Tunnelling and Underground Space Technology 81 (2018) 632–659

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Evaluation method of rockburst: State-of-the-art literature review

Jian Zhou[a,*], Xibing Li[a], Hani S. Mitri[b]

[a] School of Resources and Safety Engineering, Central South University, Changsha 410083, China
[b] Department of Mining and Materials Engineering, McGill University, Montreal, Canada

ARTICLE INFO

Keywords:
Underground engineering
Rockburst phenomena
Rockburst
Rockburst classification
Rockburst prediction

ABSTRACT

The evaluation of rockburst is becoming increasingly important as mining activities reach greater depths below the ground surface. In the literature, rockburst assessment has been tackled by many researchers with various methods. However, there has not been a study that examines and compares different rockburst assessment methods. In this paper, rockburst classification and its varying definitions are briefly summarized. A comprehensive review of the research efforts since 1965 then follows. This includes empirical, numerical, statistical and intelligent classification methods. Of particular significance is that in all the above-mentioned techniques, the review highlights the source of data, timeline of study and the comparative performance of various techniques in terms of their prediction accuracy wherever available. The review also lists current achievements, limitations and some promising directions for future research.

1. Introduction

Rockburst can be a major problem in deep underground mines causing injury to mine operators and damage to underground workings. The term "rockburst" is commonly used to describe a wide range of rock failures, which is a twentieth century phenomenon that occurs in tunnels, shafts, caverns and mines (Dowding and Andersson, 1986; Kaiser et al., 1996; Blake and Hedley, 2003; Li et al., 2017c, 2017d). Rockbursting has been a common occurrence in the mines of South Africa (Leger, 1991), China (Zhou et al., 2012a), Chile (Ortlepp, 2005), USA (Blake and Hedley, 2003), Canada (Kaiser et al., 1996) and Western Australia (Heal et al., 2006), and in tunnels in Norway (Barton et al., 1974) and China (Zhang et al., 2011). It has been reported to occur in excavations in other countries such as Russia, Sweden, Switzerland and Korea, and this is not an exhaustive list (Linkov, 1996; Ortlepp, 2005; Cai, 2013; Zhou et al., 2016a). As claimed by Suorineni et al. (2014), rockburst is the "cancer" in geomechanics of contemporary deep mining. As mining depths and locations of excavation activities have become increasingly challenging, more cases of rockbursting have occurred. It can be concluded that rockbursting may now be a universal problem.

Due to the complex nature of the rockburst phenomenon, precise rockburst prediction is quite difficult. As noted by Brown (1988), it is difficult to even reach a consensus on the definition of rockburst. Hoek and Brown (1980) also pointed out that this type of progressive failure process was still not clearly understood. Since Cook et al. (1966) first proposed a method for evaluating the rockburst of a mining layout, a variety of methods, either elaborate or simplified, ranging from empirical to theoretical and mathematical approaches for predicting rockburst potential have been developed in the past few decades with much success. However, due to the complex features of rockburst assessment systems, such as multivariable and strong interference, there is no universally accepted method to predict the timing of rockburst, and the best we can achieve today is to identify areas of high rockburst using empirical criteria, numerical models or personal experience.

Evaluation of rockbursts methods is broadly categorised in two aspects: classification of rockbursts and prediction of rockbursts potential. Different researchers have analyzed the source and damage mechanism of rockbursts from different aspects such as the energy theory, strength theory, the rigidity theory, the instability theory, the burst liability theory, the catastrophe theory, the theory of chaos, the fractal theory, the bifurcation theory and the theory of dissipative structures (Cook et al., 1966; Vardoulakis, 1984; Zhou et al., 2012a; Afraei et al., 2018), and nearly 100 rockburst empirical criteria were used to classify rockburst categories. The study of rockburst potential is an important aspect of rockburst mechanism research. It is qualitative or quantitative determination of rockburst potential on the basis of mechanism research. The evaluation of rockburst potential is mainly based on the research and understanding of the mechanical properties of rock itself under certain conditions. According to the literature review, the research on rockburst potential can be divided into two major aspects (Zhou, 2015; Zhang et al., 2016): rockburst potential of rock and

* Corresponding author.
E-mail address: csujzhou@hotmail.com (J. Zhou).

https://doi.org/10.1016/j.tust.2018.08.029
Received 1 October 2017; Received in revised form 29 June 2018; Accepted 16 August 2018

Nomenclature

UCS_{rm}	Unconfined compressive strength of rock mass, MPa
D_i	Damage index
C	Cohesion of rock mass, MPa
φ	Friction angle of rock mass
σ_θ	Maximum tangential stress of surrounding rock, MPa
σ_1	Axial stress of surrounding rock, MPa
σ_L	Axial stress of tunnel, MPa
σ_c	Uniaxial compressive strength of rock, MPa
σ_{1cr}	Rockburst critical stress, MPa
σ_t	Uniaxial tensile strength of rock, MPa
σ_{RB}	Rockburst maximum stress, MPa
K_W	is the elastic strain energy index
K_σ	is the stress drop index
K_{rb}	is the composite index
H	is the buried depth of rock sample, m
λ_0	is equal to the maximum initial principal stress of vertical axis and the ratio of principal stress to the plane, and approximately equals to σ_θ
λ_1	is the softening modulus (value of elastic modulus after the peak value of stress in the stress[HYPHEN]strain curve), GPa
λ	is the lateral pressure coefficient
θ	Intersection angle between the direction of tunnel excavation and the direction of maximum principal stress, °
lg(E/J)	is the common logarithm of the rockburst radiated energy
SD	is the standard data of the common logarithm of the rockburst radiated energy;
RMi	is the Rock Mass index
E_u	Unloading tangential modulus, MPa
E_t	Throw energy of rock fragments after failure of a specimen under uniaxial compression
E_s	Maximum elastic strain energy, $kJ \cdot m^{-3}$
E_p	Dissipated energy in the creation of microfracture and plastic deformation of the rock in one cycle of loading, $kJ \cdot m^{-3}$
E_e	Elastic energy stored in the rock through loading up to σ_A and unloading, $kJ \cdot m^{-3}$
ε_f	Strain before peak
ε_b	Strain after peak
μ	Poisson's ratio of rock
λ	Lateral pressure coefficient
γ	Rock density, $kN \cdot m^{-3}$
σ_n	Normal stress at the slipping point, MPa
φ_d	Dynamic friction angle, °
F_1	Area surrounded by strain ε axis and before the peak stress – axial strain curve
F_2	Area surrounded by strain ε axis and after the peak stress – axial strain curve
PES	Criterion of potential energy of elastic strain, kJ/m^3
E	Elastic modulus of the rock mass, GPa
E_u	Unloading tangential modulus of the rock mass, MPa
φ	Internal friction angle of rock, °
β	Intersection angle between the direction of tunnel excavation and the direction of maximum principal stress, °
D_t	Indicator of dynamic rock failure time, ms
U	Total peak strength of before rock deformation
U_l	Permanent deformation before peak or plastic deformation
Φ_k	Rock kinetic energy with destructive ejection, $kJ \cdot m^{-3}$
Φ_0	Maximum elastic strain energy, $kJ \cdot m^{-3}$
K_v	Rockmass intact coefficient
E_{se}	Seismic energy of the blast in J, $E = 10^{2.76 - \lg\tau + 2.24}$, ($\tau$ is the duration of the seismic event in s)
J	Total specific work of the explosive charge in J/kg
Q	Mass of the explosive charge (grammonite 79/21) in kg
ρ_1	Average value of the electrical resistance in $\Omega \cdot m$
ρ_2	Electrical resistance of the mass in the no-rockburst-hazard state in $\Omega \cdot m$
σ_{max}	Maximum tangential stress on the boundary of a circular opening (or σ_θ), MPa
δ_o	Radial deformation at the face
r_p/r_o	Plastic radius/radius of cavity
σ_{cm}	Rock mass strength, MPa
I_s	Point load strength of the rock, MPa
K_p	Post-peak stiffness of a discontinuity
K_e	Local mine stiffness or surrounding rock mass stiffness
F_{ob}	Applied shear stress minus the shear strength, MPa
F_{res}	Residual shear strength, MPa
e_4	Mining-induced strain energy calculated at the boundary of the opening (pillar skin)
b	Temporal coefficient value calculated in time windows
bm	Average value of b
e_c	Critical strain energy density, KN/m^3
M	Post-peak modulus, GPa
AI	Activity index
ERR	Energy release rate, KJ/m^3
PSF	Potential for stress failure
BPI	Burst potential index, %
BIM	brittleness index modified
BSR	Brittle shear ratio
D_T	Failure duration index
K_u	Brittle deformation coefficient
S	Stress index
H_{cr}	critical depth
k	Rock brittleness index
V_p	Longitudinal wave velocity of the rock mass, km/s
V_s	Longitudinal wave velocity for the intact rock, km/s
RVI	Rockburst vulnerability index
ω	Ejection rate
K_w	Rockburst variable formula
LERD	Local Energy Release Density, MJ/m^3
NR	No rockburst
LR	Light rockburst
MR	Moderate rockburst
HR	Heavy rockburst
SR	Serious rockburst

rockburst potential of rock mass engineering. The former refers to the possibility of rockburst under certain conditions. If rock does not have rockburst potential, rockburst will not occur during rock mass engineering in this kind of rock. The test method is mainly used for rockburst proneness research. The rockburst tendency of rock mass engineering, that is, is the possibility of rockburst occurring in rock engineering under certain conditions. The research method is generally based on the rockburst tendency, combining with the geological conditions of rock mass engineering, such as in-situ stress, rock layer distribution, rock structure and other conditions, according to the on-site field work. Numerical simulation is carried out on the layout and excavation process, and the stress distribution of the surrounding rock obtained is judged by corresponding criteria of rockburst classification.

This paper focuses on providing the reader with a complete review of various rockburst prediction methods. Many studies on rockburst prediction have been carried out in the past few decades, especially based on various different statistical and intelligent techniques. For instance, some studies apply single learning techniques, such as neural