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Experimental study on the prediction of rockburst hazards induced by dynamic structural plane shearing in deeply buried hard rock tunnels

Fanzhen Meng [a,b], Hui Zhou [b,*], Zaiquan Wang [a], Liming Zhang [a], Liang Kong [a], Shaojun Li [b], Chuanqing Zhang [b]

[a] College of Science, Qingdao University of Technology, Qingdao, Shandong, China
[b] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430071, China

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ABSTRACT

To investigate methods for predicting bursts induced by the shear failure of structural planes in the deeply buried hard rock tunnels, shear tests were performed under various normal stresses on completely occlusive granite joints that were created via tension splitting. In these experiments, stress drops resulting from shear off of asperities on the surface of granite rigid structural plane, which can trigger a fault-slip rockburst, were reproduced, and the acoustic emissions (AEs) were monitored during shearing. The AE characteristics were analysed, and a method based on the AE *b*-value was developed to predict stress drops and the fault-slip rockbursts induced by the stress drops. The *b*-value continuously decreased before the stress drop and dropped to approximately 0.8 or less at the point of the violent post-peak shear stress drop. Moreover, the *b*-value tended to decrease to a relative minimum during the stick-slip period when the energy increased sharply if the energy rate was greater than 10^4, and a lower *b*-value was associated with a higher rockburst probability and intensity. The *b*-value generally decreased as the normal stress increased, which increased the risk of rockburst induced by the dynamic shear failure of granite joints. Moreover, the static and dynamic shear failure of the joints was easily distinguished when the *b*-value was used as a predictor.

1. Introduction

Rockburst is a fundamental challenge confronting engineers and scholars in the field of underground tunnelling and mining and can pose a considerable threat to on-site workers and engineering equipment. For example, in one of the deepest hydraulic tunnels in the world, the Jinping II Hydropower Station in China (with a maximum overburden depth of 2525 m), more than 750 rockbursts have occurred in seven tunnels, and among these events, 44.9%, 46.3% and 8.8% have been slight, moderate and (extremely) intense rockbursts, respectively.[1] An extremely intense rockburst occurred on November 28, 2009, in a drainage tunnel. This rockburst resulted in seven deaths and one injury and completely destroyed a tunnel-boring machine (TBM). Consequently, the project was severely delayed, and serious economic loss was suffered.[2,3] As the depths of mining and civil underground construction projects increase, it is anticipated that the rockburst hazard will become increasingly intense and pervasive because of high geo-stresses.

Many researchers have extensively investigated rockburst hazards in recent years with respect to rockburst mechanisms and controls. Moreover, accurate rockburst predictions, including when (time) and where (location) they occur and how severe they are (intensity), are important for dynamic disaster prevention and reduction during the construction of tunnels. Therefore, many prediction methods have been proposed and used to generate rockburst forecasts.

To quantitatively evaluate the relationships between tomographic images of P-wave velocity and rockburst hazards in coal mines, Cai et al.[4] generated P-wave velocity tomograms with microseismic events and proposed using a "bursting strain energy" index to characterize seismic hazard maps for mining. Cloud models and the attribution weight method were used by Liu et al.[5] to predict rockburst classifications. These authors found that the weighted cloud model performed better than other empirical approaches for predicting rockburst classes. Based on the kinetic concept of a solid strength and rigid discontinuity model, Mansurov[6] proposed a technique for predicting the occurrence of strong rockbursts in mines. Four parameters were analysed: the concentration parameter, the volume concentration of seismic

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* Corresponding author.
E-mail address: hzhou@whrsm.ac.cn (H. Zhou).

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events, the 4-D concentration of seismic events and the average size of the formed faults. Cook et al.[7] introduced the energy release rate (ERR) concept to measure rockburst severity. Wang and Park[8] investigated the strain energy stored near mining pits using three-dimensional numerical modelling, compared their results with other rockburst criteria and found that strain energy analysis with numerical modelling is useful for rockburst prediction. However, according to these authors, the threshold value at which a rockburst occurs remains unknown.

When coal rock is subjected to a stress it emits electromagnetic radiation (EMR) as it deforms or fractures; therefore, EMR technology has been used to monitor mine pressure and predict dynamic disasters, such as coal and gas outbursts and rockbursts caused by coal rock failure in coal mines in Russia and China.[9–11] Frid[9,10] observed EMR anomalies before rockbursts and gas outbursts in coalmines and presented systematic criteria for their use. However, EMR parameters can only qualitatively describe the stress state and, consequently, can only provide a rough evaluation of the dynamic hazard risks. Dou et al.[11] introduced the use of elastic wave computerized tomography (CT) technology, seismic wave CT technology and electromagnetic radiation technology for monitoring and predicting rockbursts in China. However, to date, very few of these techniques have been applied in deep hard-rock civil tunnelling due to the differences in the properties of coal and hard rock.

Because the rockburst process is influenced by many external and internal factors, such as static stress, dynamic stress, geological structure, unloading rate, rock strength and brittleness, it is impractical to establish a prediction method that can consider all relevant factors. Therefore, real-time acoustic emission (AE) or microseismic (MS) monitoring may be one of the most effective methods for obtaining predictive information regarding imminent rockburst events. Because elastic waves are radiated as a result of the rapid release of energy due to the fracturing of brittle rocks, AE technology is widely used to study the evolution of rockbursts.[12–14] Hirata et al.[12] investigated the relationship between rock stress and AE at a rockburst site. Liang et al.[14] studied the precursors to rockburst in a granite tunnel model under biaxial stresses using AE and observed a sudden decrease followed by a quiet period of AE events before a rockburst. Among the available microseismic source parameters, the seismic energy, apparent stress and seismic moment were used, and thresholds for these three parameters were provided by Alcott et al.[15] to assess potential rockburst hazards in a Canadian mine. Linear empirical relationships were established among the seismic energy released due to a rockburst, the total tonnage of ore mined out and the total numbers of rockbursts and seismic events, and the resulting model was used to predict rockbursts and seismic events.[16] Feng et al.[17] proposed a microseismicity-based method to dynamically alert rockburst development processes in tunnels, and the probabilities of strain and strain-structure slip rockbursts of various intensities can be monitored in real time; however, a rockburst database must be established before the method can be used.

As illustrated by the above discussion, various prediction methods have been proposed and used by different authors. However, because of the complex characteristics of rockbursts, the problem of rockburst prediction is far from being satisfactorily resolved. Moreover, most of the findings listed above primarily focus on predicting strainbursts,[4,5,7,8,13,14,17] which are defined as bursts that occur on the periphery of tunnels in intact and hard rocks and are induced by concentrations of compression stress.[18] It is widely accepted that strainbursts are influenced by the relationships between rock strength, external stress, rock brittleness and energy accumulation; therefore, the Russenes criterion σ_θ/σ_c,[19] Turchaninov criterion $(\sigma_{\theta\max}+\sigma_L)/\sigma_c$,[20] Hoek criterion $\sigma_{\max}/\sigma_c$,[21] Kidybinskia criterion W_{et},[22] and various combinations of these criteria[5,8,23] have been proposed for comprehensively evaluating strainburst intensity. However, there is another type of rockburst, to which the above prediction methods cannot be applied, called fault-slip burst. This type of rockburst is caused by the movement of a pre-existing fault or the formation of seismically active structural zones.[3,18,24,25] Significant research effort has been directed toward illuminating the mechanism and influencing factors of fault-slip bursts by means of field investigations,[18,26,27–29] microseismic monitoring[30,31] and numerical approaches.[24,25,32–37] White and Whyatt[26] found that slip displacements along bedding simultaneously reduce the physical dimensions of stopes and increase compressive stress, leading to rockbursts. Castro and Carter[28] investigated various types of case studies that possibly lead to fault-slip bursts due to mining activities, such as the unclamping of normal stress acting on faults and stress rotation induced by the extraction of orebody. Two mining fault rupture cases were analysed and re-interpreted by Bewick et al.,[38] and the authors concluded that the fault rupture process and energy release depends on the boundary conditions (system stiffness) surrounding the failure process. Sainoki and Mitri[25,34–36] conducted a series of static and dynamic analyses to investigate the influence of the positional relationship between stope and fault, mining rate, roughness and mechanical properties of the fault on fault slip induced by ore extraction. After analysing a fault-slip burst with a magnitude of 4.2 that occurred in the Wright-Hargreaves Mine, Blake and Hedley[29] found that fault-slip bursts are triggered by a reduction in the clamping force acting on the fault and that there are no warnings related to fault-slip bursts. Ryder[24] proposed using the excess shear stress (ESS) metric to numerically assess the possible magnitude and relative likelihood of seismic activity induced by fault slip in African mines.

In spite of the many attempts to understand the mechanism of fault-slip bursts, effective means of predicting the magnitude of events and the damage caused by the seismic waves resulting from the fault-slip burst have not yet been developed because of the complexity of the mechanism governing fault behaviour and the difficulty of precisely assessing the change in stress in a complicated rock mass fabric.[25] Small-scale rigid structural planes near the tunnels also play an important role in controlling certain rockbursts in deeply buried tunnels of the Jinping II Hydropower Station, and fault-slip rockburst events may be induced by the instantaneous stress drop resulting from the breakage of fault surface asperities in dynamic conditions.[1–3,34] Although the MS monitoring technique has been widely used to monitor and predict rockbursts in deep mines and tunnels, the location accuracy is generally within several meters; thus, it is more suited for large areas and long lines of monitoring. Because the dimensions of these rigid structural planes that cause fault-slip rockbursts range from less than one meter to several meters, the MS monitoring technique is not accurate enough to locate and analyze the rockburst events. In comparison, the location accuracy of AE monitoring is much better than that of MS monitoring and can achieve accuracies of less than 1 cm in the laboratory and several cm in the field. Therefore, the AE technique is more suitable for monitoring the shear failure of small-scale structural planes.

The shear test technique is a good approach for investigating this type of burst, and the necessary experimental conditions can be created artificially. Moreover, precursory information gathered before rockbursts can be captured and analysed in detail in laboratory experiments. The results and conclusions obtained in the laboratory can be used to guide the prediction of rockbursts induced by plane or joint shearing in deep, hard-rock tunnels to reduce or prevent rockburst hazards. In this study, shear tests were performed under various normal stresses under constant normal load conditions on completely occlusive granite joints that were created via tension splitting. In these experiments, stress