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A coupled damage-hydro-mechanical model for gas drainage in low-permeability coalbeds

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ABSTRACT

In the process of coal and gas mining, the excavation and drainage drilling will induce the redistribution of stress around the working face, thus damage coalbeds. In this paper, a coupled damage-hydro-mechanical model is proposed based on the elastic damage at the unloading failure stage of coalbeds. Firstly, a constitutive model for dual-porosity coal with isotropic damage is established within the framework of strain equivalence. Its damage variable is directly related to the effective strain which depends on the initial in-situ stress, pore pressure, and gas sorption induced deformation. Secondly, a dynamic model for the permeability evolution is developed with the concept of scalar damage variable. The permeability model is applied to a three dimensional elastic damage finite element program. Finally, the excavation process and gas drainage are numerically simulated. The evolutions of gas pressure, coal permeability, and gas transport for single borehole are investigated. The numerical results show that the coupled damage-hydro-mechanical model can well match and predict the field test data and the empirical data. It is useful to evaluate the drilling and gas drainage application. Drilling can remarkably relieve the stress around the borehole, induce great damage to coalbeds and thus promotes coal permeability. The numerical simulation is helpful to evaluating gas drainage and taking effective measures to prevent the occurrences of gas outbursts in coalbeds.

1. Introduction

Many coalbeds in China have difficulties in direct gas drainage due to the high adsorption of methane, high plasticity and low permeability thus result in inefficient gas production and the risks of engineering disasters, especially the outburst of gas. However, borehole gas drainage can effectively promote gas recovery and prevent disasters as it damages the in-situ structure of coalbed in the preliminary drilling work of the borehole, and the induced damage causes gas relief, stimulates the channels for gas transport, and finally promotes gas drainage.

Borehole gas drainage is a fully coupled damage-hydro-mechanical process. The cognition of this coupling concept comes from a series of interactions of coal and gas. First of all, the inherent properties of the original coalbeds are changed by the damage during borehole drilling, such as the elastic modulus, poisson ratio and permeability of coalbeds (Cai and Kaiser, 2005; Wang et al., 2013). The permeability of coalbeds is sensitive to the change of geo-stress and pore pressure (Ostensen, 1986; McKee et al., 1988; George and Barakat, 2001). Gas transport is coupled with coal deformation. On the one hand, the compaction of coal block reduces coal permeability; On the other hand, the relief of gas pressure induces coal deformation (Connell, 2009). Moreover, the shrinkage of coalbeds induced by gas desorption leads to the changes of coal porosity and permeability (Mazumder et al., 2012; Chareonsuppanimit et al., 2014). The adsorption capacity of coal is another important factor that affecting the gas drainage. Effective gas desorption provides preconditions to gas production as the adsorbed gas represents about 90% of the total content of methane in coal (Gu and Chalaturnyk, 2005). Valliappan and Wohua (1996) proposed a fully coupled mathematical model for the migration of methane in the coalbeds and introduced the model to the simulation of gas transport. Wu and Guo (2001) proposed the theory for the movement of the methane and coalbeds to study the coupled interactions among the framework deformation of porous media, the adsorptive deformation of grain, the diffusion-

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desorption of adsorbed fluid, and free fluid flow.

The damage induced by the growth of micro cracks during borehole drilling is an essential mechanism for the failure of most brittle coals. Boreholes cause the concentration and redistribution of geo-stress as well as inducing large numbers of cracks, which leads to a series of consequences on macroscopic properties of coal (Costin, 1983). For instance, the coal deforms, the elastic modulus attenuates, and the permeability varies. According to the experimental results of Tang et al. (2002), coal permeability was a function of geo-stress induced damage (Chen et al., 2013). Situ investigations and measurements of the permeability in excavation disturbed zone showed that the permeability could increase by several orders of magnitude due to the growth and propagation of micro cracks (Dusseault and Gray, 1992; Armand et al., 2014). Jiang et al. (2010) investigated the anisotropism of damage and related variation of coal permeability in brittle coals. They found that the permeability could significantly increase with the growth and coalescence of micro cracks. They also proposed a micromechanics-based damage model for the description of anisotropic damage based on the various experiment references. Seidle et al. (1992) proposed the bundled-matchstick conceptual model to describe the naturally fractured nature of a coal deposit. Therefore, drilling activity and excavation have a great impact on the stress distribution and the damage evolution of coalbeds and it is necessary to study the influence of excavation and damage evolution on permeability in the process of borehole gas drainage.

In this paper, a damage variable was defined to describe the couplings between coal permeability and porosity based on the effective strain. The establishment of the coupled damage-hydro-mechanical model was proposed firstly, which thoroughly considered the coupling effects of coal deformation on the stress, damage and permeability. A damage finite element program was developed in this paper to simulate borehole gas drainage. Specifically, this program was developed with the FORTRAN programming language and the grid information of the model was completed in the pre-processing of ANSYS finite element analysis software. At last, the validity and reliability of the model were analyzed. The modeled results were well agreed with the field testing data and the empirical data. The numerical simulation is helpful to evaluating gas drainage and predicting coalbeds methane production. Besides, numerical simulations show that drilling can remarkably relieve the stress around the borehole, induce great damage to coalbeds and thus promotes coal permeability.

2. Theoretical model

2.1. Damage evolution law

In order to describe the dynamic damage evolution process of coalbeds, the damage variable must be defined. For a one-dimensional problem, the damage variable ω is defined as (Kachanov 1958):

$$\omega = \frac{A - A_e}{A} \tag{1}$$

where A is the initial cross sectional area of material; A_e represents the effective cross sectional area of damaged material. ω=0 is the state without damage while ω=1 is the state of complete destruction.

Typically, for one dimensional elastic damage model, the damage evolution of coal can be calculated as (Qian and Zhou, 1989):

$$\omega = \begin{cases} 0, & 0 < \varepsilon \le \varepsilon_f \\ \dfrac{\varepsilon_u\left(\varepsilon - \varepsilon_f\right)}{\varepsilon\left(\varepsilon_u - \varepsilon_f\right)}, & \varepsilon_f < \varepsilon < \varepsilon_u \end{cases} \tag{2}$$

where ε is the strain, ε_f is the threshold strain of damage evolution, ε_u is the ultimate strain.

In a three-dimensional stress state (Mazars et al., 1980): ε_1, ε_2 and ε_3 are the three principal strains, $\varepsilon = \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2}$ is the equivalent total strain, $\varepsilon_t = \sqrt{\sum_i \varepsilon_i^2}$ is the equivalent tensile strain (ε_i is the tensile strain), $\varepsilon_c = \sqrt{\sum_j \varepsilon_j^2}$ is the equivalent compression strain (ε_j is the compression strain), the damage of 3D object can be written as:

$$\omega = \left(\frac{\varepsilon_t}{\varepsilon}\right)^2 \omega_t + \left(\frac{\varepsilon_c}{\varepsilon}\right)^2 \omega_c \tag{3}$$

where ω_t and ω_c are determined by ε_t and ε_c, respectively. ω_t is the damage degree caused by the tensile strain, ω_c is the damage degree caused by the compressive strain.

2.2. Stress analysis and damage constitutive equation

The stress equilibrium equations take the form

$$\sigma_{ij,i} + f_i = 0 \tag{4}$$

where $\sigma_{ij}(i,j$=1,2,3) is the stress tensor, f_i is stress caused by the body forces per unit volume.

Based on the adsorption deformation theory (Wu and Guo, 2001), coal is assumed to be a linear elastic body, and its linear adsorption swelling strain writes:

$$\varepsilon^e = \frac{2a\rho_v R_m T(1 - 2v)\ln(1 + bp)}{EV_L} \tag{5}$$

where ε^e is the adsorption swelling strain in free space; E is the elastic modulus of coal, MPa; v is the Poisson's ratio of coal; ρ_v is the apparent density of coal, m^3/kg; a is the adsorption capacity per unit mass under a certain reference pressure, m^3/t; b is the adsorption constant, Pa-1; R_m is gas universal constant, J/(mol·K); T is the temperature of coal bed, K; V_L is the molar volume of gas under standard conditions, 0.0224 m^3/mol; p is the gas pressure, Pa.

Considering that the coal grains are point-to-point contacted, one-third adsorption expansion strain is converted into expansion stress (Wu and Guo, 2001). Thus the stress equilibrium equation based on the Terzaghi's effective stress principle can be expressed as:

$$\sigma_{ij} = (1 - n)\sigma'_{ij} + (1 - n)\alpha p\delta_{ij} + n\beta p\delta_{ij} \tag{6}$$

$$\alpha = 2a\rho_v R_m T(1 - 2v)\ln(1 + bp)/(3V_L p) \tag{7}$$

where σ_{ij} is the total stress tensor; σ'_{ij} is the effective stress tensor of the solid coal; α is pore pressure coefficient caused by adsorption, β is the pore pressure coefficient; and δ_{ij} is the Kronecker delta function. Because the porosity of the coal is very small, the minor contribution of pore pressure drawdown to the effective stress is neglected compared with the large contribution of gas adsorption induced coal expansion. Thus, Eq. (6) can be written as: