Rock failure mechanisms in the surrounding rock masses with deep level tunnels and in the source areas of disastrous events

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Definition, mechanism, classification and quantitative prediction model for rockburst and pressure bump

In this paper, the definitions and mechanisms of rockburst proposed by authoritative experts are reviewed. On this basis, rockbursts are divided into the sliding mode resulted from fault slip or shear rupture and the strain mode due to rock failure according to different mechanisms. The mechanism and characteristics of two types of rockburst and pressure bump are analyzed with case studies. The quantitative prediction results for strain burst in rock (coal) pillar, strain burst and fault-slip rockburst in the surrounding rock masses are presented. The latest research achievements on quantitative prediction and numerical simulation of strain burst by considering the effect of the non-compatible deformation using the non-Euclidean geometry model are introduced.

Key words: rockburst mechanism; Fault slip; Strain burst; Quantitative prediction.

Introduction

With the development of transportation and economy, many mines and tunnels have been constructed in deep underground space. The mining depth has reached 4,000 m and the planned mining depth is up to 5,000 m. The maximum overburden depth for civil tunnels has been more than 2,500 m. Rockburst has become a universal problem for mines and tunnels excavated at great depth [1]. Rockbursts occur frequently in mines in South Africa, Chile, Canada, Australia and Russia, and tunnels in Norway, USA, China, Sweden, Switzerland and other countries. Rockbursts severely threaten the safety of construction crew and result in huge economic losses. For instance, on 28 Nov 2010, a rockburst occurred in the headrace tunnel of Jinping II Hydropower Station at a depth of 2,500 m, which killed 7 people and led to severe damage to the full-face tunneling machine.

1. Definition and mechanism of rockburst

The definition, mechanism and classification of rockbursts proposed by international authoritative experts are basically similar.

Rockburst is a physical phenomenon. Therefore, it shall be defined by description of the phenomenon. The following definition and mechanism of rockburst are quoted:

(1) Rockburst is catastrophic rock failure, characterized by rock fragmentation and ejection from the surrounding rock masses, accompanied by sudden and violent energy release [2].

(2) Excavation of an underground cavity or change of an existing cavity leads to stress change in the surrounding rock masses. The change in stress state may trigger slippage on pre-existing discontinuities or result in failure of rock masses near the cavity [3]. The first type is defined as rupture of existing fractures, and the second type is defined as brittle failure of a certain volume of rock [3].

(3) For occurrence of rupture rockburst, the in situ or induced stress level shall be high enough so as to re-activate the movement of existing fault surfaces or initiate the movement of geological structural planes, or create fractures (new “fault”) in the rock mass. Rockburst is the result of dynamic failure of rock mass [1].

(4) The essence of seismic events (rockburst) in mines is that the surrounding rock mass has obtained a certain amount of kinetic energy [4].

(5) Mining-induced rockbursts are related to unstable equilibrium state, including a) slippage on the pre-existing discontinuities; b) Fracturing of rock masses [3].

2. Classification of rockburst and pressure bump

Rockbursts may be classified into different types due to different appearance. However, the essence of physical phenomenon is the same.

The terms, “seismic event”, “dynamic event”, “dynamic phenomenon”, “dynamic instability”, “catastrophe”, and “catastrophic instability”, have similar meanings, which indicate the catastrophic process from an equilibrium state to another state, accompanied by release of excess energy by stress waves. It can occur in various scales. In specimens under loading, it appears at mesoscopic scale and between molecules, accompanied by acoustic emissions; In mines, it appear in the form of rockburst other than acoustic emissions; In the crust, in addition to the relatively small catastrophe, sometimes violent catastrophe may occur, such as earthquakes [5].

Two types of rockburst are in fact two types of catastrophes: volume instability and contact instability [5]; Type I rockburst is caused by fault-slip events; Type II rockburst is caused by rock failure, including strain burst in the surrounding rock masses and strain burst in rock pillars [3].

The dynamic failure in form of rockburst can be generally divided into two types. The first type is usually called strain burst, which is caused by rock failure; the second type is caused by fault slip or shear rupture. The main difference between the two types is as follows: For the first type, the disturbance source (excavation) and rockburst are coincident; For the second type, the disturbance source and the corresponding rockburst are separated at a considerable distance. The energy associated with fault-slip rockburst is generally much higher than that for strain burst. Fault-slip rockbursts are often much intensive than strain bursts. Roadway within tens or hundreds of meters may be damaged by a single fault-slip rockburst in mines [1].

A great amount of seismic events in hard-rock mines belong to fault-slip rockbursts [6].

Accumulated evidences in South Africa mines show that slippage along the pre-existing planar or near planar discontinuities or fresh fractures play a dominant role.

The influence of blast wave on rockburst shall not be neglected. 89 out of 114 (or 78%) rockburst events at depth of 700–900 m in Mentougou Mine were triggered by explosion. More than 50% of rockbursts at depth of 700 m in Longfeng Mine were also induced by blasting. It can be inferred that coal at such depths is in a quasi-stable equilibrium state. The blasting-induced rockbursts may lead to fatal accidents. Roof burst also occurred in some mines. The more adverse effect of hard-rock roof is that roof burst may extend far ahead of the long-wall working face, and further leads to instability and rockbursts.

In order to analyze the similarities and differences between pressure bump and rockburst, the investigation results for two major pressure bump accidents in two mines in China are presented:

(1) Comprehensive analysis of pressure bump accident in Huafeng Mine: Pressure bumps occurred at a few working faces in 4# coal seam. Above the Huafeng Jintian coal seam is 500-800m conglomerate layer, which is hard and intact. Fracturing of the conglomerate layer generated impact

loading on the underlying coal rock, which is the main mechanical source of pressure bumps at the working face in 4# coal seam.

(2) Investigation report for “11.3” major pressure bump accident in Qianqiu Mine of Yima Coal Group: 10 were killed and 64 were injured. The roof stratum in the mining area is extremely thick glutenite layer (380–600 m). The accident occurred near the F16 regional thrust fault which has a fault throw of 50–500 m. The stratum is locally vertical or inverted, and the tectonic stress is extremely high. This region is highly prone to strong pressure bumps. During mining, the underlying F16 thrust fault was activated by the overlying glutenite layer, which spontaneously triggered pressure bump accidents with huge energy.

Based on the aforementioned definition, mechanism and classification of rockbursts, and the investigation results on two pressure bump accidents, the following judgments on the mechanism of pressure bumps can be made: in mines with multiple strata and roadways, a great amount of fractures have been accumulated in the rock masses (coal) after multiple excavations. The continuously fractured or non-continuously fractured rock blocks are in a quasi-stable equilibrium state, which belongs to contact-surface quasi-stable equilibrium, or shear quasi-stable equilibrium state. When blasting or roof rupture occurs, propagation of blasting wave or impact of roof rupture induces instability of the quasi-stable equilibrium state, leading to occurrence of pressure bumps. The mechanism of the pressure bump is of the same type with the fault-slip rockburst or shear rockburst, belonging to generalized rockburst.

3. Quantitative prediction and numerical simulation of rockburst

Rockbursts often result in casualties and equipment damage. Forecast of rockburst is necessary and pressing. However, the complexity of rockburst mechanism has made rockburst prediction very difficult. First of all, due to randomness and complexity of rockburst mechanism, accurate prediction of the occurrence time of rockburst is impossible. Nevertheless, rockbursts are mainly determined by stress changes induced by excavation in deep rock masses. Rapid development of geological investigation techniques, in situ stress measurement techniques, rock mechanics theories and methods, and numerical simulation methods has made quantitative prediction and numerical simulation of rockbursts possible.

Now is the time for development of quantitative prediction models. Such quantitative predictions can only be realized by elaborate combination of numerical modelling and field observations [1, 4].

4. Principle of quantitative prediction for strain rockburst

The strain burst can be further divided into two types: rockburst in rock (coal) pillars and rockburst in the surrounding rock mass. They have slightly different principles of quantitative prediction, which will be discussed in the following sections.

4.1. Quantitative prediction of strain burst in rock (coal) pillar [3].

Prediction of strain burst in rock pillar is based on the principle that the dynamic failure (rockburst) of rock pillar is similar to the mechanism of violent failure of rock specimen by a flexible testing machine. As pointed out by Petukov [9, 10] and Cook [11] in 1950s–1960s, it is nowadays well known that the test has to be performed by a stiff testing machine in order to obtain the full stress-strain curve of rock specimen under uniaxial compression. On the contrary, if a flexible testing machine is employed, violent failure occurs in the rock specimen during the stress declining stage. A stiff testing machine means that the machine has a stiffness higher than the specimen; otherwise, the machine is flexible. Figure 1 shows the effect of relative stiffness on the failure property of rock specimen.

The key to quantitative prediction of rock pillar rockburst is calculation of the stiffness of the rock pillar and surrounding rock mass. If the post-peak stiffness of rock pillar is higher than the stiffness of surrounding rock masses, rockburst is likely to occur. Otherwise, progressive failure will occur (collapse).

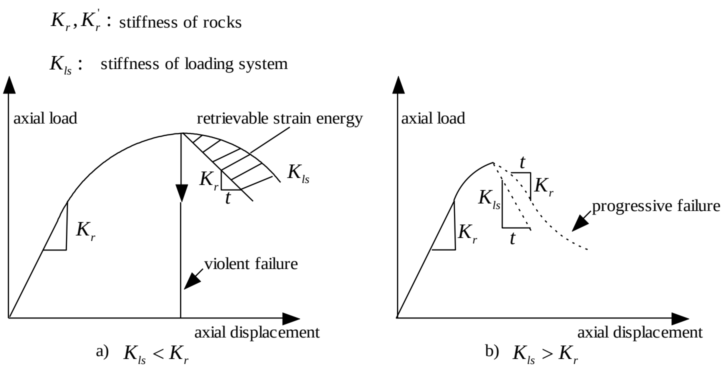
(1) Calculation of stiffness of rock pillar ($K_{\mathrm{pr}}, K'_{\mathrm{pr}}$)

(a) Stiffness of long rock pillar (plane strain type) (unit thickness)

$$K_{\mathrm{pr}} = \frac{EB}{H(1-\nu^2)} \quad \text{(pre-peak)}, \tag{1}$$

$$K'_{\rm pr} = \frac{E'B}{H(1-v^2)} \quad \text{(post-peak)}, \qquad (2)$$

where E, E' are the elastic modulus of rock mass before and after peak, respectively; v is the Poisson's ratio; B is the pillar width and H is the pillar height.



(a) $K_{ls} < K_r$ (b) $K_{ls} > K_r$

Fig. 1. Effect of relative stiffness between rock specimen and loading system on the failure property under uniaxial compression [11]

(b) Correspondingly, for stiffness of narrow rock pillar, we have

$$K_{\rm pr} = \frac{EBS}{H(1-v^2)}, \qquad (3)$$

$$K'_{\rm pr} = \frac{E'BS}{H(1-v^2)}, \qquad (4)$$

(2) Calculation of stiffness of the surrounding rock mass ($K_{\rm ls}$).

The calculation model is shown in Figure 2.

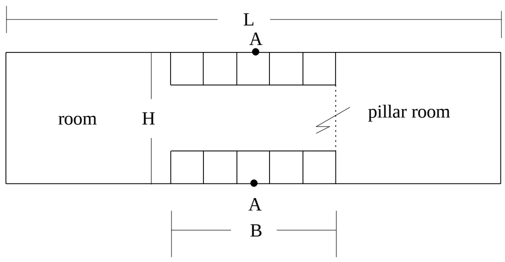


Fig. 2. Calculation model for stiffness of surrounding rock mass

For long rock pillars, two-dimensional computation is performed. For narrow rock pillars, three-dimensional computation is required. A curve can be plotted based on the loading $BS\sigma_{\rm p}$ and the displacement D at Point A. The slope of this curve is the local stiffness $K_{\rm ls}$ of the surrounding rock mass.

$K_{\rm ls} < K'_{\rm pr}$ rockburst (violent failure),

$K_{\rm ls} > K'_{\rm pr}$ progressive failure (collapse).

The above is the principle for qualitative prediction of rock pillar burst. The principle for quantitative prediction of rock pillar burst is the same as the below-mentioned strain burst in the surrounding rock mass and will be discussed in the following section.

4.2. Quantitative prediction of strain burst in surrounding rock mass.

In order to quantitatively predict the location and scale of strain burst in the surrounding rock masses and the rock block ejection speed, the following three issues need to be solved [8]:

(1) Where rock fracturing occurs in surrounding rock mass: the stress field after excavation can be determined by the non-Euclidean geometry model considering non-compatible deformation [8].

(2) How rock fracturing occurs: the strain energy stored and energy dissipated by fracturing at each point in the surrounding rock mass. Determination of dissipated energy depends on the initiation and propagation (including both stable and unstable propagation) criteria for rock fracturing [8].

(3) When rockburst occurs: the criteria for potential rockburst, instant rockburst and delayed rockburst in the fractured zone need to be studied.

For the first problem, as the precondition for rockburst is rock fracturing, the rock mass is no longer continuous and doesn't satisfy the strain compatibility equation. The stress field in the surrounding rock mass shall be calculated using the non-Euclidean geometry model considering non-compatible deformation in rock. The solutions of the non-Euclidean geometry model are consistent with the microfracturing and stress fluctuation in the surrounding rock mass, which cannot be described by the solutions of continuum mechanical model.

Rock is a heterogeneous medium. Rock mass contains pre-existing microfractures of various scales. The distribution of microfractures is stochastic and can be determined by mesoscopic structure tests. For simplicity, the first order approximation is adopted. The pre-existing microfractures are assumed to be evenly distributed, the scale can be described by a statistical average value, and the density is obtained by the method of averaging.

The second problem can be solved by using the fracture mechanics theory. The fracturing process of the surrounding rock mass involves propagation of the pre-existing fractures along interfaces and toward the excavation boundary, stable and unstable propagation of secondary fractures, coalescence of microfractures and formation of macroscopic fractures, eventually leading to rock failure.

In order to solve the third problem, the development process of strain burst shall be understood first. It can be summarized as: Stage 1, excavation unloading leads to fracturing and fragmentation of surrounding rock masses; Stage 2, acceleration and ejection of rock fragments under stress gradient in the surrounding rock mass. Meanwhile, the strain energy is transformed to kinetic energy.

The classification of strain burst in the surrounding rock masses is based on the energy theory, i.e., the essence of dynamic failure (rockburst) is transformation of excess energy into kinetic energy [4, 5, 9]. Therefore, the kinetic energy of rock fragments is approximately equal to the difference between the strain energy stored in the surrounding rock mass under high in situ stress and the energy dissipated during rock fracturing. Based on this principle, the strain burst in the surrounding rock mass can be divided into: potential rockburst, instant rockburst and delayed rockburst.

(1) Potential rockburst: the surrounding rock masses are fractured, but no rockburst occurs; the energy dissipated during propagation of the pre-existing microfractures and secondary microfractures is greater than the strain energy stored in the rock masses (no excess energy).

(2) Instant rockburst: the length of secondary fractures is greater than the critical value, macroscopic fractures are formed due to unstable fracture propagation, and the fractured zone reaches the

excavation boundary; the total energy dissipated during secondary fracture propagation is less than the elastic strain energy stored in the surrounding rock mass.

(3) Delayed rockburst: the fractured zone does not intersect with the excavation boundary; the total energy dissipated during secondary fracture propagation is less than the elastic strain energy stored in the surrounding rock mass and the excess energy is transformed into kinetic energy of rock fragments; the movement of rock blocks leads to fracturing and ejection of rock masses on the shortest path to the excavation boundary.

Prediction of fault-slip rockburst [5]

The following assumptions are made for prediction of fault-slip rockbursts: there is only one fracture surface; the rockburst is related to the catastrophic change of shear resistance acting on the fracture surface; the orientation and location of the existing fractures are independent of stress field calculation and the orientation and location of new fractures are determined by the stress field; the fracture surface is planar, which is rational and simplifies the calculation process; the rock mass is elastic.

Firstly, the stress field induced by excavation and blasting (dynamic loading) in the surrounding rock mass shall be calculated, i.e., determination of the normal stress σ perpendicular to the fracture surface and the shear stress τ on the fracture surface (Figure 3). Whether slip occurs or not can be judged by the criterion $\tau - \tau_{\mathrm{r}} > 0$.

For excavation-induced rockbursts,

$$\tau - (\mu_{\mathrm{s}}\sigma + c) > 0. \tag{5}$$

For dynamic loading-induced rockbursts,

$$\tau - (\mu_{u}\sigma + c) > 0. \tag{6}$$

The corresponding fiction resistance τ_{r} is:

$$\tau_{\mathrm{r}} = (\mu_{\mathrm{s}}\sigma + c) \text{ or } \tau_{\mathrm{r}} = (\mu_{u}\sigma + c_{u}) \ , \tag{7}$$

where σ is the normal stress on the fracture surface; μ_{s} is static friction coefficient; μ_{u} is the ultralow friction coefficient; c is the cohesion. If $\tau - \tau_{\mathrm{r}} > 0$, slip occurs. Otherwise, the fracture surface is stable and no slip occurs.

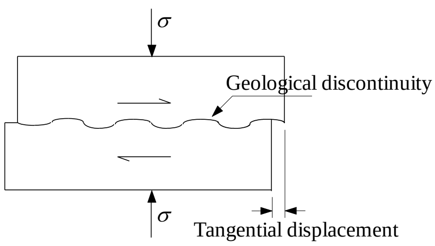


Fig. 3. Slip failures of rock mass

In order to predict the magnitude of rockbursts, the kinetic energy after rockburst shall be calculated:

$$W_{\mathrm{k}} = W_{\mathrm{r}} - W_{\mathrm{h}} \ , \tag{8}$$

where W_{r} is the energy released during rockburst; W_{h} is the energy consumed due to friction; W_{k} is the excess energy transformed into kinetic energy.

$$\left.\begin{aligned} W_{\mathrm{r}} &= \frac{1}{2}\int_A S_{\mathrm{t}}(\tau+\mu\sigma)\mathrm{d}A \\ W_{\mathrm{h}} &= \mu\int_A S_{\mathrm{t}}\sigma\mathrm{d}A \\ W_{\mathrm{k}} &= \frac{1}{2}\int_A S_{\mathrm{t}}(\tau-\mu\sigma)\mathrm{d}A \end{aligned}\right\}, \qquad (9)$$

where S_{t} is the slip displacement; A is the area of fracture surface; μ is the dynamic friction coefficient of fracture surface and $\mu_{超}$ shall be used for blasting-induced rockbursts.

For further simplicity, σ is considered to be constant in the space of slip fracture surface; the fracture surface is a disk; the slip displacement is taken as the average value S_{AV}. Then,

$$\left.\begin{aligned} W_{\mathrm{r}} &= \frac{1}{2}\int_A (\tau+\mu\sigma)S_{\mathrm{AV}}\cdot A \\ W_{\mathrm{h}} &= \mu\sigma A S_{\mathrm{AV}} \\ W_{\mathrm{k}} &= \frac{1}{2}\Delta\tau A S_{\mathrm{AV}} \end{aligned}\right\}. \qquad (10)$$

The decrement $\Delta\tau$ in shear stress during slippage is

$$\Delta\tau = \tau - \mu\sigma . \qquad (11)$$

The distribution function of slip displacement is:

$$S_{\mathrm{t}} = \frac{4(1-\nu)\Delta\tau}{\pi(1-\nu/2)G}\sqrt{R^2-r^2} . \qquad (12)$$

The average slip displacement is:

$$S_{\mathrm{AV}} = \frac{1}{A}\int_A S_{\mathrm{t}}\mathrm{d}A = \frac{8(1-\nu)\Delta\tau R}{3\pi(1-\nu/2)G}, \qquad (13)$$

where R is the radius of the fracture surface; r is the coordinates of the calculation point; ν is the Poisson's ratio; G is the shear modulus.

Procedures for quantitative prediction of rockbursts in rock engineering [3]

With the aforementioned principles and methods for various types of rockbursts, the procedures for quantitative prediction of rockburst in engineering practices are summarized as follows: Fig. 4.

Among the four steps, Step 1 is the basis. Only when the geological structural planes, initial geo-stresses and mechanical parameters of rock masses are identified, the remaining steps can be implemented. Step 2 is the key to quantitative prediction. Only if the rockburst susceptibility of various zones is analyzed, the rockburst risk in each zone can be identified and the priority of quantitative rockburst prediction for various zones can be evaluated. Depending on whether there are geological structural planes in the zone, the possibility of two rockbursts types may be analyzed in some zones, or only one rockburst type shall be checked in Step 3. Step 4 can be carried out according to Sections 4.1 and 4.2.

Identification of susceptible rock structures [3]

Three types of rock structures susceptible to rockbursts will be introduced in the following section. In other cases, the rockburst susceptibility can be determined by the excavation-induced stress field and specific location of geological structural planes.

(1) Figure 5(a) shows a tunnel being excavated close to a major fault. Excavation leads to increase of shear stress on the fault, and decrease of the normal stress on the fault. Both stress changes can trigger fault slippage and possible fault-slip rockburst.

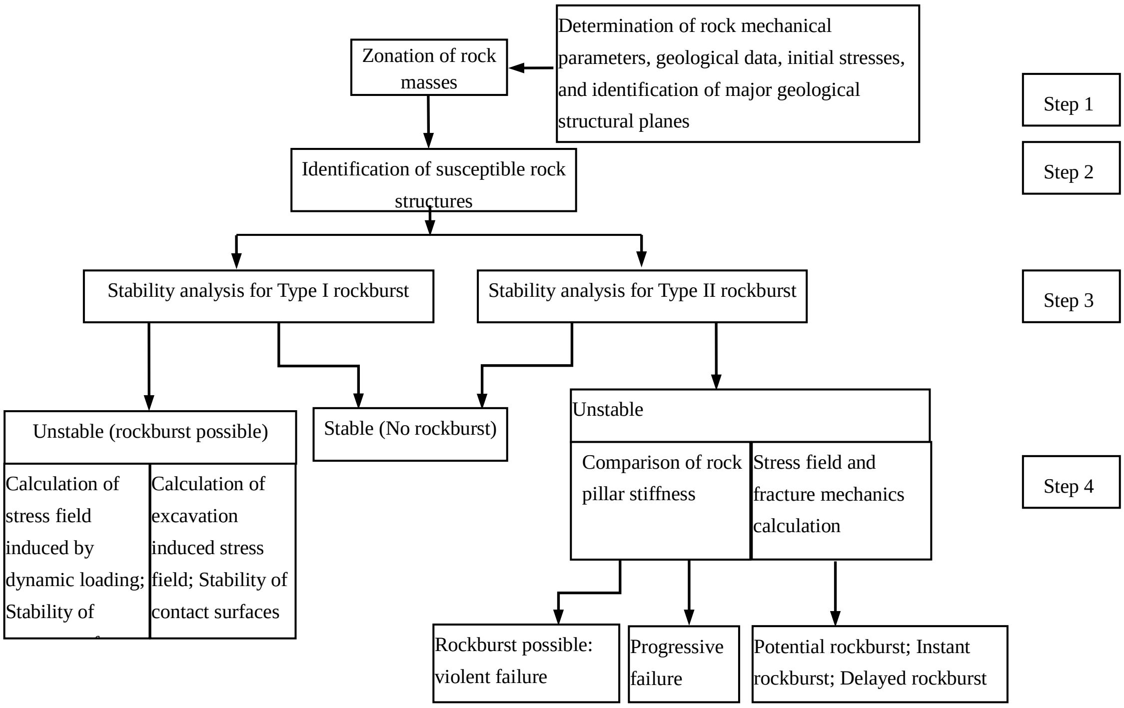
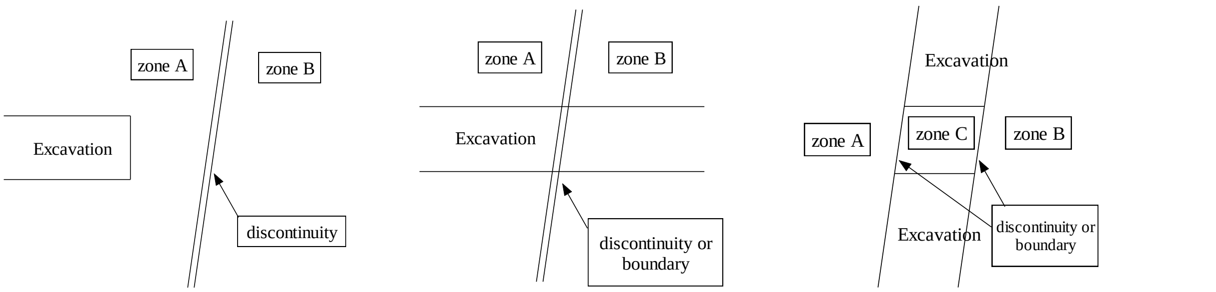


Fig. 4. Flowchart for quantitative prediction of rockbursts in rock engineering



(a) Tunnel excavated near a major fault, susceptible for fault-slip rockburst

(b) Tunnel excavated through a major fault or lithological boundary, susceptible for strain rockburst

(c) Tunnel excavated along a major fault or boundary, susceptible for strain rockburst

Fig. 5. Rock structures susceptible for rockburst

(2) Figure 5(b) shows a tunnel being excavated through a fault or lithological boundary. No fault-slip rockburst occurs at this moment. However, some rock masses close to the fault are fractured. Depending on the relative deformation of rock masses in Zones A and B, the failure may be violent (rockburst).

(3) Figure 5(c) shows a tunnel being excavated along a fault or lithological boundary. Zone C is a rock pillar. Depending on the deformation properties of rocks in Zones A and B, violent failure may occur in Zone C (rock pillar) when a certain condition is met. This case may also be applicable for an isolated rock mass structure, i.e., it is different in lithology or has an irregular geometric shape compared to the surrounding rock masses.

Conclusions

(1) From the viewpoint of phenomenology, rockburst is catastrophic failure of surrounding rock masses or rock pillars, characterized by rock fragmentation and ejection, accompanied by sudden and violent energy release. Excavation or dynamic loading leads to redistribution of stress field in the surrounding rock

masses, or directly results in fracturing and ejection of rock blocks, or leads to rock failure and ejection by slippage of the existing faults and structural planes (activated) or new structural planes.

(2) Classification of rockbursts: Type I rockburst is the strain burst or rockburst due to unstable volume changes (rock mass failure). The locations of disturbance source and rockburst damage coincide. Type II rockburst is the fault-slip rockburst or shear rupture rockburst. This type of rockburst is caused by unstable contacts between faults or fractured surfaces. The locations of disturbance source (blasting or roof rupture) and rockburst (pressure bump) are apart by a considerable distance. Type II rockburst is more prevalent and violent than Type I rockburst and it can destroy roadways within tens to hundreds of meters.

(3) Most pressure bump events in mines belong to Type II rockburst. Especially in mines with multiple strata and roadways, the existing and new structural planes and fractures are in a quasi-stable state after multiple excavations. The surrounding rock masses are cut into a rock block system by the structural plane and fractures. Under dynamic loading (blasting or roof rupture), the rock block system becomes unstable, leading to occurrence of pressure bump.

(4) The project site is divided into various zones and the susceptibility for rockburst is identified for each zone. Zonation is based on geological investigation, identification of geological structural surface ad determination of initial geo-stresses and mechanical parameters of rock masses. The stability analysis for rockburst can then be carried out. The first step is to calculate the stress field after excavation or blasting. For fault-slip rockburst, the stability of structural planes (fracture surfaces) can be checked against the relevant criterion. For strain burst, quantitative prediction can be made according to qualitative prediction and fracture mechanics equations.

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