NUMERICAL SIMULATION FOR FRACTURE NETWORK EVOLUTION IN COAL-BEARING GAS RESERVOIR RECONSTRUCTION BASED ON DAMAGE THEORY

by

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Original scientific paper
https://doi.org/10.2298/TSCI2106423L

Based on the characteristics of mechanical response of coal rock under loading, an elastic-brittle damage constitutive relation of coal rock has been proposed, which has been extended to the 3-D stress state, based on the geological strength index. Besides, a numerical calculation method based on the elastic-brittle damage theory has been developed, by analyzing the seepage-stress coupling effect. Then, a computing program for fracture network transformation has been composed to perform numerical simulation of forming process of coal rock under different working conditions, by the APDL language in the ANSYS software platform. The mechanical mechanism of fracture network forming process of coal rock has been further analyzed.

Key words: *coal-bearing gas, reservoir reconstruction, damage model, fracture network evolution, numerical simulation*

Introduction

The coal bearing strata is enriched with abundant unconventional natural gas resources [1, 2]. To exploit the unconventional gas not only supplies the conventional gas resources, but also serves as an important approach to prevent and control the coal mine gas hazards [3, 4]. At the same time, reducing the gas drainage in the process of coal mining is beneficial for reducing the greenhouse effect [5, 6].

Previous studies focus on the coal-bed CH_4 mostly, and the abundant research achievements are obtained [7, 8]. However, the research results on the exploit-ability of shale gas and tight sand gas are insufficient. Recent studies show that the reserve content of these two unconventional natural gases are abundant, and the joint exploitation of these three kinds of gas resources has obvious technical advantages, compared with the single exploitation of coal-bed methane [9-11]. Therefore, the research on fracture network evolution in coal-bearing gas reservoir reconstruction is urgent and beneficial.

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In this paper, the elastic-brittle damage constitutive relation is established based on the geological strength index (GSI). Besides, the APDL language in the ANSYS software is employed to develop the corresponding numerical calculation program, and the Weibull distribution function is introduced to establish the numerical calculation model of coal rock. Thus, the mechanism of reconstruct fracture network of coal gas reservoir has been analyzed.

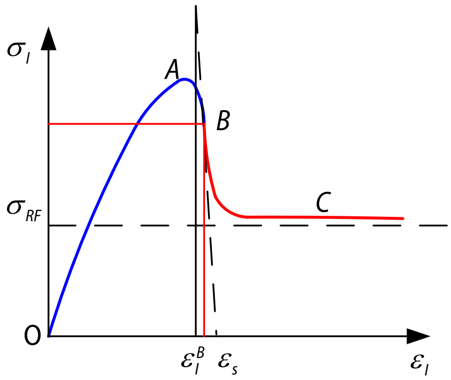


Figure 1. Unified constitutive model of coal rock

The elastic brittle damage model of coal rock

According to the mechanical experiments of coal rock, the stress-strain curve is represented by the unified model in fig. 1, which illustrates the general characteristics of the damage-fracture evolution of coal rocks [12].

Through the microscopic observation results, it is obvious that coal rock develops from distributed micro-damage to localization in the section O-A-B, and the damage increases continuously, which successively goes through the stage I – no damage, stage II – micro-crack evolution, and stage III – macro-crack nucleation. In section B-C, there are IV – macroscopic crack propagation and V – frictional slip successively. According to the curve characteristics, the damage variables for the section O-A-B of the curve are defined:

$$D = \left(\frac{\varepsilon_I}{\varepsilon_s}\right)^n \tag{1}$$

where ε_I is the first principal compressible strain with $0 < \varepsilon_I < \varepsilon_I^B$, n – the brittleness index, and ε_S – the brittle fracture endpoint (it is called the brittle limit strain in this paper). As shown in fig. 1, the curve O-A-B represents the I-II stage of rock damage evolution, and ε_S lies at the intersection point of tangent over B and horizontal axis. Provided that the damage is isotropic, the principal compressible stress in section O-A-B is written as:

$$\sigma_I = \frac{\sqrt{GSI}}{10} E_0 \left[1 - \left(\frac{\varepsilon_I}{\varepsilon_s}\right)^n\right] \varepsilon_I \tag{2}$$

where σ_I is the principal compressible stress and E_0 – the initial elastic modulus.

The curve B-C reflects two stages, including crack propagation, penetration and frictional sliding (III-IV), which are fitted by the inverse proportion function, *e.g.*:

$$\sigma_I - \sigma_{RF} = \frac{\sqrt{GSI}}{10} \frac{H}{\varepsilon_I - M} \tag{3}$$

where σ_{RF} is the residual strength of rock under uni-axial compression obtained from the stress-strain curve, and both H and M are undetermined parameters. According to the smooth connection condition of the two curves, namely, the two curves are continuous and have the same slope at point B, which is expressed:

$$M=\varepsilon_I^B-\frac{\sqrt{GSI}E_0\left[1-\left(\frac{\varepsilon_I^B}{\varepsilon_s}\right)^n\right]\varepsilon_I^B-10\sigma_{RF}}{\sqrt{GSI}E_0\left[\left(\frac{\varepsilon_I^B}{\varepsilon_s}\right)^n(n+1)-1\right]} \tag{4}$$

$$H=\frac{\left\{\sqrt{GSI}E_0\left[1-\left(\frac{\varepsilon_I^B}{\varepsilon_s}\right)^n\right]\varepsilon_I^B-10\sigma_{RF}\right\}^2}{GSIE_0\left[\left(\frac{\varepsilon_I^B}{\varepsilon_s}\right)^n(n+1)-1\right]} \tag{5}$$

The fracture through stress drop and the decline rate of stress at point B read:

$$\Delta\sigma_{BC}=\frac{\sqrt{GSI}}{10}E_0\left[1-\left(\frac{\varepsilon_I^B}{\varepsilon_s}\right)^n\right]\varepsilon_I^B-\sigma_{RF} \tag{6}$$

$$k_B=\frac{\sqrt{GSI}}{10}E_0\left[\left(\frac{\varepsilon_I^B}{\varepsilon_s}\right)^n(n+1)-1\right] \tag{7}$$

The stress-strain curve of B-C segment is given:

$$\sigma_I=\frac{\sqrt{GSI}}{10}\left[\frac{(\Delta\sigma_{BC})^2}{\left(\varepsilon_I-\varepsilon_I^B\right)k_B+\Delta\sigma_{BC}}+\sigma_{RF}\right] \tag{8}$$

If D_I is the element damage in the direction of the principal compressible stress, then damage equations are presented:

$$\sigma_I=\frac{\sqrt{GSI}}{10}E_0(1-D_I)\varepsilon_I=\frac{\sqrt{GSI}}{10}\left[\frac{(\Delta\sigma_{BC})^2}{\left(\varepsilon_I-\varepsilon_I^B\right)k_B+\Delta\sigma_{BC}}+\sigma_{RF}\right] \tag{9}$$

$$D_I=1-\frac{10}{\sqrt{GSI}}\left\{\frac{(\Delta\sigma_{BC})^2}{\left[\left(\varepsilon_I-\varepsilon_I^B\right)k_B+\Delta\sigma_{BC}\right]E_0\varepsilon_I}+\frac{\sigma_{RF}}{E_0\varepsilon_I}\right\} \tag{10}$$

Based on eqs. (1) and (10), the basic model of damage evolution equation in compressible stress direction is given:

$$D_I=\begin{cases}\left(\dfrac{\varepsilon_I}{\varepsilon_s}\right)^n, & \varepsilon_I\le\varepsilon_I^B\\[2ex] 1-\dfrac{10}{\sqrt{GSI}}\left\{\dfrac{(\Delta\sigma_{BC})^2}{\left[\left(\varepsilon_I-\varepsilon_I^B\right)k_B+\Delta\sigma_{BC}\right]E_0\varepsilon_I}+\dfrac{\sigma_{RF}}{E_0\varepsilon_I}\right\}, & \varepsilon_I>\varepsilon_I^B\end{cases} \tag{11}$$

The equation of principal compressible stress and strain is given:

$$\sigma_I = \begin{cases} \dfrac{\sqrt{GSI}}{10} E_0 \left[1 - \left(\dfrac{\varepsilon_I}{\varepsilon_s}\right)^n\right] \varepsilon_I, & \varepsilon_I \le \varepsilon_I^B \\ \dfrac{10}{\sqrt{GSI}} \left\{ \dfrac{\left(\Delta\sigma_{BC}\right)^2}{\left[\left(\varepsilon_I - \varepsilon_I^B\right) k_B + \Delta\sigma_{BC}\right] E_0 \varepsilon_I} + \dfrac{\sigma_{RF}}{E_0 \varepsilon_I} \right\} \varepsilon_I, & \varepsilon_I > \varepsilon_I^B \end{cases} \tag{12}$$

Based on the stress-strain curve of coal rock, the elastic-brittle damage constitutive model relation of coal rock based on GSI is established, which can accurately describe the elastic stage, micro-crack evolution stage, macroscopic crack nucleation, and macroscopic crack propagation in the process of coal rock compression failure.

The evolution law of fracture network and factors

Basic parameters

In order to simulate the propagation of fractures accurately, the seepage-damage coupling finite element method is used in this paper [13]. By defining the behaviors of mesoscopic units, which are placed into the balanced system of the whole reservoir, and calculating them to identify the fracturing unit, its damage situation is determined. Fracturing units gradually damage and connect, resulting in fractures, damaged units, and a fracture network eventually.

The mesoscopic disorder is introduced into a model through the Weibull distribution function [14]. Assuming that the disorder is only reflected in the difference of the elastic modulus of the mesoscopic element, the Weibull probability density function of elastic modulus is given:

$$f(E) = \frac{m}{\hat{E}} \left(\frac{E}{\hat{E}}\right)^{m-1} \exp\left(-\frac{E}{\hat{E}}\right)^m \tag{13}$$

where $\hat{E}$ is the scale parameter, E – elastic modulus, and m – Weibull modulus or shape factor. Monte Carlo simulation technology is used to generate random elastic modulus, which assigns each unit to complete the disordered distribution of initial defects [15, 16]. The tabs. 1 and 2 show the damage and seepage parameters in the damage-seepage coupling model of intact coal rock. For different non-intact coal rock mass, their parameters can be calculated by GSI.

Table 1. Physical and mechanical parameters of coal seam

Parameter	value
Mass denstiy	2500 kg/m^3
Permeability	$0.055 \cdot 10^{-3} \mu m^2$
Biot coefficient	0.8
Weibull scale parameter	1 GPa
Weibull shape factor	3
GSI	90
Elastic modulus	12.92 GPa
Poisson ratio	0.3
Depth	400 m

Influence of GSI on fracture propagation and evolution

The GSI can be used to measure the development degree of joint fractures in coal rock. An appropriate development degree is conducive to the formation of closed network. Coal rocks with different GSI contain different natural fractures. In the process of reservoir reconstruction, fig. 2 shows that the fracture propagation and the evolution of coal rocks with GSI of 95 and 70, respectively. It can be seen in fig. 2(a) that a single fracture along the direction of maximum principal stress is mainly

Table 2. Damage parameters of coal seam

Compressed stress state		Tensile stress state	
Parameter	Value	Parameter	Value
Uni-axial compressible strength	21.31 MPa	Uni-axial tensile strength	1.13 MPa
Ultimate compressible strain	0.03	Ultimate tensile strain	0.0006
Compression residual stress ratio	0.5	Tensile residual stress ratio	0.5
Inter friction angle	20°	Cohesive force	2.5 MPa

formed due to the larger GSI, high degree of integrity of coal rock, few natural fractures, and relatively uniform material properties. The GSI in fig. 2(b) is 70. The main trend of fractures evolves along the direction of maximum principal stress.

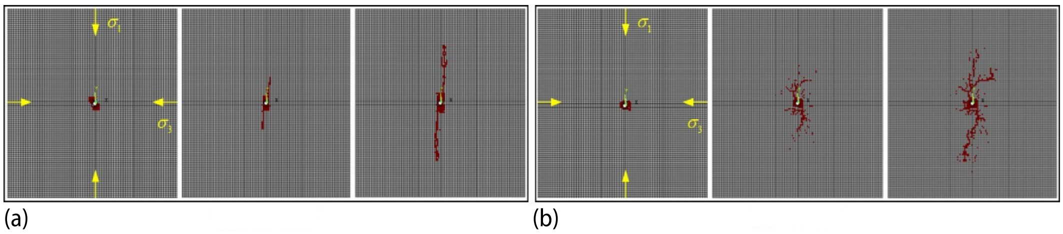


Figure 2. Damage evolution patterns of the fracture with different GSI values; (a) the GSI = 100 and (b) the GSI = 70

Influence of principal stress direction on evolution of fracture network damage

During the transformation of the fracture network, the principal stress direction is the main factor affecting the fracture propagation direction. The material produces apparent strain in the direction of the minimum principal stress, so that the fracture evolves along the direction of the maximum principal stress. Under the action of water pressure, the element is stretched. When the strain reaches the limit strain in the direction of minimum principal stress, the element is damaged. It can be seen in fig. 3 that fractures expand along the direction of maximum principal stress.

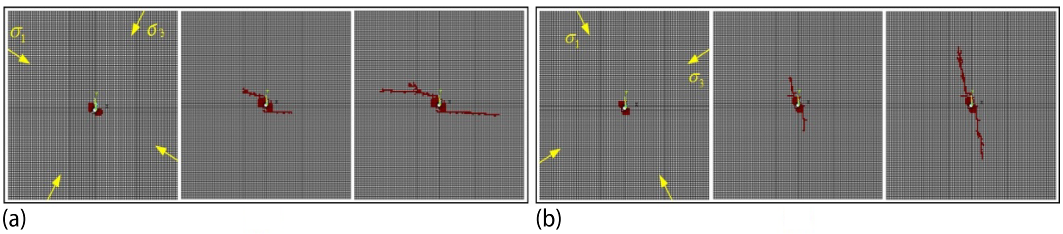
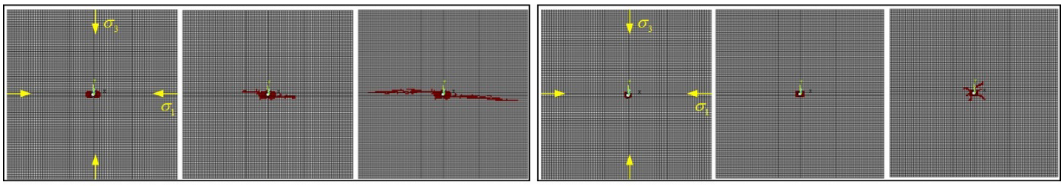


Figure 3. Relationship between damage evolution of fracture and maximum principal stress; (a) the angle between the direction of maximum principal stress and the *x*-axis is 30° and (b) the angle between the direction of maximum principal stress and the *x*-axis is 60°

Influence of stress ration on the evolution of fracture network damage

During the transformation of fracture network, if the difference between two principal stresses is large, the evolution of fracture network damage is mainly controlled by principal stress, so only a single crack can be formed along the direction of the maximum principal stress.

In fig. 4, the stress ratio has a greater impact on the evolution of fracture network. When the stress ratio is 5, the fracture evolves and expands along the direction of the maximum principal compressible stress. When the stress ratio is 1, the fracture loses the advantageous direction of expansion, but expands in all directions. This sign indicates that the stress ratio is large, and the fracture track is straight and smooth, while the stress ratio is small, and the fracture is zigzags and rough. Therefore, the principal stress is closer to the size, and the fracture network tends to be formed.



(a) (b)

Figure 4. Damage evolution patterns of the fracture with different stress ratios; (a) the stress ratio is 5 and (b) the stress ratio is 1

Conclusions

In the present work, the elastic-brittle damage constitutive relation of coal rock was established based on the GSI, and the APDL language was used to develop the corresponding numerical calculation program. The numerical calculation model of the coal rock was established by introducing the Weibull distribution function, and the key control factors of the joint network were simulated and analyzed. It is shown that the direction of fracture propagation is affected by the stress ratio under the bi-axial state.

Acknowledgment

This study is sponsored by the National Natural Science Foundation of China (41772163, 51804099), the Foundation for Higher Education Key Research Project by Henan Province (18A440012), the Fundamental Research Funds for the Universities of Henan Province (NSFRF180330), the Virtual Simulation Experiment Teaching Project of Henan Province, the Research and Practice Project of Educational and Teaching Reformation of Henan Polytechnic University (2019JG074), the Natural Science Foundation of Henan Province (202300410182, 182300410206), the project of Henan Key Laboratory of Underground Engineering and Disaster Prevention (Henan Polytechnic University).

Nomenclature

D_I – element damage, [–]
D – damage variables, [–]
E_0 – initial elastic modulus, [GPa]
$\hat{E}$ – scale parameter, [GPa]
GSI – geological strength index, [–]
k_B – decline rate of stress at point B, [–]
m – Weibull modulus or shape factor, [–]
n – brittleness index, [–]

Greek symbols

$\Delta\sigma_{BC}$ – fracture through stress drop, [MPa]
ε_I – first principal compressible strain, [–]
ε_I^B – first principal compressible strain at point B, [–]
ε_{RF} – residual strength under uni-axial compression, [–]
ε_S – brittle limit strain, [–]

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Paper submitted: March 27, 2020
Paper revised: June 15, 2020
Paper accepted: August 9, 2020