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A new energy index for evaluating the tendency of rockburst and its engineering application

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ABSTRACT

Based on energy-transfer analysis of triaxial unloading tests under four different controlling conditions, the rock burst energy release rate (RBERR)-an energy index combining the local energy release rate (LERR) and the limit energy storage rate (LESR), was proposed. LERR refers to the values of the elastic strain energy release of an element after brittle failure, which indicates that RBERR > 0 can be used to determine whether the element belongs to an excavation damage zone. RBERR was implemented to simulate the evolution process of rock damage and failure with advancing excavation face. The results predicted using RBERR were consistent with those obtained from an actual rockburst. In addition, a synthesis method based on microseismic (MS) monitoring information and RBERR simulation analysis was implemented for the Huainan coal mine. A study on the spatial-temporal evolutional laws of MS events built relationships between MS monitoring information and excavation process and; consequently, the potential danger areas of rockburst were determined. RBERR was used to analyze the location and intensity of rockburst in potential danger areas, which could be valuable in the design of rockburst- resistant measures in deep- buried construction.

1. Introduction

Rockburst is a hackneyed type of unstable geological hazard in high initial geostress areas, which is always induced by excavation unloading and constitute a serious threat to the safety of personnel and equipment during construction (Chen et al., 2012; Li et al., 2012; Yan et al., 2015; Zhao et al., 2016). Different degrees of rockbursts occurred in underground engineering construction in China, such as Tianshengqiao, Ertan and Jinping. It has become one of the main technical bottlenecks limiting the construction of deep- buried structures. Studies on the mechanism and prediction of rockburst, have great engineering significance, which can offer scientific solutions for improved safety during construction (He et al., 2007; Zhang et al., 2011; Gong et al., 2012; Fan et al., 2015).

Based on different mechanisms, rockburst can be categorized into strainburst, buckling, face crush/pillar burst, shear rupture, and fault-slip burst (Ortlepp and Stacey, 1994). In a broad sense, buckling type rockburst is regarded as strainburst, and shear rupture type rockburst is regarded as fault- slip rockburst. Many factors are at play in the mechanism of rockburst, including seismic event, geology, geotechnical, and mining. In order to study rockburst mechanisms, a series of laboratory tests have been carried out in recent years. Li et al. (2016) investigated the impact failure characteristics of rock subjected to coupled static and dynamic loads using a modified split-Hopkinson pressure bar (SHPB). Cho et al. (2005) conducted rock dynamic tensile tests to investigate the fracturing process of rock samples under dynamic loading. Gu et al. (2014) conducted similar material model tests of ejective rockburst, and found that ejective rockburst is caused by energy supplements on rockburst body from surrounding rock. In order to study the shear failure characteristics of structural planes, Meng et al. (2016) conducted direct shear experiments using model materials, and found that structural planes played a decisive role in fault- slip rockburst. A valid method to highlight rockburst behavior and mechanism is by investigating the course of rockburst under unloading disturbance and this can be achieved using triaxial unloading test. A series of rockburst tests were performed using the rockburst simulating system of China University of Mining and Technology, Beijing. He et al. (2015) conducted static unloading tests and dynamic loading tests to investigate the inoculation mechanism, failure characteristics and occurrence conditions of rockbursts under different circumstances.

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In essence, rockburst is the sudden release of elastic strain energy stored in rock mass under excavation unloading. The stress-strain state of rockburst is, in a sense, uncertain. Because of this uncertainty, it is difficult to determine a reasonable stress criterion to predict rockburst. Furthermore, rockburst is a dynamic destabilizing phenomenon driven by energy. Based on the energy- transmitted rule in the process of rock failure, an energy criterion for rock failure, can be applied to investigate dynamic characteristics and to evaluate rockburst. So far, many scholars (Cai et al., 2001; Hajiabdolmajid et al., 2002; Xie et al., 2004) have studied dynamic mechanical behavior on the basis of energy theory, and have recorded significant success, which will be useful for disaster warning in underground construction. Jaeger and Cook (1966) pointed out that failure criterion based on stress state cannot indicate whether catastrophic failure or progressive failure occurred. They indicated that the energy- transmitted process induced by excavation must be taken into account when assessing the stability of underground construction. While investigating the rockburst in South African gold mine, Cook (1966) stated that the released energy is one of the most important factors responsible for inducing rockburst, and then proposed the energy release rate, which is widely used. In order to assess susceptibility to rockburst after excavation face is formed, Mitri et al. (1999) proposed the burst potential index, which indicates that rockburst is very likely to occur as rock energy storage rate reached the limit of energy storage. Wiles (1998) pointed out that the local energy release density (LERD) should be combined with stress condition to evaluate rockburst, that is, only stress condition approaching rock mass strength can LERD be used to predict the rockburst. Beck and Brady (2002) has deepened the understanding of the local energy release density (LERD); they came up with the modeled ground work, which indicates the change in energy before and after failure of rock mass. Jiang et al. (2010) developed the local energy release rate (LERR) in order to understand rockburst from the viewpoint of energy release, and the results show that LERR can satisfactorily predict the intensity of rockburst and the depth of the outburst pit. Although the above mentioned indices can assess the position and intensity of rockburst to some extent, they do not remove the restriction of different stress paths and stress state.

In order to propose a new prediction method of rockburst without the influence of stress paths and stress state, unloading confining pressure tests were conducted for brittle sandstone under different controlling conditions. A new energy index-the rock burst energy release rate (RBERR) is proposed, whose simulation results dovetailed neatly with results from actual rockbursts in the tunnel. Then, a comprehensive method combined with MS monitoring technique and RBERR was applied to the X mine in Huainan coal mine, which was verified to successfully predict the position and intensity of rockburst. This study can offer new directions for rockburst evaluation in deep-buried underground constructions.

2. Proposed new energy index

2.1. Energy index for rockburst evaluation

Rockburst often occurs under excavation unloading conditions in highly stressed ground as a sudden and violent failure of rocks. In order to understand the mechanism of rockburst, unloading confining pressure tests were conducted using brittle sandstone under different controlling conditions. There were four controlling methods: axial loading and radial constant (Scheme I), axial loading and radial unloading (Scheme II), principal stress difference constant and radial unloading (Scheme III), and axial constant and radial unloading (Scheme IV). The brittle sandstone was obtained from depths in Huainan coal mine. The stress-strain curves of the sandstone samples under different controlling conditions are shown in Fig. 1.

According to the test results, the total energy absorption, dissipated energy and elastic strain energy of the sandstone samples during the entire loading and unloading process were accurately calculated, and the rule of energy accumulation and release in sandstone samples under unloading was systematically analyzed. It was found that the maximum strain energy stored in the rock before failure depends only on the confining pressure and unloading rate, which are unrelated to loading and unloading paths (see Table 1). The same conclusion was reported by Chen et al. (2009). The maximum strain energy is defined as the limit energy storage rate (LESR). When the unloading rate remains unchanged, LESR can be expressed as a function of the confining pressure p_c (see Fig. 2).

Based on the above-mentioned theory, here we propose a new energy index called rock burst energy release rate (RBERR), to assess the intensity and location of a strain-type rockburst. The formula for RBERR can be written as:

$$RBERR = \frac{LERR}{LESR} = \frac{U_{i\max} - U_{i\min}}{LESR} = \frac{U_{i\max} - U_{i\min}}{f(p_c)} \tag{1}$$

where LERR is the local energy release rate of the ith element, and it refers to the sudden release of energy stored in the rock mass per volume when the strain energy concentrated in a local area of the rock is larger than its limiting capacity during excavation. The $U_{i\max}$ and $U_{i\min}$ are the peak and minimum values of the elastic strain energy intensity before and after brittle failure of the ith element respectively, which can be expressed as

$$U_{i\max} = [\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3)]/(2E) \tag{2}$$

$$U_{i\min} = [\sigma'^2_1 + \sigma'^2_2 + \sigma'^2_3 - 2\nu(\sigma'_1\sigma'_2 + \sigma'_2\sigma'_3 + \sigma'_1\sigma'_3)]/(2E) \tag{3}$$

where σ_1, σ_2 and σ_3 are the three principal stresses corresponding to the peak strain energy of the element, and σ_1', σ_2' and σ_3' are the three principal stresses corresponding to the minimum strain energy of the element. ν is the Poisson's ratio and E is Young's modulus. As previously mentioned, LESR is the limit energy storage rate, which is not affected by stress paths, and can be expressed as a function of the confining pressure p_c. Therefore, LESR is introduced to avoid LERR's dependence on stress state and failure mode. RBERR represents the ratio of the energy release of an element generating brittle failure to the limit energy storage of that element. The energy release of an element is more violent with increasing RBERR, and there is a higher probability of rockburst. In addition, LERR refers to the values of elastic strain energy release of the element after brittle failure, that is RBERR > 0 can be used to determine whether the element belongs to excavation damage zone.

2.2. Elastic-brittle-plastic model

From engineering practice, two main theories emerge: unloading excavation under high- stress condition usually leads to brittle failure of hard rock, and the parameters of the surrounding rock in the excavation damage zone are continually changing, including the elastic modulus E, cohesion c, and friction angle φ. Based on the above theories, an elastic-brittle-plastic model—rock mass deterioration model (RDM) was proposed (Jiang et al., 2010), which indicates that the deterioration resulting from microcrack propagation can lead to a reduction in the deformation modulus and cohesion, as well as increase in the friction angle in the excavation damage zone. The general, the plastic strain ε^p is used to represent the degree of damage of the material, as expressed in Eqs. (4) and (5).

$$\varepsilon^p = \sqrt{\frac{2}{3}(\varepsilon_1^p \cdot \varepsilon_1^p + \varepsilon_2^p\varepsilon_2^p + \varepsilon_3^p\varepsilon_3^p)} \tag{4}$$

$$\begin{cases} E(\varepsilon^p) = E_0 \cdot f_E(\varepsilon^p) \\ c(\varepsilon^p) = c_0 \cdot f_c(\varepsilon^p) \\ \varphi(\varepsilon^p) = \varphi_0 \cdot f_\varphi(\varepsilon^p) \end{cases} \tag{5}$$

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