents the characteristics of 'saddle shape' with higher at two ends and lower at the middle of goaf. The permeability decreases in the compressive stress zone around the goaf, and increases in the tensile stress zone. The increase of leakage affects the water resource conservation and mining safety.

Key words: *water inrush, damage evolution, overlying strata, seepage law*

Introduction

The coal resources are abundant in the Ordos Basin of Inner Mongolia and Tarim Basin of Xinjiang. The water-conducting fracture zone of the coal seam in the Jurassic coalfield is highly developed, which makes the overlying Cretaceous sandstone aquifer easy to conduct. Mine water inrush not only causes production safety problems, but also the shortage of water resources. The contradiction between the large amount of water inrush caused by mining and the safe exploitation of coal resources also needs to be solved urgently. It is of great significance to study the law of water loss under mining for groundwater resources protection and safe mining.

Scientific prediction on the amount of water inflow of mining goaf is important for improving the control technology and ensuring the mining safety [1]. Wang *et al.* [2] and Cui *et al.* [3] believe that mine water inrush is mainly caused by the interaction between the fissure extension, seepage state and stress evolution, which leads to the rock damage and rupture to form a penetrating water-conducting channel. Guo *et al.* [4] and Yang *et al.* [5] investigated the parameter changes of stress and seepage during the mining, respectively. Zhao *et al.* [6, 7] established the aquifer groundwater loss analysis model and summarized the aquifer *lateral* direct *and vertical leakage* composite water loss model. Although many researches on water inrush problem have been conducted, but the issues on the theory of stress-seepage-damage coupling in rock strata and the law of damage evolution during mining are still not clear yet.

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Governing equations

According to the theory of elastic mechanics and porous media, the displacement field equation in the elastic zone of rock mass is given [7]:

$$Gu_{i,kk} + \frac{G}{1-2\nu}u_{k,ki} - \alpha p_{,i} + f_i = 0 \tag{1}$$

where G is the shear modulus of rock mass, $G = 2E(1 + \nu)$, ν – the Poisson ratio of rock mass, E – the elastic modulus of rock mass, u_i – the displacement component in the i direction, α – the Biot's coefficient, $0 < \alpha \leq 1$, and p – the pore pressure of rock mass.

Darcy's law is mainly used to describe the fluid-flow in rock mass. It takes the effect of gradient pressure and permeability into account for describing the fluid-flow. According to the porous media theory, the flow governing equation which is based on the mass conservation equation of fluid and Darcy's law can be given [8]:

$$-\nabla\left[\rho\frac{k_{dc}}{\mu}\left(\nabla p_{dc} + \rho g\right)\right] = Q_m \tag{2}$$

where k_{dc} is the permeability of rock mass, ρ – the fluid density, μ – the hydrodynamic viscosity coefficient, p_{dc} – the pore pressure of porous rock mass, and Q_m – the source-sink term.

For the dynamic evolution distribution of damage in the rock mass, the damage equation under the uniaxial stress state is expressed [9]:

$$D = \begin{cases} 0 & (0 < \varepsilon \leq \varepsilon_f) \\ \dfrac{\varepsilon_u(\varepsilon - \varepsilon_f)}{\varepsilon(\varepsilon_u - \varepsilon_f)} & (\varepsilon_f < \varepsilon \leq \varepsilon_u) \end{cases} \tag{3}$$

where D is the damage variable, ε_f – the limiting strain of damage evolution threshold under the uniaxial stress state, and ε_u – the ultimate strain.

For 3-D stress state, the equivalent total strain can be expressed:

$$\varepsilon = \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2}$$

The equivalent tensile strain:

$$\varepsilon_t = \sqrt{\sum_i \varepsilon_i^2}\,(\varepsilon_i > 0)$$

and the equivalent compressive strain

$$\varepsilon_e = \sqrt{\sum_j \varepsilon_j^2}\,(\varepsilon_j < 0)$$

The damage variable can be expressed:

$$D = \alpha_t D_t + \alpha_e D_e \tag{4}$$

where $\alpha_t = (\varepsilon_t/\varepsilon)^2$ and $\alpha_e = (\varepsilon_e/\varepsilon)^2$.

According to the relationship between the porosity of rock and stress state [10]:

$$\varphi = (\varphi_0 - \varphi_r)\exp(-\alpha_\varphi \sigma_v) + \varphi_r \tag{5}$$

where φ_0 is the original porosity, φ_r – the limit value of porosity under high pressure, α_φ – the porosity stress sensitivity coefficient, and σ_v – the effective average stress, expressed:

$$\sigma_v = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} - \alpha p \tag{6}$$

where σ_1, σ_2, and σ_3 are the three principal stresses, respectively, α – the Biot coefficient, and p – the pore pressure of rock mass.

The permeability of rock mass will change with the damage evolution, expressed [11]:

$$k = k_0 \left(\frac{\varphi}{\varphi_0}\right)^3 \exp(\alpha_k D) \tag{7}$$

where k is the permeability after damage, k_0 – the initial permeability, and α_k – the sensitivity coefficient of permeability to damage.

Project background and numerical model

The rock strata conditions of coalmining in a basin are shown in fig.1. Considering the effect of the stratum self-weight and the boundary conditions, a 3-D numerical calculation model is established. The dimensions are 5000 m × 50 m × 350 m in length, width and height, respectively.

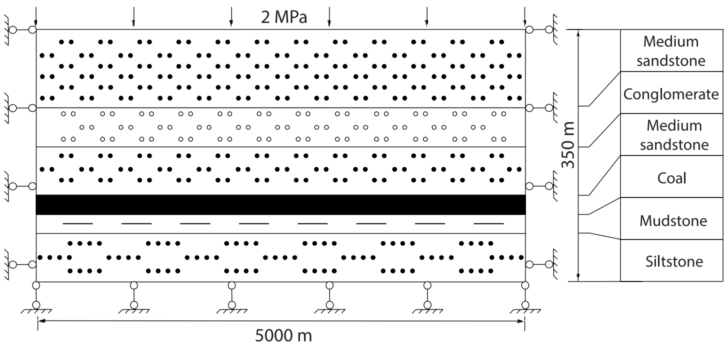

Figure 1. Calculation model of coal mining

The physical and mechanical parameters of rock strata used in the calculation model are given in tab. 1. The lateral and bottom boundaries of the calculation model are the roller support, and the vertical distribution load of the equivalent overburden weight is applied to the top boundary of the model. The length of working face is 210 m. The goaf is connected with the atmosphere, and the boundary pore pressure value is approximately atmospheric pressure.

Table 1. Physical and mechanical parameters of rock

Stratum	Density [kgm^{-3}]	Elastic modules [GPa]	Cohesion [MPa]	Friction angle [°]	Poisson ratio	Porosity	Permeability coefficient [m per day]
Medium sandstone	2500	1.3	3.25	32	0.29	0.22	0.050
Conglomerate	2790	2.2	5.57	37	0.24	0.35	0.008
Medium sandstone	2500	1.3	3.25	32	0.29	0.22	0.050
Coal	2110	1.7	3.02	31	0.28	0.15	0.030
Mudstone	2500	2.5	3.10	39	0.29	0.17	0.010
Siltstone	2600	1.9	3.75	35	0.26	0.30	0.017

Results and analyses

The stress in the *surrounding rock* of goaf will be redistributed during mining, then the *abutment pressure* generated in the lateral side of coal roadway. The distribution of abutment pressure can be divided into four zones roughly, as shown in fig. 2 and fig. 3. *Abutment pressure* of *surrounding rock* 200 m in front of working face is at the level of the original rock stress state, and has been affected a little by mining. Within 100-200 m in front of working face, the stress concentration degree is relatively small. The significant influence zone of rock stress is within the range of 0-100 m from the edge of goaf, and the abutment pressure reaches the peak value of 27.5 MPa at about 20 m in front of working face. The largest stress concentration coefficient is about 2.9. The abutment pressure of overburden rock reduces within the mining goaf due to stress-relaxation of mining excavation.

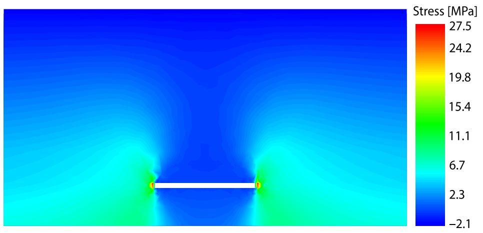

Figure 2. Abutment pressure distribution

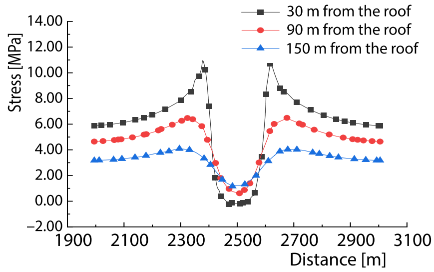

Figure 3. Abutment pressure curve

After mining, the large-scale suspension of roof appears, the overlying strata comes about bending settlement, and the floor rock strata expands toward the goaf. Local tensile failure of rock strata appears on the edges of the roof and floor. The damage distribution of overlying strata presents a *saddle-shaped* feature, as shown in fig. 4. The damage evolution height of roof is larger at two ends and lower at the middle of the goaf. The damage degree of the roof reaches 0.6, and the height of damage evolution is about 120 m under the condition of full mining. The damage degree of the floor strata reaches 0.75, and the depth of damage evolution is about 40 m.

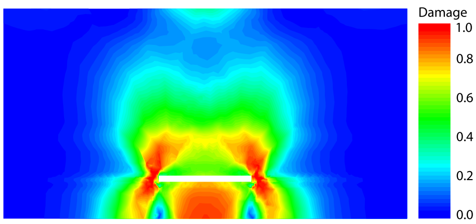

Figure 4. Mining damage cloud chart

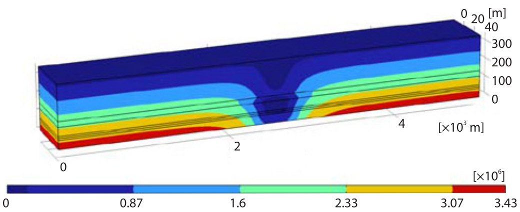

Figure 5. Pore water pressure distribution

As the edge of goaf is open to the atmosphere, the pore water pressure drops to atmosphere level along the edge of the goaf. The distribution of pore water pressure in aquifer is shown in figs. 5 and 6. It can be seen that the cone of pore pressure relief is formed in the overlying stratum.

The porosity and permeability will change with the evolution of damage, which causes the increase of the water flow velocity in strata. The distribution of the porosity after mining is shown in fig. 7. The porosities of rock stratum on the both sides of the goaf reduce about 50% due to the compression of *abutment pressure*, and the porosity of rock stratum within the goaf range, which is subjected to tensile stress, increases about 1.5 times.

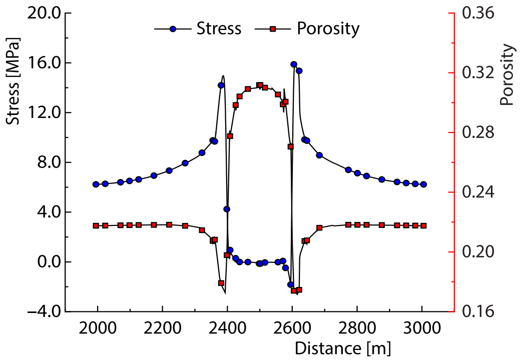

Figure 6. Pore water pressure curve

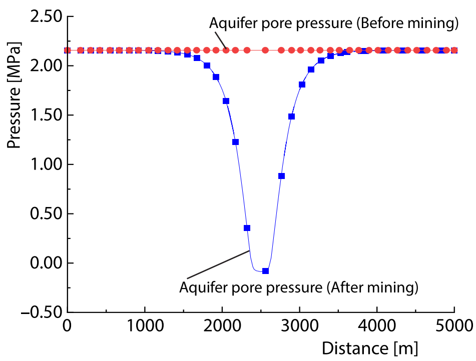

Figure 7. Porosity distribution of overburden rock

Because of the damage expansion of rock mass, pore water in rock strata migrates along the damage zone to the goaf. The seepage velocity is obviously increase around the goaf, and seepage vectors after mining is shown in fig. 8. Based on the results of the simulation, the water loss in the rock strata can be obtained by integrating the seepage velocity along the edge of the mining goaf. It can be seen that the total water inflow of the mining goaf of 210 m working face is 0.051 m^3/s, of which 0.031 m^3/s comes from the roof water inflow, accounting for 60%. The lateral side water inflow is 0.004 m^3/s, which is smaller than the floor water inflow of 0.015 m^3/s. The water inflow of each edge of the goaf for different working face lengths are shown in fig. 9.

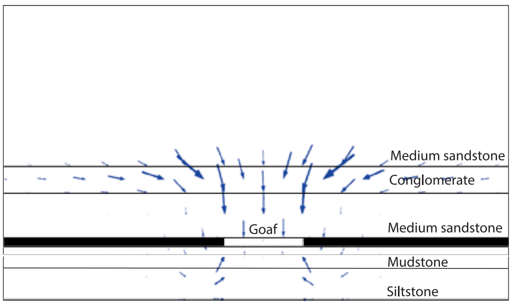

Figure 8. Seepage vector diagram

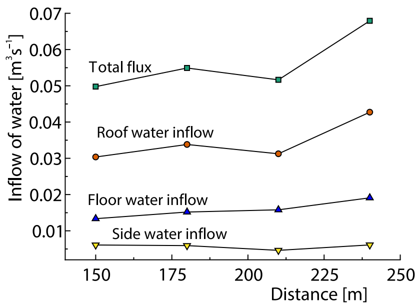

Figure 9. Inflow of water

Conclusion

The stress-seepage-damage coupling model is established, and the damage and seepage laws under the influence of mining are calculated. The stress concentration phenomenon is obvious at both ends of goaf. The damage zone presents the characteristics of *saddle shape* with higher at two ends and lower at the middle of the goaf.

Acknowledgment

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Nomenclature

f – body force,[Nm^{-3}]
g – acceleration of gravity, [ms^{-2}]
k – permeability of rock, [m^2]
p – pore pressure, [Pa]

Greek symbols

ε – strain value, [–]
ρ – the fluid density, [kgm^{-3}]
σ – stress value, [Pa]

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