Numerical simulation research on failure law of surrounding rock in coalbed methane well

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Abstract The entire process of fracturing at different sections, were namely 1-1(wellhead), 2-2(well middle), 3-3(well bottom), was simulated to study the failure law of surrounding rock at different depths. The failure mechanics of borehole rock mass was analysed using Realistic Failure Process Analysis (RFPA) software. The results showed that as the depth of wells continues to deepen, the crack propagation was restrained relatively by inhomogeneous materials in rock mass. In addition, with the increase of inhomogeneous materials in the surrounding rock, the brittle of rock and peak strength of the fracture gradually increase. The entire process of rock failure was corresponded to three stages, namely damage initiation, restriction propagation and rock failure. As the depth of wells deepens, the steps in damage initiation gradually decreased compared with the steps in restriction propagation stage. As the confining pressure continues to increase, the accumulated energies in the rock mass reached the peak strength of the crack, it would immediately violently crack.

1. Introduction
The problem of borehole instability mainly refers to the failure of the borehole wall during drilling and the loss of its carrying capacity eventually collapses. However, with the rapid development of exploration, complex terrain structure and development of unconventional wells lead to various types of geotechnical engineering projects such as borehole instability et al. Therefore, there is an urgent need to study the borehole instability and ensure the safe mining.

Researchers around the world have extensively investigated the borehole instability problem. The main reason of the borehole instability is stress concentration, Ding et al. (2017) and Zhang et al. (2013) analyzed the model for borehole stability based on Mogi-Coulomb criterion, Hoek-Brown criterion. Zhang et al. (2010) studied the inclined well instability based on Mogi-Coulomb criterion, Drucker-Prager criterion. Qu et al. (2010) studied the effects of bottom hole pressure on borehole instability. Zhou et al.( 2010) analyzed borehole instability under the microscopic size using the acoustic emission (AE) system. Liu et al. (2016) analyzed the ultra-short radius radial wells using the ABAQUS simulation software. Physicochemical test methods have been carried out to analyzed the borehole instability projects such as log interpretation, FMI imaging logging, acoustic emission (AE) et al. Al–Ajmi . (2009) analyzed the characteristics of vertical well and inclined well under different horizontal crustal stress and anisotropic formation respectively. Liu et al. (2015) studied the coal bed methane(CBM) and producing pattern in Luan Mining
Area. Li et al. (2010) proposed the method of real-time monitoring in coal seam based on back-propagation (BP) neural networks algorithm.

The current problem of CBM mining is well instability. However, the researchers on the well stability are mainly focused on mechanics researches. Researches are insufficient for the crack law of entire borehole. With the deepening of the borehole wall and the increasing of internal confining pressure, the complex formation conditions lead to the caving pressure is hard to predict caused by the fracture deformation of rocks gradually becomes ductile, which pose significant threats to the stability of well. Based on this problem, this paper analyzed the well rock mass combined inhomogeneous materials such as glutenite et al, taking stratum structure of Lu’an mining area as the research object, the cross-sections in different location, which contain different proportions of inhomogeneous, were considered. In addition, the entire process of cracking at different cross-sections of well rock mass were analyzed using RFPA software, then changing trend of various stress and cracking law at different locations were analyzed.

2. Theoretical Model

A quadrilateral element was adopted, length of the model was \( L=1000\text{mm} \), to divided into \( 250 \times 250 = 62500 \) elements and the finite model was established by using RFPA software. Due to the different inhomogeneous materials in the rock mass at different locations of the borehole, the material properties of the model was established as rock matrix properties, the homogeneous materials of rock mass and the inhomogeneous materials inside rock mass were 3, 10 respectively, Table 1 summarizes the rock specific parameter setting.

| Parameter name          | Rock          |
|-------------------------|---------------|
| Elastic Modulus E/GPa   | 4             |
| homogeneous             | 3, 10         |
| Compressive Strength    | 50            |
| friction angle /°        | 30            |
| Poisson ratio           | 0.25          |
| Porosity                | 0.1           |
| coupling coefficient    | 0.2           |
| pore pressure coefficient | 0.5         |
| Porosity                | 0.1           |

The cross-sections at different location, namely 1-1(wellhead), 2-2(well middle), 3-3(well bottom), were analyzed and simulated respectively. The proportion of inhomogeneous materials increases with
increasing well depth and the initial value of confining pressure is 5mpa with the water pressure of 5mpa with the increment of each step of 0.05Mpa. The proportion of inhomogeneous materials is set from 10% to 15% to 20% to increase as the depth of the well deepens. Figure 1 shows that three locations in well.

3. Simulation results

3.1 Effects of inhomogeneous materials on crack
In the same section, Figure 2 shows, in addition to the cracks caused by confining pressure, macroscopic cracks of varying degrees, which are in the shape of zonal or flake, are formed around the inhomogeneous materials in the rock mass. Asymmetry in crack initiation caused by the effects of inhomogeneous materials and the cracks in the upper part of the wellhead are mainly propagated in a manner that bypasses the inhomogeneous materials. The formed cracks are meandering. At the same time, passivation occurs at the tip of the cracks, some cracks occur at the junction of the two materials, and more microcrack branches are formed. The microcracks in the lower part of the borehole pass through near the inhomogeneous materials and some cracks even run through the inhomogeneous materials. However, the further propagation requires more energy accumulation while the inhomogeneous materials play a certain role of restraint and offset the accumulated energy to prevent cracks from continuing to propagate.

![Figure 2. Crack propagation law: (a) crack simulation; (b) Similar material experiment (Meng.et al).](image)

3.2 The variations law of acoustic emission
As shown in figure 3(a) of 1-1 crack law of cross-section, the rock mass is relatively inhomogeneous materials in this cross-section, and the requirement energies of initiation crack are less near the wellhead. In term of the figure 3(a) of 1-1 numbers of AE from step 0 to 5 shows that the numbers of AE at the rock mass are relatively obvious at these steps. In step 5 to 22, the numbers of AE are more regular, energies are continuously accumulated. At this time, the distribution of microcracks is relatively random. In step 22 to 25, the numbers of AE increased sharply. This is caused by the formation of macroscopic cracks that are formed by the connection of continuously generated microcracks in the upper part of the wellhead. Cracks cannot continue to expand under the constraint of inhomogeneous materials, as shown in the figure3 (a) 1-1 cross-section in rock mass. In the right side of the wellhead, the cracks are continuously connected to form a main crack through the entire wellhead. In the lower part of the wellhead, there is no constraint of inhomogeneous materials, a main crack formed that is relatively symmetrical to the right side of the wellhead and run through the wellhead. The fluctuation of AE numbers is fairly obvious from step 25 to 32, which shows the
macroscopic cracks are generated in rock mass and the rock failure is caused by the connection of two main cracks which is ran though borehole.

Figure 3. The crack evolution law of surrounding rock on 1-1 cross section: (a) the failure law of rock mass; (b) the variations law of acoustic emission.

In the initial stage the numbers of AE are greatly fluctuated, as shown in figure 4 (b) the variations law of acoustic emission in 2-2 cross-section. The numbers of AE are up to 710 in step 0 to 3, but in step 3 to 22, AE single step increment are all less than 100. In addition, Figure 4(b) 2-2 crack law on cross-section shows that there are different degrees of damages, are in shape of spot, strip or connected pieces, along the inhomogeneous materials. The numbers of AE increase dramatically, energies are continuously accumulated at the microcracks. Below the borehole, the secondary cracks are generated, propagating from top to bottom, along the main cracks, the numbers of AE fluctuate greatly in the step 22 to 25. The numbers of AE first decreased sharply and then increased dramatically in step 25 to 30. Eventually, the connecting cracks around the wellbore run through the borehole and the rock mass is fractured at step 30 to 32.

Figure 4. The crack evolution law of surrounding rock on 2-2 cross section: (a) the failure law of rock mass; (b) the variations law of acoustic emission.

At cross-section 3-3(well bottom), the inhomogeneous materials in rock mass further increase. The figure 5(c) the variations law of acoustic emission in 3-3 cross-section shows that in step 0 to 40, AE numbers almost has no change and the brittle of rock mass is gradually enhanced. The distribution of inhomogeneous materials is relatively random with the increase of pressure.

Figure 5 (c) the failure law of rock mass in 3-3 cross-section shows that when the accumulated energies by the microcracks are large enough, the damage zones formed around the inhomogeneous materials are consecutively broken and a few cracks are expanded and transferred caused by the restrain of inhomogeneous materials. As shown in figure 5(c), there are two symmetrical main cracks
zones near the borehole. As shown in figure 5(c), when the surrounding rock reached its peak strength, it could fail immediately. At the 3-3 (well bottom), the numbers of acoustic emissions even reached 6,000 when it breaks.

Figure 5. The crack evolution law of surrounding rock on 3-3 cross section: (a) the failure law of rock mass; (b) the variations law of acoustic emission.

3.3 The variations law of stress

In order to analyse the changing characteristics of cross-section respectively, the failure of rock are mainly divided into three stages, namely damage initiation, restriction propagation, rock failure. Taking the ratio as research object which is the minimum principal stress to the maximum principal stress at each step of the crack process ie, $\sigma_3/\sigma_1$, the cracking law of entire rock mass in borehole wall is analyzed.

Compared with figure 6 the variations law of stress on 2-2 cross-section (well middle) and 3-3 cross-section (well bottom), the 1-1 cross-section (wellhead), damage initiation, takes relatively longer steps. After step 0-10, the variations law of stress on 1-1 cross-section (wellhead) has a significant increase. The variations law of stress on 2-2 cross-section (well middle) and 3-3 cross-section (well bottom), the proportion of inhomogeneous materials in the rock mass and the elastic modulus is large, the initial damage of the rock mass is less. The initial stage of the two cross-sections is only step 0-5. As shown in figure 6 the variations law of stress on 3-3 cross-section (well bottom), compared with 1-1 cross-section (wellhead), 2-2 cross-section (well middle), the transition from damage initiation to restriction propagation at 3-3 cross-section (well bottom) is relatively gentle and the AE numbers are less. In restriction propagation stage, the variations law of stress on 3-3 cross-section (well bottom) is obviously greater than the curve at 1-1 cross-section (wellhead), 2-2 cross-section (well middle). The failure of rock occurred immediately after reaching the peak strength caused by the microcracks. At the 1-1 curve, the step from 26 to 40 that changes greatly, but the process of cracking is longer. This shows that in the rock failure stage, the more inhomogeneous materials rocks have, the more violently rock failure is.
Figure 6. The stress evolution law of surrounding rock: (a) 1-1 cross-section, (b) 2-2 cross-section, (c) 3-3 cross-section. The entire process in curves is divided into three stages, which are (1) damage initiation, (2) restriction propagation, (3) rock failure.

4. Conclusions
The crack propagation was restrained relatively by the inhomogeneous materials in rock mass. The rock mass failure corresponded to three stages, which are damage initiation, restriction propagation and rock failure.

With the increase of the properties of inhomogeneous materials in rock mass, the time required for rock fractures was increased significantly in restriction propagation stage. The stage, in 1-1 cross-section (wellhead), 2-2 cross-section (well middle) and 3-3 cross-section (well bottom), was step 10 to 22, step 4-30, and step 6-35 respectively. In addition, when the surrounding rock reached its peak strength, it could failure immediately. At the 3-3 cross-section (well bottom), the numbers of AE even reached 6,000 when it breaks.

The rock mass is mainly sandstone and contains some inhomogeneous materials such as some gravel. Due to the effects of confining pressure and inhomogeneous materials, the rocks are complex, natural materials that may contain several types of damage, which cannot be considered as homogeneous materials in engineer projects.

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