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A fuzzy comprehensive evaluation methodology for rock burst forecasting using microseismic monitoring

Wu Cai[a,b,*], Linming Dou[a,*], Min Zhang[a], Wenzhuo Cao[b], Ji-Quan Shi[b], Longfei Feng[a]

[a] State Key Laboratory of Coal Resources and Safe Mining, Key Laboratory of Deep Coal Resource Mining (Ministry of Education of China), School of Mines, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

[b] Department of Earth Science and Engineering, Royal School of Mines, Imperial College, London SW7 2AZ, United Kingdom

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ABSTRACT

Rock bursts have become one of the most severe risks in underground coal mining and its forecasting is an important component in the safety management. Subsurface microseismic (MS) monitoring is considered potentially as a powerful tool for rock burst forecasting. In this study, a methodology for rock burst forecasting involving the use of a fuzzy comprehensive evaluation model was developed, which allows for a more quantitative evaluation of the likelihood for the occurrence of a rock burst incident. In the fuzzy model, the membership function was built using Gaussian shape combined with the exponential distribution function from the reliability theory. The weight of each index was determined utilising the performance metric *F* score from the confusion matrix. The comprehensive forecasting result was obtained by integrating the maximum membership degree principle (MMDP) and the variable fuzzy pattern recognition (VFPR). This methodology has been applied to a coal mine in China to forecast rock bursts. To select MS indices for rock burst forecasting using the fuzzy evaluation model, laboratory acoustic emission (AE) measurements of coal samples collected from the mine were performed. The model parameters were first calibrated using historical MS data over a period of four months, during which six rock burst incidents were observed. This calibrated model was able to forecast the occurrence of a subsequent rock burst incident in the mine.

1. Introduction

Rock bursts, characterised by rapid and violent release of the elastic strain energy due to rock mass failure, pose a serious risk to the safety of underground engineering (Cook, 1965; Bräuner, 1994; Ortlepp and Stacey, 1994; Cai, 2013). In underground coal mines, rock bursts sometimes lead to secondary hazards such as gas outbursts and dust explosion. In recent years, with the increase of mining depth and intensity, rock bursts have become more frequent in coal mining (Jiang et al., 2017; Zhang et al., 2017a). Multiple casualties caused by rock bursts were reported in USA (Wikipedia, 2007; Todd and Newsome, 2014), Australia (NSW Department of Industry, Resources and Energy, 2015) and China (Cai et al., 2014a; Lu et al., 2015). Especially in China, the statistics show that the number of mines experiencing rock burst incidents increased from 32 in 1985 to more than 177 by the end of 2015.

During underground longwall mining, the removal of solid coal results in the abutment stresses shift along with the direction of face advance. Three disturbance zones are usually formed in the overburden strata when a longwall panel of sufficient width and length is excavated, i.e., caved zone, fractured zone and continuous deformation zone, which corresponds to the post-peak fractured zone DE, pre-peak plastic zone BD and elastic zone AB in the horizontal mining direction, respectively, as shown in Fig. 1. Accordingly, microseismicity (MS) may be induced in the surrounding coal/rock, by the stress redistribution and other mining related activities such as blasting vibration, roof and floor strata fracturing, and fault reactivation. The induced MS, in turn, may generate a dynamic force which has a bearing on the total stresses.

Building upon above stress behaviours of underground coal mining, various mechanisms for rock bursts have been proposed from the perspectives of rock strength, strain energy, rock stiffness, stability and burst liability (Cook, 1965; Hudson et al., 1972; Singh, 1988; Linkov, 1996; Wang and Park, 2001; Cai et al., 2016b; Zhang et al., 2017b). More recently, the role of MS induced dynamic stresses during mining, in addition to the prevailing static stresses in the initiation of rock bursts, has been extensively researched through laboratory tests (Hua and You, 2001; He et al., 2010; Su et al., 2018), numerical modelling (Zhu et al., 2010; Cao et al., 2016b; Weng et al., 2017; Wang and Cai, 2017) and theoretical analysis (Dou et al., 2014; Mendecki, 2016; Yuan et al., 2018). In response to these mining-induced behaviours, MS

* Corresponding authors at: School of Mines, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China (W. Cai).
E-mail addresses: caiwu@cumt.edu.cn (W. Cai), lmdou@cumt.edu.cn (L. Dou).

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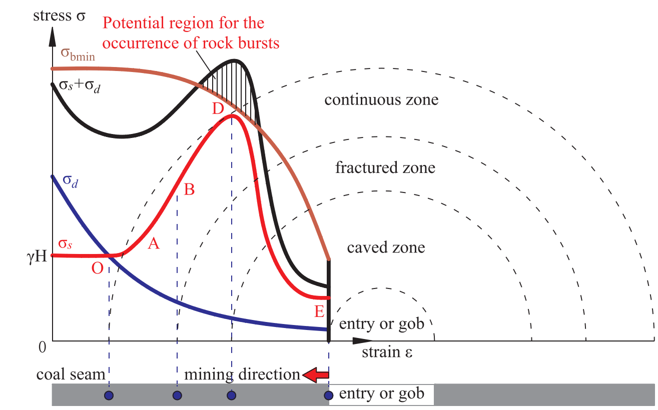

Fig. 1. Schematic representation of rock bursts in relation to the static and dynamic stresses. γ is the average unit of overburden weight, H is the mining depth, σ_s is the static stress, σ_d is the dynamic stress, and σ_{bmin} is the critical stress when rock burst occurs.

monitoring has been widely used to evaluate the static and dynamic stresses (Tang et al., 2010; Xu et al., 2011; Feng et al., 2015; Lu et al., 2015; Si et al., 2015; Cai et al., 2014b; 2016a; Wang et al., 2016; Cao et al., 2016a; He et al., 2017; Dai et al., 2017).

Based upon the analysis of MS monitoring data, a number of indices for evaluating rock burst tendency have been proposed regarding statistical features and source mechanism parameters for individual rock burst incidents (Table 1). These indices are concerned with three elements (aspects) characterising MS events: (1) magnitude distribution, (2) spatial distribution, and (3) temporal distribution. It has been noted that successful application of individual index tends to be incident specific, reflecting the complex nature of rock bursts under different mine conditions.

To address above shortcoming, attempts to use a combination of indices have been made. Tang and Xia (2010) used apparent stress/volume and b value, both of which are concerned with MS magnitude in an underground copper mine. Lu et al. (2015) and Wang et al. (2017) used indices covering both magnitude (total/maximum MS energy, fault total area, b value and Z value) and temporal distribution (event count and dominant frequency) in underground coal mines. As well as the indices for magnitude and temporal distribution, Dai et al. (2017) also considered MS spatial distribution (fractal dimension) in evaluating the recorded MS events in an underground powerhouse. In these studies, the temporal trend of the indices is monitored, and based upon which, judgement is made on whether "MS abnormality" is observed for each individual index. Since MS abnormality may be observed only for some of the indices, the final decision is subject to uncertainty.

This study aims to develop a methodology for rock burst forecasting involving the use of a fuzzy comprehensive evaluation model to evaluate the MS indices, which allows for a more quantitative evaluation of the likelihood for the occurrence of a rock burst incident. In the fuzzy evaluation model, the Gaussian shape membership function, the confusion matrix, the maximum membership degree principle (MMDP) and the variable fuzzy pattern recognition (VFPR) are used. The application of this methodology has been successfully demonstrated in a coal mine in China.

Table 1
Summary of the commonly used MS indices for the forecasting of rock bursts.

Name	Basic equations	MS aspects	Key references	Common features
Number of events $\sum N$	Total number of MS events in a given time window	Temporal	Srinivasan et al. (1997)	Statistical feature indices.
Amount of energy $\sum E$	Total amount of MS energy in a given time window	Magnitude		
b value	$\log N(M) = a - bM$ $N(M)$ is the cumulative number of MS events having magnitude larger than M, and a and b are constants. It has been shown in laboratory studies, field observations, and numerical simulations that the slope of this distribution curve depends on stress conditions	Magnitude	Gutenberg and Richter (1944); Li et al. (2017); Cao et al. (2018)	
Lack of shock b_L	$b_L = \frac{\log e}{M_{mean} - M_{min}}$ M_{mean} is the mean magnitude and M_{min} is the minimum magnitude of given MS events	Magnitude	Aki (1965)	
Fault total area	$A(t) = \sum_{k=k_0}^{k-1} N(k) \bullet 4.5^{k-k_0}$ k_0 is the lower limit of the statistical MS energy level, and k is the energy level of each event. $N(k)$ is the event count of MS energy level k (correspondingly, the energy is 10^{k}-10^{k+1} J)	Magnitude	Lu et al. (2015)	
Source concentration degree	$S_d = \sqrt[3]{\sqrt{\lambda_1 \cdot \lambda_2 \cdot \lambda_3}}$ λ_1, λ_2, and λ_3 are standard orthogonal eigenvectors of the covariance matrix of MS hypocentre parameters x, y, z	Spatial	Cai et al. (2014b)	
Seismic diffusivity	$d_s = (\bar{X})^2/\bar{t}$ $\overline{X}$ is the mean distance between consecutive events and $\bar{t}$ is the mean time between events	Temporal and spatial	Mendecki (1996)	
Fractal dimension	$D = \lim_{r \to 0} \frac{\lg C(r)}{\lg r}$	Spatial	Xie and Pariseau (1993)	
	$C(r)$ is the correlation integral of the energy or number of MS events, and r is the energy or spatial radio scale	Magnitude	Feng et al. (2016)	
Moment tensor	Percentage of the shear component of moment tensor	Magnitude	Gibowicz and Kijko (1994); Xiao et al. (2016)	Source mechanism parameters.
Apparent stress/volume	$\sigma_A = \frac{\mu E_A}{M_0}$, $V_A = \frac{M_0^2}{\mu E_A}$ μ is the shear rigidity modulus, E_A is the MS energy, and M_0 is the MS moment	Magnitude	Mendecki (1996); Tang and Xia (2010)	
Energy index	$EI = \frac{E_A}{\bar{E}(M_0)}$ $\bar{E}(M_0)$ is the average energy released by events of the same MS moment	Magnitude	Mendecki (1996); Tang et al. (2010); Xu et al. (2011)	
Energy ratio	Ratio of the S- and P-wave energies (E_S/E_P)	Magnitude	Gibowicz and Kijko (1994)	