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Tunnelling outburst potential affected by mechanical properties of coal seam

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ABSTRACT

Coal and gas outburst is greatly affected by the stress distribution in front of the heading face when tunnelling in high gassy coal seam. In this paper, the $FLAC^{3D}$ software and Mohr-Coulomb failure criterion are used to study the stress differences in front of the heading face. A total of 31 homogeneous models are built to study the stress differences affected by the coal seam mechanical properties. And another 8 kinds of heterogeneous models are built to study the stress differences affected by the abruptly changes of coal seam mechanical properties.

When tunnelling in homogeneous coal seam, the large elastic modulus of coal seam will increase the stress peak value in front of the heading face, but do not change the stress peak position. The small internal friction angle will push the stress peak far away from the heading face. Therefore, the range of stress-relief zone in front of the heading face could significantly increase. The small cohesion of the coal seam will also push the stress peak far away from the heading face, but will result in an increase in the stress peak value. The Poisson ratio and tensile strength of the coal seam have little influence on the value and position of stress peak. As the elastic modulus decreases, cohesion and internal friction angle can greatly increase the displacement of the coal in front of the heading face. Taking into account both the mechanical properties of coal seam and the corresponding stress peaks, gas outburst is not easy to occur in the homogeneous coal seam.

When tunnelling in heterogeneous coal seam, the abrupt change of coal seam elastic modulus greatly affects the stress concentration peak. If the cohesion of the coal seams also changes greatly with the elastic modulus, the stress peak will be enhanced. The abrupt change of coal seam cohesion and Poisson ratio have a slight influence on the stress concentration, while the abrupt change of internal friction angle of coal seam have little effect on the stress concentration. An outburst accident is most likely triggered when the cohesion and elastic modulus of the coal seams change greatly at the same time.

Outcomes of this study is very beneficial for the prediction and prevention of coal and gas outburst. Meanwhile, this study provides a reference for the setting of mechanical properties of the coal seam and rock layers in the numerical simulation of mining.

1. Introduction

Coal and gas outburst is one of the most severe accidents when tunnelling in high gassy coal seam. The stress evolution in front of the heading face are the key factors to cause coal and gas outburst. With the increase in mining depth, the in-situ stress increases significantly, and gradually becomes the most important factor leading to gas outburst (Guo et al., 2017; Shadrin, 2016). At present, it is generally believed that the high stress concentration in front of a heading face will accumulate elastic energy. When the high stress suddenly drops and breaks the coal, the instantaneous failure will release huge elastic energy. Then a coal and gas outburst may be triggered immediately (Zhang et al., 2014). Therefore, accurately understand the stress distribution and evolution is very meaningful for gas outburst prediction and prevention. However, it is very difficult to test the stress quickly, for the heading face moves with the dynamic excavation (Chen et al., 2015). Numerical simulation maybe an effective method to calculate the stress distribution and evolution.

The stress and displacement in front of heading face are closely related to the coal seam strength and its change (Li et al., 2017; Yang et al., 2018). For example, the mechanical properties of soft and hard coal seam vary widely, the stress and displacement distribution in front

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of heading face are different when tunnelling in soft and hard coal seams, and the outburst potential are also different (Skoczylas et al., 2014; Yang et al., 2017). When driving a roadway in a coal seam, the abrupt change of mechanical property of coal is the key factors that lead to the differences in stress distribution and evolution in front of the heading face. Most of the coal and gas outbursts happened at geological zones (Chen et al., 2017a,b; Guo et al., 2017; Zhai et al., 2016), because the coal and rock properties around the geological zone is heterogeneous distribution. For example, the mechanical property of the coal seam near a fault is different (Wesolowski, 2016), and the coal seam suddenly thickened area, magma intrusion area, local temperature rise area and so on have shown great heterogeneity (Kong et al., 2016).

The stress distribution and evolution in front of the heading face can be calculated according to the mechanical properties of coal and rock (Zhao and Zhang, 2015). At present, we only know that the mechanical properties of coal seams have an influence on the roadway stress characteristics, but there are many kinds of mechanical properties of coal seam. For example, when using Mohr-Coulomb failure criterion, it is necessary to provide mechanical properties such as elastic modulus, Poisson ratio, cohesion, internal friction angle, tensile strength, density of coal and rock (Alfarge et al., 2017). However, how do these mechanical properties and their abrupt change affect the stress displacement distribution in front of the heading face? And which one has the most significant impact? We are still not clear. The traditional understanding stays at the macro level, and has not been in-depth analysis of the specific mechanical parameters on the impact of the roadway stress. This is very unfavorable for the accurate evaluation of the stress distribution and evolution.

Numerical simulation is effective some times in underground engineering, but it's difficult to determine the accurate mechanical properties of coal and rock. First, the mechanical properties of coal seam are difficult to determine in situ, most of the properties are tested in laboratory by standard specimen (Boutrid et al., 2015; Chang et al., 2015). These standard specimen can't fully reflect the cracks, joints and other structures in coal and rock layers, so it is difficult to accurately get the actual mechanical properties of the coal and rock layers by the lab experiment (SEO et al., 2016). In addition, soft coal is difficult to be produced as a standard specimen. In order to make the numerical simulation more accurate, we have to adjust the parameters to make the simulation results closer to the reality. But there are many kinds of parameters in numerical simulation, and how to adjust parameters is more effective. Therefore, the setting of mechanical properties of coal and rock layers has not been well solved. The study in this paper will provide the results.

In this paper, a numerical model is built to simulate a roadway driving in coal seam. We systematically study how does the mechanical properties of homogeneous coal seam affect the stress and displacement distribution in front of the heading face? And which is the most significant? Then we study how does the abrupt change of the properties of coal seam affect the stress and displacement distribution in front of the heading face? And which is the most significant? The results will provide theoretical guidance for the prediction and prevention of coal and gas outburst. And the results will also provide reference for the determination of mechanical properties in numerical simulation.

2. Research methods

FLAC^{3D} is a three-dimensional explicit finite-difference program for engineering mechanics computation, simulating the behavior of three-dimensional structure built of soil, rock or other materials that undergo plastic flow when their yield limits are reached (Yang et al., 2012). The Mohr-Coulomb model is the conventional model used to represent shear failure in soils and rocks, and many models such as strain-hardening/softening model and ubiquitous-joint model are based on the Mohr-Coulomb model (SEO et al., 2016; Cheng et al., 2017). In this paper, the FLAC^{3D} with the Mohr-Coulomb model is applied to simulate the stress and displacement distribution and evolution in front of the heading face when tunnelling in a coal seam. The model is shown in Fig. 1, the red points with coordinates are used to mark the key position. The center of the model is the location of the origin of the coordinates. The model length is 80 m, along X coordinates from −35 to 45 m. The width is 66 m, along the Y direction from −33 to 33 m. The model height is 66 m, along the Z direction from −33 to 33 m. The thickness of the coal seam is 3.2 m. The roadway height is 3.2 m, and the width is 4.8 m. The roadway drives along the X coordinates from −35 to 0 m. The model contents 788,544 zones and 815,625 grids. In this model, the boundary effect is fully considered. The boundary effect is reduced by increasing the thickness of the surrounding rock. The roller boundary is applied to the bottom and four side faces of the model, the grids can slide on the plane, but can't leave it. The stress boundary is applied on the top.

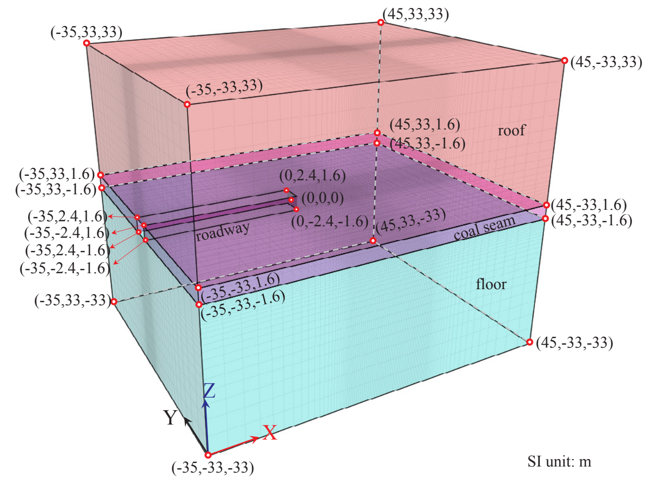

Fig. 1. Numerical calculation model and the key point coordinates (SI unit: m).

When Mohr-Coulomb criterion is used in the model, the elastic modulus, Poisson ratio, internal friction angle, cohesion, tensile strength and density of coal and rock layers need to be assigned. In order to study how the mechanical properties affect the stress and displacement in front of the heading face, the standard mechanical properties of the coal seam and rock are determined firstly (Table 1). The mechanical parameters of the standard coal and rock cannot be too large or too small. Therefore, we can analyze how the stress distribution changes when a certain mechanical parameter become larger or smaller. In this paper, the mechanical parameters of standard rock and standard coal are determined based on the numerical simulation in references and personal experiences (Yang et al., 2012, 2018; Wesolowski, 2016). The numerical calculation and analysis can be carried out under the condition of standard parameters, and also provide a large scope for the change of some mechanical parameters. Then, the influence of mechanical properties can be studied by changing only one mechanical property of the standard coal seam. The research program is shown in Table 1. For example, by changing elastic modulus, we can get 5 kinds of research schemes (No.2–No.6), together with standard coal seam and rock (No.1), there are 6 kinds of comparative research schemes, the elastic modulus varies between 0.5 and 10 GPa.

Note: in Table 1, E is elastic modulus, P is Poisson ratio, T is tensile strength, C is cohesion, F is internal friction angle and σ_0 is original ground stress.

It is also necessary to apply initial stresses in the model. The original ground stress in Table 1 is the initial stress on the z = 0 m plane, negative values indicate compressive stress, the initial stresses at different depth are calculated from the density of the coal and rock. The stress at different depth is calculated by the following formula:

$$\sigma_z = \sigma_0 + \rho g z \tag{1}$$

where z is the depth, (m); σ_z is the stress at z depth, (MPa); σ_0 is the

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