Evolution law of stress-deformation-permeability of coal pillar along gob and its effect on stability of coal pillar

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Abstract. The interaction between stress field and seepage field is mainly manifested in two aspects: on the one hand, the change of stress field causes the change of structural plane such as joints and fractures in rock mass, and then changes the permeability of rock mass; On the other hand, the seepage force of seepage field will change the original stress state in rock mass. The two aspects of stress field and permeation field influence and interact with each other all the time, reaching a dynamic stable state, and this dynamic relationship forms the fluid-solid coupling mathematical model. Permeability coefficient is a bridge of interaction and coupling between stress field and seepage field. Only by establishing the relationship between permeability coefficient and stress field or strain field, can the influence of stress field on seepage field be reflected and the real fluid-solid coupling analysis be realized. As a governing equation as important as the constitutive equation in the coupled numerical analysis of stress field and seepage field, permeability coefficient-volumetric strain can be used in numerical analysis to make the calculated results more consistent with engineering practice.

1. Introduction
As is known to all, weak rock mass is a porous material composed of mineral particles of different scales and shapes. Due to various internal forces and long diagenesis and transformation in a certain stress environment, there are a lot of voids and cracks in its interior. Different types of loads continuously affect the seepage field at the same time. The constant change of stress field caused by the external environment will also lead to the change of the internal pores, cracks and crack surfaces of the weak rock mass, thus changing the permeability of the rock mass in a variety of complex environments.

Coal’s mechanical properties have the characteristics of low strength, low elastic modulus and high Poisson's ratio. The deformation and failure process of coal and rock controls the change of its permeability. The permeability of coal and rock decreases slightly with the increase of strain at the stage of microcrack closure and elastic deformation. After the elastic limit, with the increase of strain, the coal enters the stage of crack propagation. The permeability of the coal enters the stage of crack
propagation, and the permeability increases slowly at first, and then increases sharply with the crack expansion. The permeability reaches the maximum in the strain softening stage after the peak strength, and then decreases sharply. In the residual strength stage, the permeability of coal rock decreases gently.

In many projects, the effect of stress field generated by different loads also constantly affects the seepage field, which changes the permeability of rock mass in a variety of complex environments. The change of the stress field inside the soft rock mass is closely related to the change of the seepage field. The stress field leads to the change of the permeability of the rock mass, so the seepage field also changes accordingly. The constant change of the seepage field will also change the stress condition of the soft rock [1-3]. Therefore, it is of great practical significance for the safety of coal and basic engineering to strengthen the study of strain and permeability under the action of convection-solid coupling.

2. Calculation models

2.1. Permeability calculation model

Previous studies have shown that the traditional classical seepage does not consider the dynamic change of porosity and permeability, but for the actual engineering rock mass, porosity and permeability coefficient are dynamic and change with the different stress and strain states of the rock mass [4]. Literature [5] obtained the relationship curve between coal permeability coefficient and volumetric strain in the process of total stress and strain through experiments, and fitted the corresponding equations. The test results show that the permeability coefficient is a double-value function of the volume strain during the volume shrinkage and expansion of the coal sample:

Reduction in volume:

\[ K_1 = 1.3356 \times 10^{-2} - 4.2334 \times 10^{4} \varepsilon_v - 4.9957 \varepsilon_v^2 \]  

Expansion in volume:

\[ K_2 = 1.4292 \times 10^{-4} - 1.0007 \varepsilon_v - 4.3923 \varepsilon_v^2 + 1.4318 \times 10^3 \varepsilon_v^3 - 4.4124 \times 10^4 \varepsilon_v^4 + 3.7185 \times 10^5 \varepsilon_v^5 \]  

2.2. Weakening criterion of coal pillar by water immersion

Previous studies have shown that the strength of coal decreases obviously under long-term water immersion [6]. In the numerical analysis process, the calculation process of residual coal pillar weakening is as follows.

When the coal pillar infiltrates into the pore water pressure (the pore water pressure of the coal pillar is greater than 0), the coal body reaches the state of saturated water, and the saturated water content of the coal body \( \eta \) is

\[ \eta = \frac{\rho_w \phi}{\rho_w \phi + \rho_m} \]  

Where, \( \phi \) is the porosity of coal sample, \( \rho_w \) and \( \rho_m \) are densities of water-containing and dry coal samples (kg/m³), respectively.

The relationship between porosity and permeability of coal sample is as follows

\[ \frac{k}{k_0} = \left( \frac{\phi}{\phi_0} \right)^3 \]
Where, $\phi_0$ is the porosity of the block before deformation, $k_0$ and $k$ is the permeability of the block before and after deformation (mD).

3. Numerical model
Taking the roadway facing narrow coal pillar in working face as the research object, a numerical calculation model was established by using FLAC3D software. The size (length and height) of the model was 100 m and 34 m, and the thickness of overburden from the upper part of the model to the ground was 300 m. The additional load (7.5 MPa) was simulated, while the boundary conditions were restricted.

Table 1. Model composition and corresponding parameters.

| Rock layer          | Thickness /m | Bulk modulus /GPa | Shear modulus /GPa | Cohesion /MPa | Tensile strength /MPa | Friction angle /° | Density /kgꞏm$^{-3}$ |
|---------------------|--------------|-------------------|--------------------|---------------|-----------------------|-------------------|-----------------------|
| Fine sandstone      | 8            | 6                 | 3.5                | 8             | 3.6                   | 48                | 2600                  |
| Coal                | 3            | 4                 | 2.2                | 4.5           | 1.8                   | 38                | 1790                  |
| Sandy mudstone      | 3            | 4.9               | 2.8                | 5.1           | 1.9                   | 45                | 2200                  |
| Grit                | 5            | 3                 | 1.5                | 3.8           | 1.2                   | 43                | 1900                  |
| Siltstone           | 2            | 3.6               | 2.5                | 4             | 0.9                   | 35                | 1800                  |
| Grit                | 13           | 3                 | 1.9                | 3.8           | 1.2                   | 36                | 2000                  |
| Coal gangue         | 6            | 1.4               | 0.2                | 1.3           | 0.7                   | 23                | 1500                  |

Table 2. Parameters of coal.

| Bulk modulus /GPa | Shear modulus /GPa | Cohesion /MPa | Tensile strength /MPa | Friction angle /° | Density /kgꞏm$^{-3}$ | Permeability coefficient /cmꞏs$^{-1}$ | Water pressure /MPa |
|-------------------|--------------------|---------------|------------------------|-------------------|-----------------------|---------------------------------------|--------------------|
| 4                 | 2.2                | 4.5           | 1.8                    | 38                | 1790                  | 1e-9                                  | 0.03               |

4. Stability analysis of coal pillar

4.1. Permeability evolution model based on volume strain
The traditional classical seepage mechanics does not consider the dynamic changes of porosity and permeability. For the actual engineering rock mass, porosity $\phi$ and permeability coefficient $k$ are dynamic changes, which change with the different stress and strain states of the rock mass. Therefore, a mathematical model considering the dynamic changes of permeability coefficient must be adopted or established.

Considering the influence of the evolution of coal pillar permeability coefficient on coal pillar deformation, and comparing with the traditional results that do not consider the change of coal permeability coefficient and do not consider the influence of water on coal pillar, the following three calculation conditions are set in this paper:

Working condition 1: The influence of water is not considered;
Working condition 2: The calculation model takes the permeability coefficient as a constant value and carries out calculation and analysis;
Working condition 3: The seepage dynamic evolution model based on volumetric strain is adopted for calculation and analysis.
(1) The evolution law of coal pillar permeability coefficient and the relationship between volumetric strain and time are shown in Fig. 2. It can be seen from the figure that the closer the coal pillar is to the goaf, the greater the variation of the permeability coefficient is. Finally, the permeability coefficient reaches a stable value of $1.31 \times 10^{-8}$ at the boundary between the coal pillar and the goaf and remains unchanged thereafter. Compared with the initial given permeability coefficient increased by 1 order of magnitude. The change of volumetric strain is consistent with the change of permeability coefficient, which is consistent with the increase of permeability after a large number of derived cracks are caused by the emergence of water in the goaf at the side of coal pillar in practical engineering.

4.2. Stability analysis of coal pillar

Fig. 1. Pore water pressure distribution

Fig. 2. Distribution of permeability coefficient

Fig. 3. Porosity distribution
The reduction in coal strength due to water flooding is known as coal weakening. Weakening coefficient indicates the influence degree of water on coal strength weakening. With the increase of coal water content, the elastic modulus, compressive strength, cohesion and internal friction angle of coal are weakened to varying degrees. As shown in Fig. 3 and 4, the distribution law of porosity is basically consistent with that of permeability coefficient. As water content weakens the coal pillar, the pore water pressure of the coal pillar increases, the wetting range increases, the plastic zone extends deeper into the coal pillar, and the plastic zone range increases.

5. Conclusion
1) User subroutines were embedded into the finite element software FLAC3D, the calculation of unilateral goaf water pressure influence on the stability of coal pillar, the results show that the coal and rock dynamic evolution of permeability coefficient is, the more near the water permeability coefficient change, the greater the contrast according to the results of the permeability coefficient of different coal pillar position, show that the dynamic evolution model and numerical program is accurate and reasonable.

2) The comparison and analysis between the traditional fixed permeability coefficient and the dynamic evolution model of permeability in this paper is made. The calculation results show that the change of pore water pressure in coal rock is smaller under the fixed permeability coefficient condition, while the change of pore water pressure is larger under the dynamic evolution model. The permeability coefficient obtained by the evolution model is one order of magnitude larger than the constant value of the permeability coefficient.

3) According to the characteristics of water softening of coal body, the fluid-solid coupling calculation related to water content is further carried out. The calculation results show that, due to the weakening of water content, the pore water pressure of coal pillar increases, the wetting range increases, the plastic zone extends deeper to the coal pillar, and the plastic zone range increases.

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