

A model of rockburst including geological dynamic conditions and mining

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ABSTRACT

Rockburst poses a serious threat to mining safety and can occur under certain combinations of geological and mining conditions. A model of fault-slip burst based on the energy distribution in the rock mass was developed to investigate the mechanics of rockburst and to determine guidelines for safe excavation and operation of underground coal mines. In this model, the energy of the fault involved in the rockburst is assumed to be spherical. The rockburst energy is a combination of the energy from the spherical fault-slip rock mass and the elastic energy from the rock mass ahead of the roadway excavation. We derive the threshold energy for rockburst occurrence from the critical energy condition based on the balance of dissipated and released energy. This method can be applied to estimate the safe distance that tunnel excavation can advance towards the geological structure before rockburst occurs.

KEYWORDS: rockburst; energy; mechanics; geological structure; spheroid

1. INTRODUCTION

Rockburst is a sudden and violent failure of a large volume of overstressed rock, resulting in the instantaneous release of large amounts of accumulated energy (Mine Safety and Health Administration, 1984). Rockburst often leads to rock failure and collapse. It can cause damage to mines, injuries to mine workers, and disruption to mining activity. Several factors are known to affect rockburst: the depth of mining, properties of the rock mass (lithology, elastic modulus, strength, and quality), thickness of the mined deposit, the geological structure of the mine area, and geotechnical characteristics of the rock mass. Additionally, some mining factors can influence the occurrence of rockburst: the mine design, mining method, roof control method, pattern of deposit excavation, concentration of mining operations, and the spatial limits of the mining operations (Dou and He, 2001; Hudyma, 2004; Zhang et al., 2009; Butra, 2010).

The occurrence of rockburst, a sudden rock failure characterized by the breaking up and expulsion of rock from its surroundings, implies that a large amount of energy was released. Cook (1966) defined rockburst as an energy phenomenon and developed the energy release rate (ERR) method. Hoek and Brown (1980) provided graphic illustrations of explosive brittle fracturing in deep hard-rock mines. The only feature common to most rockbursts is that the rock failure is sudden and the strain energy is released from a volume of stressed rock (Ortlepp 1983). Salamon (1983) investigated the

energy changes that occur during mining activities and showed that part of this energy is stored in the rock mass surrounding the excavation. Generally, the instability occurs if the elastic energy released in the deformation process is greater than the fracture energy. He also pointed out three sources for this energy release: a) the strain energy stored in the surrounding rock mass, b) the change in the potential energy of the rock mass, and c) the slippage along the rock wall contact. Petukhov and Linkov (1983) associated the instability of rock mass with rockburst or coal bump and noted that if the potential energy accumulated in the high-stress zone is high enough to destroy the rock near the mine's working area, a rockburst will occur. Mitri et al. (1999) used the energy storage rate (ESR) as a measure of the underground conditions rather than as an indicator of seismicity. Beck (2002) proposed a quantitative assessment and interpretation of rockburst in a hard rock mine using the "factor of safety". Zhao et al. (2003) proposed the minimum energy principle of rock dynamic failure. Xie et al. (2009) established a strength-loss criterion associated with the intensity of energy dissipation and a failure criterion associated with the strain energy release.

Rockbursts occur under certain combinations of geologic and mining conditions. The connection between rockburst and the geology of the mining area was made following the first reported rockburst, which occurred on the 2500 level of the Sunshine Mine in April 1939 (Whyatt, 2002). Brown (1984) indicated that rockbursts induced by mining are

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associated with unstable equilibrium states that may involve: a) slips on pre-existing discontinuities; b) fracturing of rock mass. This leads to the definition of two broad classifications of rockbursts: (1) Type I rockburst, resulting from fault slip events; (2) Type II rockburst, resulting from the failure of the rock mass itself, including strain burst and pillar burst. A degree of rockburst hazard is inevitably associated with the stress near the mine working area and the distance between the mine wall and the maximum stress zone (Petukhov and Linkov, 1983). Recognition of the geologic features that contribute to rockburst events is an important part of strategic planning aiming to minimize these hazards. Many rockburst events are associated with geological factors such as faults, folds, irruptive rock, and tectonic stress. (Batugina and Petukhov, 1990; Driad-Lebeau et al., 2005; Wang et al., 2012; Drzewiecki, 2013). The authors used the term ‘geological dynamic condition’ to describe this state (Han et al., 2013; 2014). Experience in the Coeur d’Alene district in Idaho, USA indicates that certain rock types and various kinds of discontinuities increase the risk of rockburst. Whyatt (2002) showed that ultimate stress state is created by the action of the pre-mining and mining induced stresses. The *in-situ* stress, as well as the rockburst hazards, varied with the geological features in the Coeur d’Alene district (Whyatt 2000).

In China as of 2012, there are 142 coal mines which have had rockbursts. As mining operations become deeper, the frequency and intensity of rockbursts has been increasing accordingly. The prediction and prevention of rockburst is very important for mining safety and continuous operation. Many rockbursts are affected by the geological structure around the mine area and by the mining operation. The current study investigates the energy of the rock mass in mines and the processes of energy release and equilibrium, in order to gain a better understanding of the occurrence of rockburst in various geological and mining conditions.

2. ENERGY OF ROCK MASS

The conservation of energy in rock during its deformation and failure is a dynamic process that represents energy conversion and the equilibrium of the mechanical energy produced by external loads, thermal energy, and the internal energy of the rock according to the non-equilibrium thermodynamic theory. Initially, the rock is in a stable equilibrium state (Figure 1, Position a). After external loading, the rock begins to deform. The mechanical energy produced by the external load and thermal energy is continuously converted into internal energy of the rock. Therefore, the internal rock energy increases and the rock gradually departs from the initial stable

state. For a certain load, a dynamic equilibrium exists among the work of the external load, the thermal energy, and the internal energy; thus, the rock is in a steady state. When the external load become too large, the steady state of the rock moves to the nonlinear non-equilibrium region, away from the equilibrium zone; hence, the rock mass becomes unstable. At the critical state (Figure 1, Position b), the rock state changes abruptly to another state (Figure 1, Position c) with relatively low internal energy, leading to the collapse of the rock. The high stress level destabilizes the rock; whether the rock fails is determined by the internal energy dissipation and the nonlinear dynamic mechanism (Peng, 2011).

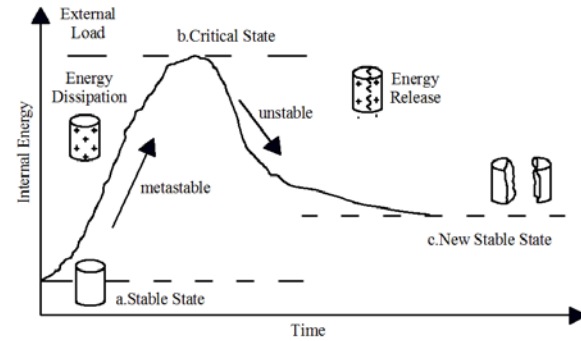


Figure 1: Thermodynamic change during rock deformation and failure (Peng, 2011).

According a rock volume element produce deformation under loading, the total input energy produced by external load is U , as shown in Figure 2 $U = U_i^d + U_i^e$ (1) where U_i^d is the dissipated energy and U_i^e is the releasable elastic strain energy.

The releasable elastic strain energy U_i^e can be described as

$$U_i^e = \frac{1}{2E} [\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu (\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3)] \quad (2)$$

where E is the elastic modulus; μ is the unloading Poisson's ratio; and σ_1 , σ_2 and σ_3 are the major principal stress, intermediate principal stress, and minor principal stress, respectively.

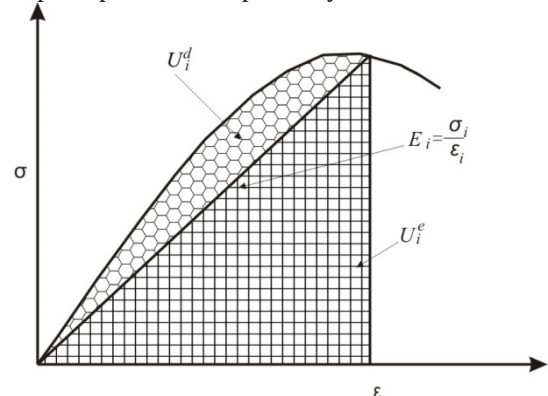


Figure 2: Relationship between dissipated energy and releasable strain energy of rock volume element (Xie et.al 2005).

3. ROCKBURST OCCURRENCE AT MINING AND GEOLOGICAL STRUCTURE

We constructed a model of a fault-slip rockburst that includes the mining conditions and geological dynamic conditions. The model simulates a fault ahead of the roadway excavation work. The area influenced by the fault is a sphere with a radius R . As the roadway is excavated, a plastic and an elastic zone are produced ahead of it. The distance between the sphere boundary and the working end of the roadway excavation is L . L_p and L_e are the lengths of the plastic zone and elastic zone that develop ahead of the excavation, respectively. H is the height of the roadway and L_o is the length of the undisturbed zone - original zone. The stress in the plastic and elastic zones is lower than in the original zone (Figure 3.a).

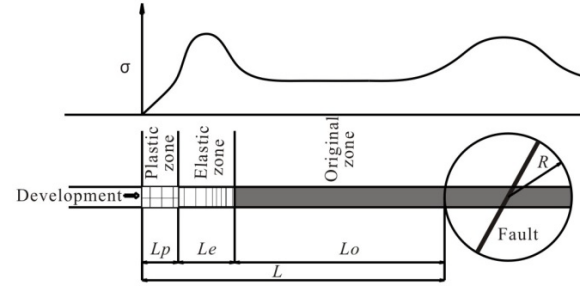
The rock mass attains energy from the deformation of the rock mass at the *in-situ* stress field; it depends on the volume of the rock mass and the *in-situ* stress. We assume that the energy source of the geological structure involved in the rockburst is contained within the sphere. The elastic energy of the sphere U_G is

$$U_G = \frac{2\pi}{3E} [k_1^2 + k_2^2 + k_3^2 - 2\mu(k_1k_2 + k_1k_3 + k_2k_3)] \rho^2 g^2 H^2 R^3 \quad (3)$$

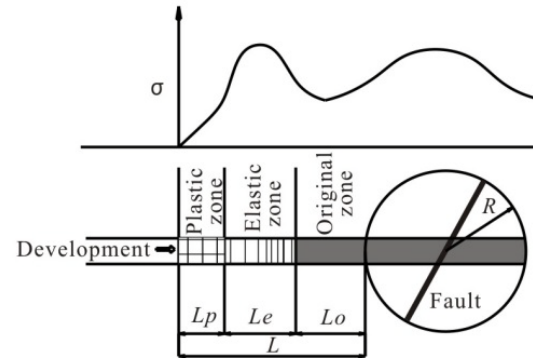
where ρ is the density of the overburden; g is the gravitational acceleration; H is the depth; E is the elastic modulus of the rock; k_1 , k_2 , and k_3 are the ratios of σ_1/σ_h , σ_2/σ_h , and σ_3/σ_h , respectively, where $\sigma_h = \gamma g H$ is the pressure of the overlying strata.

As the roadway is excavated, the fracturing of the coal and rock extends forward, the head of the excavation becomes closer to the sphere of influence, and the volume of the elastic zone gradually decreases (Figure 3.b). When the elastic zone is too small to resist the superimposed stress, rock failure will occur and a large amount of energy will be released (Figure 4). The sphere will also release much energy. This leads to the occurrence of a rockburst. The energy released from the sphere after failure is:

$$\Delta U = U_G - U_z \quad (4)$$



(a)



(b)

Figure 3: A model of mining and geological dynamic condition.

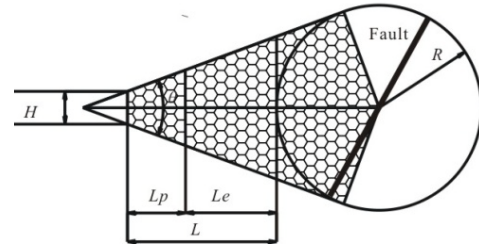


Figure 4: The energy calculation diagram of rockburst.

where U_z is the gravitational energy. According to the principle of minimum energy of the failed rock, the minimum energy of the failed elastic zone is

$$U_{sd} = \frac{\sigma_c^2 V}{2E} \quad (5)$$

where V is calculated as follows

$$V = \frac{1}{3} \cos^2 \frac{\theta}{2} \sin \frac{\theta}{2} \pi R^3 + \frac{1}{3} \frac{\cos^4 \frac{\theta}{2}}{\sin \frac{\theta}{2}} \pi R^3 - \frac{1}{3} \pi \frac{\sin^2 \frac{\theta}{2}}{\cos^2 \frac{\theta}{2}} \frac{\cos^2 \frac{\theta}{2}}{\sin \frac{\theta}{2}} (R - R - l_e)^3 \quad (6)$$

$$\cos \frac{\theta}{2} = \frac{2hR \pm 2\sqrt{h^2 R^2 + (2R + l)l} [4(l + R)^2 + h^2]}{4(l + R)^2 + h^2} \quad (7)$$

$$\sin \frac{\theta}{2} = \sqrt{1 - \cos^2 \frac{\theta}{2}} \quad (8)$$

The parameters in equations (6), (7), and (8) are

shown in Figure 4.

The elastic energy of this zone is

$$U_{SE} = \frac{1}{2E} \int [\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)] dV \quad (9)$$

The energy released in the rockburst U_C can be expressed as

$$U_C = \Delta U + U_{SD} - U_{SD} \quad (10)$$

where ΔU is the energy released from the sphere, U_{SE} is energy of the elastic zone, and U_{SD} is the energy released from the elastic zone during rock failure.

The minimum energy required for the rockburst to occur is expressed as

$$U_{min} = \frac{1}{2} \rho v_0^2 \quad (11)$$

where v_0 is the velocity of the ejected rock during the rockburst event, and $v_0 \geq 10$ m/s (Ortlepp and Stacey, 1994; McGarr, 1997).

If $U_C \geq U_{min}$, then rockburst will occur. Thus, $U_C = U_{min}$ is the critical condition for rockburst occurrence.

This method can be applied to calculate the length of the elastic zone l_e and then determine the distance of rockburst treatment.

4. CASE STUDY OF THE LAOHUTAI COAL MINE

4.1 Background

The Laohutai coal mine is located in the central Fushun coal field, Fushun city, Liaoning Province. To the east lies the Longfeng coal mine and to the west is the Shengli coal mine. The length of the coal seam strike from east to west is 5 km and the width along the dip in the north-south direction is 2 km (Figure 5).

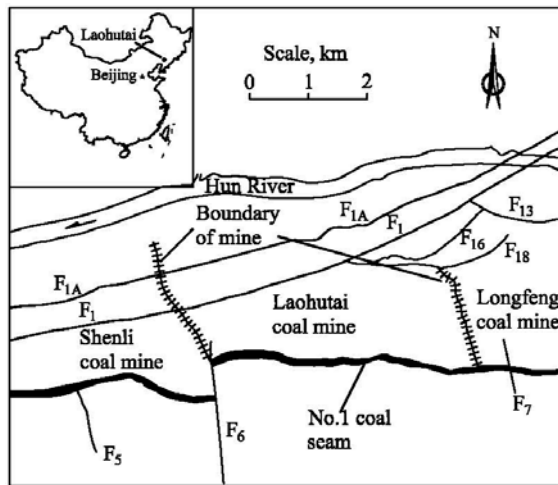


Figure 5: Location and regional geology of Laohutai coal mine.

The overlying rocks include argillite, shale, and oil shale. The thickness of the main coal seam, coal seam No.1, varies from 0.6 to 110.5 m, with an average thickness of 58 m. The main geological structure of the Laohutai coal mine is a syncline trending NEE. The wings of the syncline are asymmetric; the south wing extends smoothly while the north wing inclines abruptly, and is even inverted. There are 14 large faults, including F_1 , F_7 , F_{26} , and F_{18} . The largest one is F_1 which has a drop of more than 1000 m. The deepest buried depth of the coal seam is more than 1000 m.

The Laohutai coal mine is one of the largest state-owned coal mines in China and has been operating for more than 100 years. The mining method is fully mechanized top coal caving and the annual production is about 3 million tons. The Laohutai mine has been associated with various operational challenges such as gas outburst, rockburst, spontaneous combustion, and water inrush and is considered one of the most hazardous mines in China. Rockburst events occurred in 1975 and reached a peak in 2001 (Figure 6). The maximum magnitude of rockburst at the Laohutai mine was $M_L 3.7$. Figure 6 shows the mine rockbursts and associated seismicity during 1993–2014.

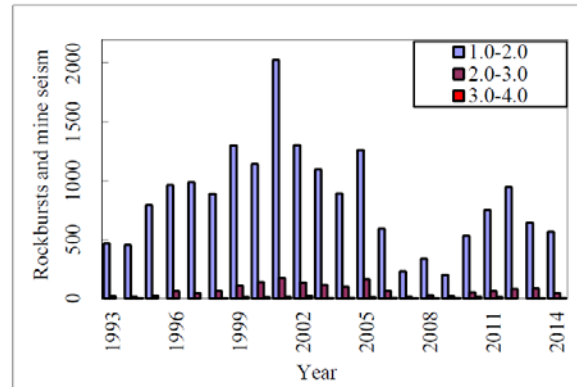


Figure 6: Rockburst and mine seism during 1993-2014.

4.2 Rockburst of Longwall 73005

Longwall 73005 (LW73005) is located in the central part of the Laohutai coal mine at a depth of 749–802 m. Figure 7 shows the layout of LW73005. There are eight faults in LW73005: F_3 , F_7 , F_{26} , F_{32} , F_{36} , F_{37} , F_{38} , and F_{39} .

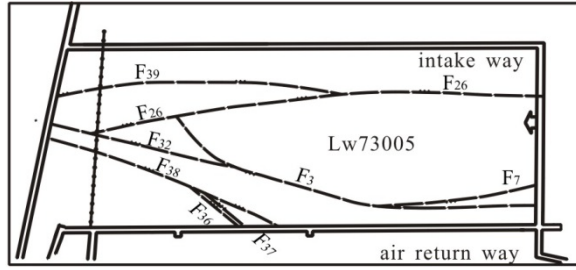


Figure 7: Layout and geological structures of LW73005.

Fault F_{36} was encountered during the excavation of the air return roadway. We use our model to estimate the special range of the energy released by drilling or/and blasting near the fault. According to *in-situ* stress measurements of the Laohutai coal mine, the ratios k_1 , k_2 , and k_3 in Eq. (3) are 2.0, 1.0, and 0.7. The energy of the sphere can then be described as

$$U_G = \frac{2\pi}{3E} (5.49 - 8.2\mu) \rho^2 g^2 H^2 R^3 \quad (12)$$

When the rockburst occurs, the energy released from the sphere is

$$\Delta U = \frac{2\pi(10.2\mu^2 - 12.69\mu + 4.49)\gamma^2 H^2 R^3}{3E(1-\mu)} \quad (13)$$

The result is shown in Table 1. The bigger the ΔU of sphere, the bigger the l_e , and the longer the distance of treatment. Based on the calculation, the safe distance of treatment is 36 m. Thus, when the development of roadway reaches a distance of 36 m from F_{36} , drilling and/or blasting should be carried out to release energy and prevent a fault-slip burst.

Table1: Parameters of spheroid and distance of treatment.

No.	Work face	H (m)	h (m)	R (m)	l_p (m)	ΔU (MJ)	l_s (m)
1	LW73005	778	3.6	6.3	2	91	36

5. CONCLUSIONS

According to the theory of energy exchange and equilibrium in rock mass we constructed a model of fault-slip burst in a mining environment. The geological structure is included and assumed as a sphere during the rockburst occurrence. The rockburst energy is a combination of the energy of the sphere and the energy of the elastic zone that develops ahead of the tunnel excavation. Part of the energy is dissipated in the elastic zone. When that energy rises above the critical rock failure energy, rockburst will occur. This method can be applied to estimate the safe distance and the rockburst treatment that should be taken when performing roadway excavation towards a geological structure, before rockburst occurs.

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