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Numerical simulation of spatial distributions of mining-induced stress and fracture fields for three coal mining layouts

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ABSTRACT

In this study, the spatial distributions of stress and fracture fields for three typical underground coal mining layouts, i.e. non-pillar mining (NM), top-coal caving mining (TCM) and protective coal-seam mining (PCM), are modeled using discrete element software UDEC. The numerical results show that different mining layouts can lead to different mining-induced stress fields, resulting in diverse fracture fields. For the PCM, the mining influenced area in front of the mining faces is the largest, and the stress concentration factor in front of the mining faces is the lowest. The spatial shapes of the mining-induced fracture fields under NM, TCM and PCM differ, and they are characterized by trapezoidal, triangular and tower shapes, respectively. The fractal dimensions of mining-induced fractures of the three mining layouts decrease in the order of PCM, TCM and NM. It is also shown that the PCM can result in a better gas control effect in coal mines with high outburst potential. The numerical results are expected to provide a basis for understanding of mining-induced gas seepage fields and provide a reference for high-efficiency coal mining.

1. Introduction

Underground coal mining in highly gassy coal seams can cause stress redistribution and large-scale movement of the strata, which result in the development of fracture field. The complex fracture fields increase stratum permeability and thereby provide the major channels for gas migration and drainage (Qian and Xu, 1998; Xie et al., 2011). Therefore, study of stress and fracture fields is critically important to develop techniques for efficient coal mining and gas extraction.

During mining, the coal and rock in front of the mining face experience dynamic stress changes due to the decrease in confining stress, which will increase stratum deformation induced by in situ stresses in the rock subsequently (Xie et al., 2011, 2016). Song et al. (1984) theoretically described the distribution of abutment pressure during coal mining in combination with field application. Singh et al. (2011a, b) studied the evolution of mining-induced stress fields during coal mining under different geological conditions and estimated the range of influenced area and the ultimate mining-induced stress over the coal pillars. Several studies (e.g. Mark et al., 2007; Guo et al., 2012; Jiang et al., 2012; Shabanimashcool and Li, 2012, 2013) focused on the stress evolution in a longwall mining face and presented the optimum location for gas extraction based on field monitoring and numerical simulations. He et al. (2007, 2015) proposed the longwall mining "cutting cantilever beam theory" and formulated the "110 mining method", which is considered as the third mining science innovation. Using this method, one working face, after the first mining cycle, only needs one advanced roadway excavation; while the other one is automatically formed during the last mining cycle without coal pillars left in the mining area (He et al., 2015). Compared with the conventional pillar mining method, the peak stress in roof cutting non-pillar mining (NM) method can be decreased by 11.8%–20.3% (He et al., 2018). Xie et al. (2011) simulated the mining-induced mechanical behaviors of rock for

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different mining layouts in the laboratory and revealed the relation between the mining layout and the mechanical behaviors of rock. However, most of these aforementioned studies focused solely on exploring the variation in mining-induced stress, but the spatial distribution and variations in the stress fields for different mining layouts are rarely reported.

It is known that the stress in front of the working face changes drastically as mining progresses. This provides the basic driving force for fracture generation and development. To understand the mining-induced fracture networks, theoretical analysis, numerical simulation, rock-like material test, field test, and other approaches are basically used. Qian and Xu (1998) studied the distribution characteristics of mining-induced fractures in the overlying strata, and revealed that the fractures are presented in the form of O-shaped circle. Yasitli and Unver (2005) numerically analyzed the deformation, displacement, stress and fracture evolution of a thick coal seam. Due to the complexity of the fracture field and its spatial distribution, fractal geometry provides an alternative to describe the fracture fields. Zhou et al. (2012) presented the self-similarity of fracture distributions in rock masses by means of model experiments on similar materials and fractal geometry. Gao et al. (2013) analyzed the spatial distribution and evolution of mining-induced borehole wall fractures using borehole video equipment.

The spatial distribution and evolution of fracture fields during coal mining have been studied extensively; however, there are few reports on how fracture fields are produced by different mining layouts. In this context, the mining-induced stress and fracture fields produced by three mining layouts are analyzed using discrete element method, in order to provide the basis for the coupling problem between the mining-induced stress-fracture-seepage fields and different mining layouts for the purpose of high-efficiency coal mining.

2. Analyses of mining-induced stress and fracture fields

During coal mining, the stress field changes significantly due to rock unloading, providing the conditions for the formation of mining-induced fracture networks. The complex fracture field expands to form gas seepage pathways, which greatly changes the permeability of the coal seam. Unfortunately, the distribution and evolution of the mining-induced stress and fracture fields for different mining layouts are not well known.

2.1. Mining-induced stress fields

Various studies (e.g. Xie et al., 2011, 2016) discussed the stress fields generated by different mining layouts. NM is a type of mining that removes the coal pillar in a mined-out area (goaf) or leaves small coal pillars between the underground roadway and the goaf (see Fig. 1a) (Zhang et al., 2016; He et al., 2018). In Fig. 1, γ is the bulk density of overlying strata; H is the mining depth; K is the abutment pressure coefficient; and L_1 and L_2 are the lengths of the abutment pressure of the decreasing and increasing sections, respectively (Zhang et al., 2016). Top-coal caving mining (TCM) mainly develops a mining face along the bottom of a thick coal seam and loosens the coal at the face by abutment pressure or by blasting with the overlying coal removed after being caved (Fig. 1b) (Xie et al., 1999, 2016; Alehossein and Poulsen, 2010; Zhang et al., 2014; Yu et al., 2015). Protective coal-seam mining (PCM) is the first step of mining performed on a seam to eliminate the risk of gas or rock outbursts during subsequent mining operations (Fig. 1c) (Yuan, 2008; Yang et al., 2011; Chen et al., 2014). The distribution of the stress field in front of the mining face varies for each of these mining layouts. In the NM, when the coal pillar is removed, the stress imposed by the adjacent goaf will be superimposed on the coal mass in front of the mining face. For the three mining layouts, the stress will be the greatest for the NM. In the TCM, as the goaf is relatively larger, both the scale of the mining-induced stress field and the peak stress are relatively larger. In the PCM, the protective coal-seam yields stress relief during the early stages of mining so that the peak stress is smaller.

2.2. Mining-induced fracture fields

For the three mining layouts, it is obvious that fractures can be developed in the overlying strata due to stress changes. As the mining advances, the fracture networks gradually propagate to the overlying strata and along the direction of the working face. In the NM, because the coal pillar is small or absent, the stress field changes significantly. The fracture field is widely distributed and the fractures in the coal near the mining face are frequently observed. In the TCM, due to the intensive mining activities and large mined-out volume generated, coal itself is more fractured and the extent of the fracture field is greater than that of PCM. In the PCM, where the mining width of the protective layer reaches an appropriate size, the volume of protective coal-seam will experience compression and swelling phases, and finally reach a stable stage. The fracture field of the protective layer is fully developed over the goaf, where it provides favorable conditions for gas control of the adjacent seams.

3. Numerical simulations of mining-induced stress and fracture fields

3.1. Simulation procedures

Numerical simulation is carried out using the commercial discrete element software UDEC4.0. The discrete element method allows for limited displacements and rotations of discrete elements including complete separation of elements. Prefabricated fractures are added to the model. The bottom of the model is fixed as shown in Fig. 2. Then the tensile stress is applied to both sides of the model, allowing for the coalescence of cracks in the middle of the model. An inverse analysis can be carried out by adjusting the model parameters. It is possible to make the blocks equivalent to the intact module where the discrete fractures are added. When the boundary condition is assumed, some cracks will open, propagate and finally coalesce.

3.2. Model setup

To minimize the boundary effects on the model, the model length is defined as 300 m, the height of the overlying stratum is assumed to be 50 m, and the height of the underlying rock mass is set to be 15 m. Numerical simulations are conducted based on the geological and mining conditions of the 8212 working face in the Tashan Mine, Shanxi Province, China, where the coal seam is located at the depth of 469.4 m. To compare the three numerical models, three mining layouts (i.e. NM, TCM and PCM) are numerically analyzed at the same depth, as shown in Fig. 3. It is assumed that both sides of the model have only vertical displacement and the horizontal displacement is zero. It is also hypothesized that the horizontal and vertical displacements of the underlying rock formations are both zero. The in situ gravitational stress is applied to the upper boundary with respect to the overburden depth. As for the NM model, stress of 1.3 times the original gravitational stress is applied due to the strike abutment pressure. The models for all three mining layouts simulate a mining face advance of 60 m.

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