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Assessment of energy release mechanisms contributing to coal burst

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ABSTRACT

Coal burst is a dynamic release of energy within the rock (or coal) mass leading to high velocity expulsion of the broken/failed material into mine openings. This phenomenon has been recognised as one of the most catastrophic failures associated with the coal mining industry, which can often lead to injuries and fatalities of miners as well as significant production losses. This paper aims to examine the mechanisms contributing to coal burst occurrence, with an emphasis on the energy release concept. In this study, a numerical modelling study has been conducted to evaluate the roles and contributions of difference energy components. The energy analysis presented in this paper can help to improve the understanding of energy release mechanisms especially under Australian conditions.

1. Introduction

Coal burst is one of the most hazardous problems encountered in underground coal mines, which occurs at different locations in a variety of mining systems and operations. This phenomenon always involves a violent and dynamic energy release with large rock mass/coal deformation and ejection that can cause severe damage to openings, equipments and may result in fatalities and injuries.

The first coal burst occurrence was reported in Britain in 1738 [1]. Since then, international experiences are available in Canada, South Africa, USA, former Soviet Union, China, India, France, Germany, Poland and Czechoslovakia. Rice classified coal bursts as two general types, namely excessive pressure bumps and shock bumps, and further mentioned that pressure bumps are caused when pillar stress exceeds bearing strength [2]. Shock bumps are induced by the breaking of thick, massive strata at a considerable distance above the coal-bed, causing the immediate roof to transmit a shock wave to the coal.

Coal bursts occur under the effects of complex environments of geology, stress and mining conditions. Various researchers attempted to develop empirical relationships between the identified critical parameters and coal burst proneness, and the phenomenon has been studied from varying perspectives [3–5]. There have been many hypothesised mechanisms discussed as potential driving mechanisms causing coal bursts. From these studies, four critical conditions for the coal burst occurrence can be identified, and the stress environment must be sufficiently high to result in rock failure; a situation must exist which can result in a state of unstable equilibrium [6,7]. This could be a low friction bedding plane, for example, where the potential exists for the coefficient of friction to drop rapidly from its static to dynamic value once movement is initiated along this plane; a change in the loading system and a large amount of energy has to be stored in the system.

It has been recognised that the unstable release of potential energy of the rock mass around the excavations, mainly in the form of kinetic energy, contributes to the coal burst occurrence. Part of this energy is consumed by fracture formation, and the remaining energy is transformed into kinetic energy [8,9]. When the source is located a close approximate to the critical surface, this kinetic energy causes the coal fragments to be ejected. When the source is located in a plane of weakness within the rock mass, the released energy induces shear displacements along the plane, which in turn producing vibrations that induce rock ejections when they reach the excavation boundaries [10].

This paper addresses the energy concepts associated with coal burst phenomenon by conducting analyzes on coal pillars using numerical modelling. ABAQUS/explicit models were developed to model the dynamic behavior of a single pillar under applied quasi-static and dynamic loading. The pillar capacity under both quasi-static and dynamic loading has been assessed and the effects of the pillar width to height (w/h) ratio under different loading conditions have been studied.

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2. Energy based approaches

Energy based approach method is one of the common methods to determine the critical regions in the rock mass/coal structures. Cook et al. are one of the pioneers to consider the effect of the energy changes throughout the mining activities as well as excavations [11]. Salamon describes in great detail several energy quantities that are needed to assess the energy release rate when acting through the induced displacements (W), the strain energy content of the volume (Vm) of the rock to be mined (U'), the change in strain energy in the volume (V) of the system that remains unmined (U), and the total work done by the contact and body forces on the permanent supports (Ws) [12].

The first coal burst mechanism is concerned with the perception of energy release, since the coal burst is caused by a dynamic and unstable release of energy within the excessive stresses in the rock mass (coal) during the mining process. In view of the energy contemplations, there are a variety of energy modules. Potential energy is the stored energy of a place in which held by coal, and there are two forms of potential energy including gravitational potential energy and elastic potential energy. Gravitational potential energy is the function of the vertical position or height. Strain energy is the energy stored in coal, due to deformation, and the external work done on the coal is causing it to alter from its unstressed state, which is usually transformed into strain energy.

In the 1960s, the concept of energy release rate (ERR) was initially used by South African researchers in evaluating rock burst potential for deep hard rock mines. The ERR was found to have a reasonable correlation with the risk or potential of coal bursts through an extensive analysis of the coal burst database. Since 1980s, the ERR was implemented in a range of numerical models to investigate the potential coal bursts. Maleki et al. utilized energy calculations with elastic-plastic models to analyze mining plans for burst-prone mine [13]. Heasley used a strain-softening model for energy calculations applied to coal bumps [14]. Sears and Heasley incorporated ERR into the boundary element code LaModel to analyze potential coal bursts [15]. Recently, Poeck et al. developed an approach to assess the potential for coal bumps in room and pillar mines through the use of energy concepts, focusing on the interface properties between the coal and overlying rock [16]. Using this approach they back analyzed the Crandall Canyon Mine in the United State collapse. Previous research in South Africa found that the level of ERR has a significant correlation with the occurrence of rock bursts and the extent of rock fracturing increases with increasing ERR values [12,17,18].

The major energy factors that should be taken into account to evaluate the possibility of the rock/coal burst occurrences are strain energy, external work done, kinetic energy and internal energy or stored energy, which is extracted by the strain energy and it is not converted to the kinetic energy. In the simplest approach, strain energy + external work = kinetic energy + internal energy. There are also other forces that may contribute to kinetic energy release, such as gas expansion energy, which is not considered in this study.

The above simple equation can present the relationship between the induced energy due to external events, which is illustrated by strain energy, and converted energy which are presented with kinetic energy and internal energy. The proportion of the strain energy and kinetic energy is a significant factor to determine whether the strain energy can be released as a kinetic energy or it would be totally destructive energy.

Eq. (1) is suggested as a benchmark to determine the possibility of stored energy situation, which can help to prevent the coal burst occurrence. In this case, both α and β (where $\alpha \geqslant 2$ and $\beta \geqslant 2$), are mathematical parameters which are fully dependent on the expected accuracy in the suggested analytical approach.

$$\left(\frac{E_{kinetic}}{E_{strain}}\right)^{\alpha} + \left(\frac{E_{internal\ work}}{E_{strain}}\right)^{\beta} = 1 \quad (1)$$

Eq. (1) can be accumulative, due to the effect of the time increments in the dynamic analysis. Given that the impulsive loading is applied throughout the different time increments with the different loading magnitudes, Eq. (1) can be written as:

$$\left(\sum_{i=1}^{i=t}\left(\frac{E_{kinetic}}{E_{strain}}\right)_i\right)^{\alpha} + \left(\sum_{i=1}^{i=t}\left(\frac{E_{internal\ work}}{E_{strain}}\right)_i\right)^{\beta} = k \quad (2)$$

where k is a constant value; and t the maximum number of the time increments.

Therefore, the proportion of $\left(\frac{E_{kinetic}}{E_{strain}}\right)^{\alpha}$ is one of the key factors for determining critical sections. For different mining structural systems, it can be assumed that if the proportion of $\left(\frac{E_{kinetic}}{E_{strain}}\right)^{\alpha}$ is equal or higher than 1, there is less likelihood of coal burst occurrence. The kinetic energy, which is a combination of induced works in different layers which can cause moving layers as well as releasing kinetic energy to the different part of the mining structure, can be presented as:

$$E_{kinetic} = \left(\sum\left(\int(\delta_{xx}\cdot A_{xx}\cdot \varepsilon_{xx}\cdot l_x)dx + \int(\delta_{yy}\cdot A_{yy}\cdot \varepsilon_{yy}\cdot l_y)dy + \int(\delta_{zz}\cdot A_{zz}\cdot \varepsilon_{zz}\cdot l_z)dz\right)\right)$$

where $\delta_{xx}, \delta_{yy}, \delta_{zz}$ are the stress components in the different directions; A_{xx}, A_{yy}, A_{zz} the effective area in the different directions; $\varepsilon_{xx}\cdot l_x$ the amount of slip in x direction; $\varepsilon_{yy}\cdot l_y$ the amount of slip in y direction; $\varepsilon_{zz}\cdot l_z$ the amount of slip in z direction.

The factor of $\left(\frac{E_{kinetic}}{E_{strain}}\right)^{\alpha}$ can be represented by:

$$\left(\frac{E_{kinetic}}{E_{strain}}\right)^{\alpha} = \left(\sum\left(\frac{\int(\delta_{xx}\cdot A_{xx}\cdot \varepsilon_{xx}\cdot l_x)dx}{E_{Strain}}\right) + \sum\left(\frac{\int(\delta_{yy}\cdot A_{yy}\cdot \varepsilon_{yy}\cdot l_y)dy}{E_{Strain}}\right) + \sum\left(\frac{\int(\delta_{zz}\cdot A_{zz}\cdot \varepsilon_{zz}\cdot l_z)dz}{E_{Strain}}\right)\right)^{\alpha} \quad (3)$$

Eq. (3) indicates how the slip in different directions can play a key role in releasing the stored energy in the different layers. The amount of the slip between the layers is partially either dependent on the joint properties or structural confinement in the free edges (for instance, the presences of geological structures such as faults, dykes, sandstone channels, and joints). Underground excavations can result in stress concentration as well as stress redistributions on to face and adjacent pillars. Due to the complexity of the causes and mechanisms contributing to coal burst occurrence, a comprehensive 2D and 3D finite element (FE) modelling study has been conducted to numerically evaluate the accuracy and the validation of the above analytical assessments of coal burst occurrence.

3. Numerical modelling strategy

Numerical modelling can provide valuable insight into potential failure modes and bearing capacity in a given mine setting. It is particularly useful for undertaking parametric and sensitivity analyzes to better understand the nature and level of uncertainty, or residual risk, associated with design procedures. The current state of knowledge, albeit incomplete, can also be exploited to manage risk by undertaking a comparative risk assessment. In the current study, a quarter of a single pillar was developed (Fig. 1).

Furthermore, Fig. 2 presents the full geometrical details of the developed model. A surface to surface contact was assigned between engaged surfaces to simulate the interaction between the coal and the rock. Thus, both the overburden and the roof were