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Influence of fault slip on mining-induced pressure and optimization of roadway support design in fault-influenced zone

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ABSTRACT

This paper presents an investigation on the characteristics of overlying strata collapse and mining-induced pressure in fault-influenced zone by employing the physical modeling in consideration of fault structure. The precursory information of fault slip during the underground mining activities is studied as well. Based on the physical modeling, the optimization of roadway support design and the field verification in fault-influenced zone are conducted. Physical modeling results show that, due to the combined effect of mining activities and fault slip, the mining-induced pressure and the extent of damaged rock masses in the fault-influenced zone are greater than those in the uninfluenced zone. The sharp increase and the succeeding stabilization of stress or steady increase in displacement can be identified as the precursory information of fault slip. Considering the larger mining-induced pressure in the fault-influenced zone, the new support design utilizing cables is proposed. The optimization of roadway support design suggests that the cables can be anchored in the stable surrounding rocks and can effectively mobilize the load bearing capacity of the stable surrounding rocks. The field observation indicates that the roadway is in good condition with the optimized roadway support design.

1. Introduction

Fault is a tectonic fracture in the Earth's crust along which slippage has taken place (Bryant, 2013). It can be classified as normal, reverse and strike-slip types according to the direction in which the relative movement of hanging wall and footwall has taken place. Due to the significant stress redistribution, irregular deformation of rock masses and a large amount of elastic energy accumulated around reverse fault plane, most major catastrophic fault slip had occurred around the world (Castro et al., 2009; Orlic and Wassing, 2013; Jiang et al., 2014). The fault slip mainly refers to a sudden and intense fault slip induced by extraction of longwall panel in coal mining industry, which could cause significant damage to mine openings where men and machinery are present. Therefore, prediction and prevention of fault slip have been major safety concerns for long-term mine safety and productivity in underground coal mines.

Numerous studies have been conducted to obtain a comprehensive understanding of fault slip. Firstly, the prediction and prevention of fault slip must take into account the fault geometry and associated structures. The imaging and mapping of fault structure therefore play a significant role in investigating fault slip. Based on this idea, a high-resolution seismic reflection technique was used by Gochioco and Cotten (1989) to locate faults in coal mines. In their work, several faults were detected and interpreted from the seismic section and the displacement of faults was estimated additionally to design a safer and more productive coal mine in the faulted zone. Kecojevic et al. (2005) presented a computer mapping for multiple coal seams and multiple reverse faults in Columbia using MineScapek geological modeling software, and pointed out that the effective mapping of faults in coal mining is critical for reasons of economics and safety. In order to obtain a three-dimensional (3D) and visual fault model, Scheidhauer et al.

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(2005) developed an efficient 3D high-resolution seismic reflection system in Switzerland. Furthermore, Peng et al. (2008) and Du et al. (2015) developed a 3D seismic integrated interpretation system to investigate the distribution of primary fault structure in Guqiao coal mine in China. Similarly, Hlousek et al. (2015) presented an investigation of a 3D seismic survey acquired near Schneeberg in the western Erzgebirge.

Deep mining conducted under tectonic stress conditions induced by the fault reactivation or fault slip could lead to the occurrence of coal bumps. According to Jiang et al. (2014) and Jiang (2014), occurrence of serious coal bumps in Yima mining district in 2011 in China could be explained as a consequence of the intensive compressive stress imposed during the reactivation process of fault F16. Therefore, many efforts have been made for better understanding of the mechanism of fault reactivation. Based on the large amount of survey data obtained from several coal mines with faults in the US, Wallace and Morris (1986) conducted a review work and pointed out that the fault surface was absolutely not a planar and the irregularities characteristics would constraint the study of the fault slip. Therefore, the characteristic of fault reactivation is significantly correlative with the roughness of fault surface. Recently, Sainoki and Mitri (2014a,b, 2015) conducted a series of researches to simulate the effect of fault slip with various methods. In their works, the influences of mining depth, friction angle, dilation angle and stiffness of fault on the fault slip were investigated. In addition, the fault-surface roughness and slip weakening behavior were also studied to estimate the fault slip intensity by the $FLAC^{3D}$ code. Also, Jain et al. (2013) focused on the fault angles to simulate the fault reactivation phenomenon.

In the past decades, occurrence of coal bumps induced by the fault slip has been increasing due to the increasing mining depth and concentrated tectonic stress. Hence, the collection of precursory information for the fault slip is imperative in the controlling and prevention of coal bumps. According to Jiang et al. (2013), the high-risk fault slip could be determined by the sharp increase of normal and shear stresses monitored in and around the fault plane. Singh et al. (1998), Vishal et al. (2012), and Tripathy and Singh (2016) conducted a series of rock slip tests to obtain the value of critical velocity to study the transformation of the stick slip motion to steady motion. Considering the potential coal bumps risk induced by the coupling effect of fault and coal pillar, Li et al. (2014) pointed out that the occurrence of coal bumps in the fault and pillar areas was induced by the concentration of static stress on the pillar and the dynamic stress induced by fault reactivation. Besides, the monitoring of seismic event was proved to offer significant insights into the fundamental nature of the coal bumps (Cook, 1964; Ortlepp, 2002; McKinnon, 2006; Li et al., 2011; Singh et al., 2012; Jain et al., 2013). The incorporated microseismic and mining-induced pressure prediction system (Jiang et al., 2011; Liu et al., 2014) and distributed microseismic monitoring system (Dou et al., 2012; Cai et al., 2014) are effective for predicting the fault slip over the past decades in China.

As mentioned above, a large number of experimental studies, numerical investigations and field tests have been undertaken for characterizing the fault geometry and associated structures, analyzing the mechanism of fault reactivation and predicting the fault slip induced by mining activities. However, there are few studies on the influence of the multi-fault structure on the mining-induced pressure and obtaining a representative characteristic of deformation of overlying strata under dynamic pressure in the fault-influenced zones to optimize roadway support design. In addition, the studies of characteristic of mining-induced pressure with and without fault influences are also rarely reported. Therefore, in order to further optimize the roadway support design system for the fault-influenced zone, a physical model with two fault structures is established according to the geological conditions of an underground coal mine in Shanxi Province, China. The studies of mining-induced pressure in the uninfluenced and fault-influenced zones are conducted to characterize the overlying strata collapse. An optimization of roadway support design for fault-influenced zones is carried out to maintain the roadway stability and the field tests are conducted to verify the effectiveness of roadway support design.

2. Background of coal mine

2.1. Mining site

The physical model is established according to the geological setting of Zhengli underground coal mine in Shanxi Province, China. In addition, the field test is also conducted in this site. The Zhengli coal mine has an annual production of 1.5 million tons of raw coal. The mining site of Zhengli coal mine is 5 km long along the north-south direction and 3.2 km wide along the east-west direction, covering a total mining area of 9.26 km^2. Fig. 1 presents the mining layout of mining area #1 of Zhengli coal mine. There are four mineable coal seams in this coal mine. The coal seam #4^{-1} is being mined currently with a dip angle of 9° and an average mining height of 3.9 m. The surrounding rocks mainly consist of mudstone, sandy mudstone, fine-grained sandstone, and medium-grained sandstone. The general stratigraphy of this mine is shown in Fig. 2. The mine currently uses the longwall mining method at the depths from 645 m to 720 m below the ground surface.

2.2. Geological setting of main studied area

A major research project undertaken recently by China University of Mining & Technology, Beijing (CUMTB) in collaboration with Zhengli coal mine is to characterize the mining-induced pressure influenced by the fault structure. As shown in Fig. 1, based on the geological conditions of the haulage roadway of longwall panel #14^{-1}103 in mining area #1, the physical model is established and the field test is conducted. Since the mining panel #14^{-1}103 is being mined, the haulage roadway is in service under dynamic pressure. It has an overburden depth of 650 m, and is 1589 m long along the strike direction and 180 m wide along the dip direction. The mining coal seam is about 4 m thick. The geological core log of the surrounding rocks shows that the main roof is fine-grained sandstone with an average thickness of 5.4 m and uniaxial compressive strength of 41 MPa. The panel floor is composed of mudstone and is approximately 3.6 m thick. The roadway is of rectangular shape with a width of 4.5 m and height of 2.8 m. The roof support system in the roadway consists of bolts, cables and steel mesh. Fig. 3 shows the layout of the original support design of haulage roadway for longwall panel #14^{-1}103 with detailed support parameters.

The presence of seven faults (Table 1) has been predicted in mining area #1 before the mining of Zhengli coal mine begins by means of drilling and electromagnetic radiation exploration. Among these faults, faults F36 and F37 located in longwall panel #14^{-1}103 are the major geologic disturbance that greatly interrupt coal seam and severely interfere the mining operation. With the influence of the two faults, several accidents occurred in the process of mining and are summarized as follows: (1) Since the presence of faults could weaken the roof and ribs of roadway, the sudden and severe roof collapse have taken place for many times; (2) Since the dynamic pressure induced by the coupling effect of mining activities and fault reactivation is imposed on the original support system, many bolts have been damaged. Therefore, the influence of fault structure on the mining-induced pressure should be understood and the support design should be specially optimized for the fault-influenced zone.