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Development of a time-dependent energy model to calculate the mining-induced stress over gates and pillars

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ABSTRACT

Generally, longwall mining-induced stress results from the stress relaxation due to destressed zone that occurs above the mined panel. Knowledge of induced stress is very important for accurate design of adjacent gateroads and intervening pillars which helps to raise the safety and productivity of longwall mining operations. This study presents a novel time-dependent analytical model for determination of the longwall mining-induced stress and investigates the coefficient of stress concentration over adjacent gates and pillars. The model is developed based on the strain energy balance in longwall mining incorporated to a rheological constitutive model of caved materials with time-varying parameters. The study site is the Tabas coal mine of Iran. In the proposed model, height of destressed zone above the mined panel, total longwall mining-induced stress, abutment angle, induced vertical stress, and coefficient of stress concentration over neighboring gates and intervening pillars are calculated. To evaluate the effect of proposed model parameters on the coefficient of stress concentration due to longwall mining, sensitivity analysis is performed based on the field data and experimental constants. Also, the results of the proposed model are compared with those of existing models. The comparative results confirm a good agreement between the proposed model and the in situ measurements. According to the obtained results, it is concluded that the proposed model can be successfully used to calculate the longwall mining-induced stress. Therefore, the optimum design of gate supports and pillar dimensions would be attainable which helps to increase the mining efficiency.

1. Introduction

With the development of the mechanized longwall mining methods, underground coal mining has been improved from both production and productivity points of view. However, there are still certain risks in mining that can result in unacceptable level of safety. Generally, one of the hot issues relates to roof fall and ground control (Peng, 1986). Knowledge about the level of stress in a rock mass is very important for underground mining, because many underground mining problems involve stress determination in order to provide the safety considerations. However, determination of stress level in the surrounding rock mass of underground openings is a complex task associated with the geological conditions, the mechanical properties of rocks, the state of in situ stresses, and so on. Indeed, design of a system in rock mass needs to answer a number of questions related to the mechanical behaviors of material, such as fracture, yield, fatigue, stress, and creep (Singh and Verma, 2005).

In the case of longwall mining, accurate estimation of stress level in surrounding rock mass is important for the stability analysis and evaluation of optimum shape and support requirements for longwall panels and side entries (Peng, 2006). However, there are a number of factors that influence the stress distribution around a mined panel. Before the longwall panel extraction, the weight of overburden is uniformly distributed over the coal seam with the relatively strong roof and floor rocks. After the coal seams extraction within a considerable panel width, the roof rock strata fractured and then caved. This process causes disturbance of the original equilibrium conditions. However, potential energy balance requires that the stress distribution in the area has to be readjusted in order to reach a new equilibrium state. As a result, a destressed zone occurs in the panel roof rock strata and the load previously supported by the extracted material is transferred to the surrounding gates and pillars (Peng, 1986). Generally, the caved and fractured zones are at least partially destressed. Accordingly, the overburden weight above the combination height of the caved and fractured zones (height of destressed zone) is shifted to the neighboring solid sections. Indeed, the induced stress is determined by the difference between the weight of the overburden and the weight of destressed zone.

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There are several methods for evaluation of the stress distribution around a longwall panel, i.e. in situ measurement, laboratory physical simulation, numerical modeling, and analytical modeling. In situ measurements and laboratory physical simulation are time-consuming, difficult, and expensive (Jiránková et al., 2012). Numerical modeling is a commonly used method to evaluate stress distribution around underground openings. However, it is time-consuming and requires a large number of input variables. The later limitation depends on the available measured data and may need some estimations or assumptions (Suchowerska et al., 2012). Analytical modeling is a simple and inexpensive method that includes the useful and reliable results in most cases.

In the present study, a new time-dependent analytical model is developed to determine the mining-induced stress and the coefficient of stress concentration (ratio of secondary to primary stress) over gates and pillars based on the strain energy balance in longwall mining. For this purpose, the height of destressed zone above the mined panel is firstly calculated in long-term condition. Then, based on the back-calculated abutment angle, stress transferred to the gates and pillars is determined. The theoretical analysis in this research is supplemented by a specific example of model application to calculate the coefficient of stress concentration over gates and pillars in Tabas coal mine of Iran.

2. Stress distribution around longwall panel

Due to the extraction of the coal seam in longwall mining, state of stress equilibrium in the surrounding rock mass is disturbed and the stress redistribution occurs. The portion of the overburden weight over the destressed zone that is not supported by the extracted area (goaf) is transferred to the adjacent solid abutments, such as gates and pillars. This stress is transferred due to longwall mining and called "mining-induced stress". In the past, a number of attempts to utilize field observations, theoretical, empirical and numerical approaches were made to understand the nature and amount of mining-induced stress variation in and around an underground excavation due to longwall mining. Considering an infinite, elastic, isotropic and homogenous nature of coal measure formations, Salamon (1964) developed an analytical equation to evaluate the stress distribution at the edge of a longwall panel. Whittaker and Singh (1979) concluded that the peak abutment stress ranges from 4 to 5 times the cover load for UK longwall mining conditions. Wilson (1982) studied the extent of the induced stress zone and found that the cover pressure distance for the safer pillar design conditions is equal to 0.3 times the working depth. Peng (1986) showed that the peak abutment stress is in the range of 1.5–5 times the cover load. Based on the field measurement and numerical modeling, Majdi (1988) developed an empirical equation to calculate the coefficient of stress concentration due to longwall mining. Trueman (1990) proved that the distance at which cover pressure is reached in the goaf is the function of extracted seam thickness and bulking factor of the immediate roof rock strata.

Majumder and Chakrabarty (1991) found that the mining-induced stress increases with the decreasing extracted seam thickness. Mark (1990) developed an equation to estimate the abutment load during final extraction of coal based on the concept of abutment angle which is known as analysis of longwall pillar stability (ALPS). Sheorey (1993) showed that the peak stress around the longwall face will reduce to the cover pressure at a distance of 0.12 times the working depth. Taking into account the typical values of geometric parameters and rock mass properties, Heasley (1998, 2000) considered homogenous stratification of overburden to derive an analytical equation in order to calculate the induced abutment stress. Based on the numerical modeling, Toraño et al. (2002) proved that the coefficient of stress concentration over the roadways is approximately 2.3 times the cover pressure. Yavuz (2004) demonstrated that an increase in mining height causes increase in cover pressure distance. According to field measurements and laboratory investigations conducted by Jayanthu et al. (2004), the maximum vertical stress over rib and stook decreases with increase in working height during depillaring. Based on the numerical modeling, Yasitli and Unver (2005) proved that the front abutment pressure increases to 14.4 MPa and then decreases gradually toward the initial field stress value (5.75 MPa). According to in situ measurements conducted by Ouyang et al. (2009), the maximum mining-induced stress is equal to 17.5 MPa (the related coefficient of stress concentration is equal to 1.85). By using the numerical modeling, Singh and Singh (2010) showed that the maximum induced stress is equal to 12.1–19.9 MPa in different situations.

Yang et al. (2011) studied the stress evolution with time and space during longwall coal mining. They showed that the maximum abutment stress is approximately 1.67–2 times the original one when the coal seam is mined 20–30 m. The finite element modeling performed by Khanal et al. (2011) demonstrated that the maximum induced vertical pressures is approximately 4 times the in situ pre-mining stress. By using the numerical modeling, Yu et al. (2011) found that the vertical stress over the roadway varies from 13 MPa to 17 MPa (the related coefficient of stress concentration is equal to 1.95–2.55). Xie et al. (2011) performed field monitoring using stress sensors and showed that the maximum stress concentration factors of the stope side and tunnel side are 1.24 and 1.08, respectively. Likar et al. (2012) found that the maximum coefficient of stress concentration around a longwall panel is equal to about 1.8, 2.1, and 1.7 obtained from the in situ measurement, mathematical and numerical modeling, respectively. Khanal et al. (2012) proved that the front abutment stress can reach 15 MPa and the vertical stress on chain pillar can be seen to reach as high as 27 MPa. By using the numerical modeling, Song et al. (2012) found that the maximum stress of ore pillar comes up to 13.4 MPa that is 8.5 MPa greater than the original one. Accordingly, the coefficient of stress concentration over the ore pillar is 2.73. Numerical study conducted by Dattatreyulu et al. (2012) revealed that the vertical stress in the chain pillar can be more than 40 MPa, i.e. more than 4 times the in situ pre-mining stress. According to numerical study conducted by Shabanimashcool and Li (2013), the maximum vertical stress in the pillar is about 3.2 times the in situ vertical stress. Based on the numerical study, Jia et al. (2013) indicated that the maximum mining-induced stress over the pillars is 2.87 times the original stress. According to field measurements performed by Guo et al. (2013), the maximum induced principal stress is close to horizontal one and its value is 1.5–1.7 times the gravitational stress. Verma et al. (2013) studied the effect of excavation stages on stress and pore pressure changes for an underground nuclear repository using three-dimensional (3D) finite difference method. They found that the vertical stress changes during different excavation stages. Gao et al. (2014) proved that the maximum induced vertical stress is approximately 61.6 MPa, corresponding to 2.3 times the overburden stress.

According to the above-mentioned works, there are some analytical equations to evaluate the stress distribution around a longwall panel, as shown in Table 1. Also, the coefficients of stress concentration around a longwall panel obtained by the available analytical, numerical and empirical models as well as in situ measurements presented by different researchers are given in Table 2.

3. Energy considerations in longwall mining

Extraction of coal seam in the longwall mining causes disturbance of the energy balance within a system enclosing mine