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Geomechanical types and mechanical analyses of rockbursts

Tianbin Li *, Chunchi Ma, Minglei Zhu, Lubo Meng, Guoqing Chen

State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu, Sichuan 610059, PR China

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ABSTRACT

Rockbursts generally occur in highly stressed rock masses because of underground openings. To ensure the safety of construction works, factors that play a role in predicting and preventing rockbursts should be analyzed. Based on numerous geological and mechanical analyses of rockbursts in China, six basic geomechanical types of rockbursts are classified with unique developing characteristics (rock-mass structure, crack type, failure plane, energy release, etc.), which are further divided into stress rockburst and stress-structure rockburst. The stress rockbursts are characterized by the development of micro-cracks using fracture mechanical theories; the formation of a macroscopic failure plane indicates that a state of maximum energy release is achieved (along the preferred crack path). The stress-structural rockbursts are considered a structural failure when propagating cracks intersect the existing discontinuities, which are analyzed using the catastrophe models. Finally, occurrence criteria of the six geomechanical types of rockbursts are proposed.

1. Introduction

A rockburst is a dynamic instability phenomenon occurring at underground openings with hard-brittle lithology and high ground stresses. The unloading mechanism leads to the adjustment of ground stresses (increase in tangential stress and decrease in radial stress) and sudden release of stored energy in rock masses, thus resulting in phenomena such as loosening and bursting, slabbing, ejecting, and even throwing of rock blocks (Li et al., 2010). Over the past three decades, engineers have been troubled by rockbursts occurring in several significant underground projects in China. The projects include diversion tunnels in the Tianshengqiao and Taipingyi hydropower stations, underground works in the Ertan hydropower station, Qinling extra-long tunnel of the Xikang railway, Erlangshan tunnel of the Sichuan–Tibet highway, and diversion tunnels in the Jinping II hydropower station along the Yalong River (Gong et al., 2012; Li et al., 2012). To ensure the safety of construction works in deep underground projects in the future it is necessary to understand the factors that play a role in predicting and preventing rockbursts. The occurrences of rockbursts, which are strongly related to the geological and mechanical properties of rock masses, need to be interpreted using mathematical and mechanical analyses.

Most studies on the mechanism and prediction of rockbursts are based on the applications of the strength, rigidity, energy, fractal, fracture damage, and catastrophe theories etc., and numerical analyses (Ma et al., 2016, 2015). Hoek and Brown (1980) and Russense (1974) proposed the stress–strength criteria of rockbursts for practical rock engineering. Zhao et al. (2017) modified these criteria based on observations in a division tunnel. In the rigidity theories, Petukov (1979) observed severely ruptured rock specimens during sudden unloading in an experiment conducted on a flexible testing machine. Qian (2014) calculated the stiffness of rock pillars and surrounding rocks and established a forecast model for the strain rockburst of pillars. In the energy theories, Cook et al. (1966) explained the mechanism of rockbursts as external forces breaking the mechanical equilibrium of surrounding rocks; thus, more energy is released than dissipated. Kidybiński (1981) proposed a proneness index of rockbursts (wet index) using the ratio of the elastic strain energy induced by sudden release to the dissipated energy. Song et al. (2012) predicted rockburst based on the dissipative structure theory. By applying the fracture mechanical theories, studies confirmed that the maximum compressive stress could help determine the initiation of cracks; moreover, the strain energy and dissipation energy along the crack path should be evaluated to determine the direction of crack propagation (Bobet, 2000; Sharon et al., 1996). The elementary catastrophe theories are widely used in analyses of the rockburst system, e.g., in the cusp catastrophe model (Pan et al., 2006). Previous studies show that the basic types of rockbursts are generally classified into strain burst, slip (fault-slip) burst, and their combination (Chen et al., 2015; Fan et al., 2016; Feng et al., 2012). However, these are not sufficiently related to the geomechanical nature of rockbursts and do not clearly address the process mechanism of rockbursts.

To solve this problem, studies on rockbursts were conducted in Erlangshan tunnel of the Sichuan–Tibet highway, diversion tunnels in

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* Corresponding author.
E-mail addresses: ltb@cdut.edu.cn (T. Li), nanjiguang1017@sina.com (C. Ma).

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List of symbols

σ_{ij}^{∞}	Far field stresses
σ_{ij}	Additional stresses around flaw
K_{II}	Stress intensity factor for mode II loading
β	Inclined angle of flaw
G	Energy release rate
f	Internal frictional coefficient
E	Elastic modulus
I	Moment of inertia
G_s	Shear modulus
μ	Poisson's ratio
p	Tangential compressive stress
σ_N	Cohesion/Radial rock pressure
ω	Deflection of rock beam
D	Bending rigidity of rock beam
k	Bending curvature of rock beam
U	Structural strain energy
W	External work
V	Total potential energy
ΔV	Energy release during rockburst

the Jinping II hydropower station, and Futangba tunnel of the Duwen expressway in Southwest China. The authors concluded that studies on rockburst mechanism must be based on detailed analyses of the rockburst types and geological characteristics of rockbursts, followed by a thorough mathematical and mechanical analysis. By employing this approach, geomechanical types of rockbursts with occurrence criteria were proposed, thereby providing a suitable method to predict and prevent rockbursts.

2. Developing characteristics of rockbursts

Based on the rockburst records of underground works in our research areas, Table 1 gives the general field characteristics of rockbursts.

We proposed a grading scheme for the rockbursts—slight, moderate, strong, and extreme strong—in Table 2 with corresponding characteristics.

The following are the rockburst phenomena that can be easily distinguished:

(1) Sheeting or bed spalling: Rock masses surrounding an underground opening peel off layer-by-layer, producing sheets or plates. The thickness of an individual sheet can lie in the range 0.5–10 cm. The failure plane is usually flat, exhibiting conchoidal radial patterns of fracture.

(2) Buckling break: Surrounding rock masses buckle towards the free surface affected by the high tangential stress. With the progress of fracture and energy release, rock masses fail via buckling, leading to ejection. In general, the failure plane is relatively flat in central parts and jagged along edges.

(3) Dome-like or wedge burst: Surrounding rock masses fail via shear fracture because the local stresses concentrate, followed by ejection phenomena. The failure plane is dome-like or form wedges by combining the shear and tensile-shear fractures.

Table 1
Typical underground works in China and characteristics of rockbursts.

Underground works	Situations	Lithology	Ground stresses	Rockburst characteristics
Cangling tunnel of the Taijin expressway (Wang et al., 2006)	Total length is 7.5 km; the maximum depth is 756 m.	Tuff and granite.	The maximum horizontal principal stress is 12.27 MPa.	Rockbursts occurred as shear slip or spalling off in flakes and lenticles with popping sounds.
Diversion tunnels in the Jinping II hydropower station (Li et al., 2010)	Total length is 17.2 km; general depth is 1500–2000 m; the maximum depth is 2525 m.	Triassic marble, sandy slate and chlorite schist.	The maximum principal stress is 72 MPa.	The minimum depth of rockbursts is 400 m. Rockbursts mostly occurred within 40 m from the tunnel face and in the range 2–6 h after excavation; in the sidewall with 170 cases, tunnel top 130 cases, and tunnel face 100 cases.
Diversion tunnels in the Tianshengqiao II hydropower station (Lee et al., 1996)	Total length is 9.7 km; average depth is 400 m; the maximum depth is 800 m.	Tertiary limestone and dolomite.	The maximum principal stress is 21–26 MPa.	Rockbursts occurred in the dry sections with moderate-jointed rock masses, and generally in the upper-left and bottom-right parts of tunnel.
Diversion tunnels in the Taipingyi hydropower station (Zhou and Hong, 1995)	Total length is 10.5 km; general depth is 200–600 m.	Granite and granodiorite.	The maximum principal stress is 31.3 MPa.	Rock masses behaved as spalling off with ringing sounds; otherwise, behaved as shear slip with thundering sounds. Small-scale rockburst occurred in the complete granites; otherwise, occurred in the jointed rock masses.
Diversion tunnels in the Futang hydropower station (Wu, 2003)	Total length is 19.3 km; general depth is 450–700 m.	Granite.	The maximum principal stress is 18.4 MPa.	Large-scale rockbursts occurred with thundering sounds; otherwise, occurred with ringing sounds. The shapes of failure planes are right-angle, step-like or nest-like.
Erlangshan tunnel of the Sichuan–Tibet highway (Wang et al., 1999)	Total length is 4.16 km; the maximum depth is 770 m.	Limestone, sandstone, siltstone and mudstone.	The maximum principal stress is 17.5–35.3 MPa.	>200 rockburst cases occurred close to the tunnel face, covering an accumulative length of 1095 m. They are controlled by the structure of rock masses.
Futangba tunnel of the Duwen expressway (Li, 2006)	Total length is 5.3 km.	Granite.	The maximum principal stress is 20.8 MPa.	Rockbursts mostly occurred at the exit section of tunnel. The covered length is 2692 m, accounting for 25% of total length of the twin tunnels.
Nibashan tunnel of the Yaxi expressway (Deng, 2009)	Total length is 10 km; the maximum depth is 1650 m.	Rhyolite, andesite and dolomite.	The maximum principal stress is 30–45 MPa.	The strongest rockburst occurred in the side wall with length over 40 m.
Qinling tunnel of the Xikang railway (Gu et al., 2002)	Total length is 18 km; the maximum depth is 1600 m.	Migmatitic gneiss and migmatitic granite.	The maximum horizontal principal stress is 27.3 MPa.	Slight rockbursts produced sheets. Moderate rockbursts produced flakes and lenticles. Bursting pieces of strong rockbursts can be 3.4 m and in various shapes.
Underground works in the Ertan hydropower station (Peng, 1998)	General depth is 220–480 m.	Syenite and gabbro.	The maximum principal stress in main chamber is 64.4 MPa.	Rockbursts can be characterized as three types: with popping sounds, popping and ejection of small pieces, and throwing of large rock blocks.