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Discrete element modeling of progressive failure in a wide coal roadway from water-rich roofs

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ABSTRACT

Progressive failure of roadway roofs is a common failure mechanism in underground coal mines, especially when water-rich roofs are in close proximity to the roadway. In this case study at a Chinese coal mine, the UDEC-Voronoi method was used to investigate the process of progressive roof failure in a wide coal roadway from water-rich roofs. In the numerical scheme, the studied domain was partitioned into polygonal blocks bonded through contacts with pre-defined dimensions. The parameters of polygons and contacts in the Voronoi program were calibrated to rock mass properties obtained through laboratory tests. Based upon laboratory tests and previous research findings, a time-dependent strength degradation process from water absorption was assumed and implemented in the numerical modeling. Next, the progressive failure of a roadway from water-rich roofs was analyzed in detail. The numerical results agreed well with field measurements and observations. This method was demonstrated to reproduce the real phenomenon of roof failure in all of its complexity. The numerical results revealed that the progressive failure mechanism was characterized by an initial fracturing of the roof due to strength degradation, which was followed by significant dilation as fractures grew. The large span of the roadway further contributed to the roof failure process. The results also clearly showed that shear cracks were predominant in the roof and played a major role in the behavior of the roadway roof. Additionally, support and excavation schemes that affect roof stability were observed.

1. Introduction

Underground structures are subject to weathering (e.g., action of water) that can degrade their mechanical strength and may eventually lead to excavation instability (Kasim and Shakoor, 1996; Parise and Lollino, 2011). The rate of strength degradation with time is a major factor governing the instability process (Castellanza et al., 2008). As a result, understanding the time-dependent strength degradation and associated behavior are essential to the safety evaluation of underground structures.

The strength degradation process is time dependent and can occur over months or years or within days (Molinda and Klemetti, 2008). Fig. 1 shows a roadway roof fall in the Majialiang coal mine. During roadway tunneling, groundwater infiltration is common, as shown in Fig. 1(a). Numerous laboratory tests have revealed that water absorption has a negative influence on rock strength (Poulsen et al., 2014; Wasantha and Ranjith, 2014; Zhang and Gao, 2015), especially for rocks like argillite, mudstone and silty sandstone. These rocks are common around the underground excavation of some coal mines (He et al., 2014; Ma et al., 2015). Water inflow not only weakens the rock mass strength, it reduces the bond strength of rock bolts and anchor cables (Gou et al., 2004), reducing their effectiveness. Moreover, water invasion can occur if the excavation-induced fractures connect with the roof aquifer. This can lead to roof failure with large deformation, as shown in Fig. 1(b), or, in severe cases, make the roof fall.

It is very difficult to study these complex progressive failures with theoretical methods. Instead, numerical methods are generally used. Continuum methods have been widely used for simulating the progressive failure of undersurface excavations (Parise and Lollino, 2011; Tang, 1997; Yang et al., 2012). However, it is difficult to explicitly capture the fracture generation, propagation and coalescence or to directly incorporate pre-existing discontinuities in a continuum model.

In contrast to continuum models, the discrete element method (DEM) can explicitly simulate the fracture and failure process of an underground excavation (i.e., roof collapse). The Universal Distinct Element Code (UDEC) is one of the most commonly used DEM software programs. UDEC has been utilized to mimic progressive fall of roadway and longwall mining (Alejano et al., 2008; Vakili and Hebblewhite, 2010), but the limitation of this model is that it only allows fracture development along pre-defined discontinuities. To overcome this limitation, the UDEC-Voronoi approach was adopted (Chen et al., 2015; Damjanac et al., 2007; Gao et al., 2014). This approach has been

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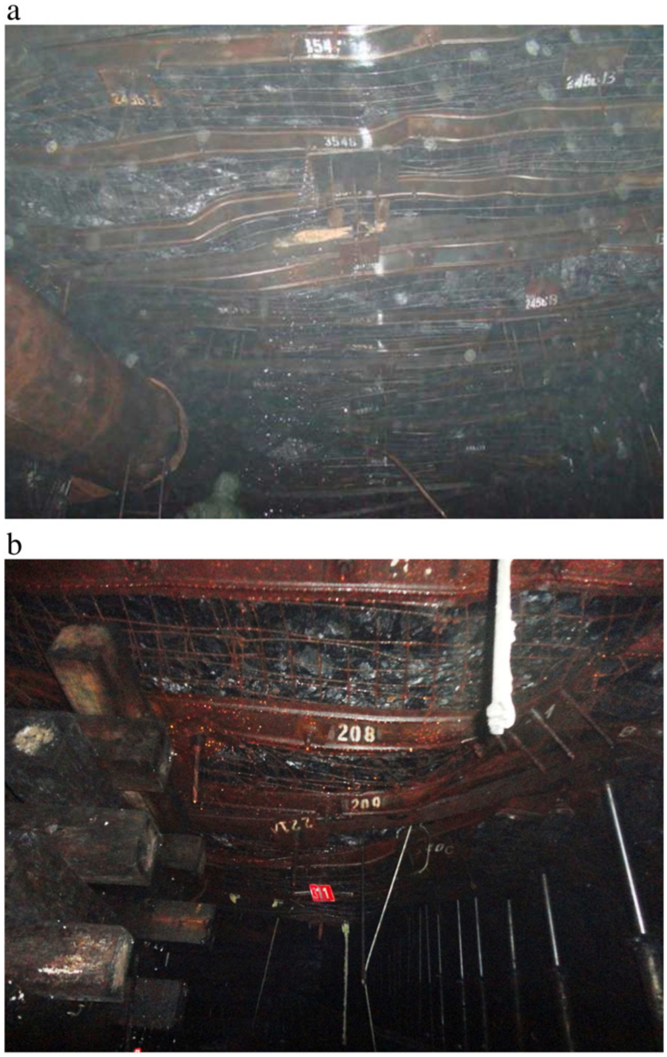

Fig. 1. Roof conditions of the roadway at Majialiang coal mine, (a) groundwater infiltration during roadway tunneling, (b) roof deformation and failure.

modified to solve discrepancies between simulations and field observations or laboratory tests (Gao and Stead, 2014).

In this paper, based on a case study at a Chinese coal mine, we present a DEM numerical approach to investigate the progressive failure of a wide coal roadway from water-rich roofs. In the numerical scheme, the studied domain was partitioned into irregular polygonal blocks that are bonded through contacts with pre-defined dimensions. The parameters of polygons and contacts in the Voronoi program were calibrated to the rock mass properties obtained through laboratory tests. Based upon laboratory tests and previous research findings, a time-dependent strength degradation process was assumed and implemented in the numerical modeling. The numerical results were calibrated against field measurements and observations. The aim of this study is to understand the roof progressive failure mechanism of the wide coal roadway. Support and excavation schemes that affect the roof stability were also considered. Finally, appropriate ground control techniques are recommended.

2. Description of the study site

This study focused on the progressive failure of a wide roadway in the Majialiang coal mine located in southern of Shuozhou city, in the Shanxi province (Fig. 2(a)). The wide roadway was driven to install mining equipment in the P14201 longwall face (Fig. 2(b)), the second panel at the mine. The width of the roadway was 9.0 m and length was 250 m in the working #4 coal seam, as shown in Fig. 2(c).

The coal seam in the study area is 9.8 m thick, and the cover depth is 604 m. Rock strata above the coal seam consist of siltstone, K5 sandstone, mudstone, #3 coal seam and a thick interbedded layer of fine siltstone and mudstone. The floor layers below the coal seam consist of mudstone, #5 coal seam, siltstone, and sandstone. A stratigraphic column from a geological bore near the roadway is illustrated in Fig. 3.

A series of laboratory tests were conducted to obtain the mechanical properties of these coal measures (Table 1). The RQD values of the coal measure rock masses were evaluated from borehole endoscopic measurements. For this, the intact rock deformation modulus was converted to rock mass properties by considering the RQD value (Zhang and Einstein, 2004):

$$E_m/E_r = 10^{0.0186RQD-1.91} \tag{1}$$

where E_m and E_r are rock mass and intact rock deformation moduli, respectively.

The rock mass strength was then calculated according to the deformation modulus ratio E_m/E_r:

$$\sigma_{cm} = \sigma_c \times \left(\frac{E_m}{E_r}\right)^n \tag{2}$$

where σ_{cm} and σ_c are rock mass and intact rock strength, respectively. The rock mass properties are listed in Table 1.

There is an aquifer in close proximity to the #4 coal seam (Fig. 3), which is mainly located within K5 sandstone (Zhang et al., 2013). The water pressure in the aquifer is much lower than the in-situ stress. Therefore, in the present study, the aquifer pressure was not considered, while the water-induced strength degradation of the rock mass was taken into account.

3. Numerical simulation using DEM

3.1. Rock property calibration

Many studies have shown that the 2D Voronoi model in UDEC reliably simulates rock mechanical responses in both laboratory tests and field observations (Damjanac and Fairhurst, 2010; Gao, 2013; Kazerani et al., 2012; Lan et al., 2010). In this numerical model, the studied domain is partitioned into polygons of pre-defined dimensions that depend on the size of the studied area. Deformable and rigid polygons are available in UDEC. However, individual polygons cannot break, i.e., all fractures must follow polygonal boundaries.

The cemented contacts between two polygons can rupture through shear or tension depending on the stress state and properties of the contact surface. Therefore, fracture development can be realistically simulated through the contact rupture initiation, growth and nucleation. The force-displacement relationship for a contact is determined by normal (K_n) and shear (K_s) stiffness of the contact. The contact properties, cohesion and tensile strength and friction angle define the contact strength. Fractures are created when the stress level at the interface exceeds a threshold value in either the tension or shear. The constitutive contact model is shown in Fig. 4.

The behavior of the model is controlled by parameters that can be divided into the following two groups (Christianson et al., 2006): (1) parameters that control the model's strength - friction angle, tensile, and cohesion strengths and (2) parameters that control the model's elastic constants - bulk and shear modulus of the blocks as well as normal and shear stiffness of the polygonal contacts. Therefore, when this method is used to analyze the mechanical responses of rock, appropriate parameters should be determined to ensure the model represents the mechanical behavior of the rock mass. In this paper, a known