Chapter 3

Rockburst concept and mechanism

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Abstract: This chapter presents a variety of rockbursts in five sections: (i) the rockburst introduction, (ii) classification according to triggering mechanisms and modeling approaches, (iii) the study of the above classifications, (iv) the criterion of rockburst, and (v) a brief summary of this chapter. Innovative work has been done in developing the 'strainburst testing machine' and 'impact-induced rockburst testing machine' that create a new era in which varied rockburst phenomena can be produced in the laboratory. New concepts are proposed regarding the stress paths for artificially produced rockbursts, the strain-burst criteria, and impact-induced rockburst criteria that take into account both the static and dynamic stress states analogous to that at excavation boundaries. This research provides us with a basis for rockburst prediction and control in the field.

1 INTRODUCTION

With fast development of economies and industrial construction, world-wide exploitation of the natural resources will inevitably proceed into deep ground. As countries across the world recognize their underground resources as a growth point for the national economy, geotechnical engineering goes into deep ground as well. The scale and depth of underground engineering for the nuclear industry, national defense industry, transportation industry, and hydraulic engineering are growing at particularly high speed. The frequencies of various disasters have increased significantly as a result of the increasing depths for underground projects. Among them the most serious problem is rockburst hazards induced by high ground stresses (Qian, 2010).

Rockbursts, as a catastrophic phenomenon in underground engineering, are characterized by a sudden, explosive expulsion or ejection of the cracked country rocks. In underground coal mining, the rockburst phenomenon is also known as coal bursts or coal bumps. Rockbursts or coal bumps cause destruction of the supporting equipment in a mining stope; distortion and destruction of the stope and drifts; casualties among the mine personnel; and even collapse of the ground surface accompanied by local seismicity. Therefore, mechanisms, forecasting and prediction, as well as control of rockbursts, have become key scientific problems to be tackled. The problems facing the community of rock mechanics are technically complex and difficult. Numerous research projects on rockburst mechanisms have been carried out across the world and notable discoveries made (He, 2006; He et al., 2010, 2012a, 2012b, 2015; Tang &
Most of the findings seen in the publications and international conferences have been on the basis of qualitative explanations. As for the forecasting and prediction of rockbursts, although quite a few successful experiences were achieved, no systematic theoretical results have been built up. Some experts even assert that there is no possibility for rockburst forecasting.

However, the degree of difficulty and scale of rock engineering in its current state in China is so large that it has been the focus of world attention. Scientists and researchers in our country should undertake overall and in-depth studies of rockburst mechanisms, and provide the development of rock engineering in deep ground with strong support in practical techniques and scientific theory (Qian, 2010). This paper presents the authors’ achievements in researching the rockburst mechanisms and their control measures, involving development of laboratory rockburst testing machines; theoretical and experimental investigations; and development of the constant resistance large deformation (CRLD) bolt, as well as its practical use in roadway support under rockburst conditions (He, 2006; He et al., 2007, 2009, 2010, 2012).

2 ROCKBURST CATEGORIZATION

A rockburst is generally defined as a sudden rock failure characterized by the breaking up and expulsion of rock from its surroundings, accompanied by a violent release of energy (Blake, 1972). Although the definition of rockburst differs from one author to another, the common ground of these definitions is the sudden release of energy in the form of a violent expulsion of rock (McMahon, 1988). Brown (1984) suggests that a rockburst should be considered as a particular manifestation of seismic activity that is induced by mining activities. In fact, the sudden failure that characterizes a rockburst can be, in itself, the source of the seismic event, or may have been triggered by a distant seismic event, or from a load transfer due to the latter (Gill & Aubertin, 1993).

It is well understood that classification and categorization of the naturally occurring phenomena in question is one of the major approaches, or the preliminary step, for further investigation in scientific research practice. Since Morrison (1942) and Blake (1972) first reported on an Indian gold mine, rockbursts have been categorized according to the phenomena (Kaiser et al., 1995); the mechanisms (Simon, 1999); the energy (Corbett, 1996); the scale and location (Ghose & Rae, 1988); the cause and effect (Jiang et al., 2007; Qi et al., 2003), as well as the detonation source mechanism of rockbursts; the relationship between the parameters of the detonation source; the first motion signs of a seismic wave; the location where the rockburst occurred and the magnitude of released energy; the stress paths that induced a rockburst; and the causes for the formation of a rockburst event (Cook, 1965; Brady & Brown, 2005; Ryder, 1988; Henry et al., 1989; Kuhnt, 1989; Corbett, 1996).

The authors categories the rockburst according to triggering mechanisms and the related laboratory physical modeling approaches. That is, a rockburst may happen in the following two conditions: (i) in a highly stressed rock mass storing a large amount of the strain energy during roadway excavations or a face stopping phase, and (ii) in less stressed and deformed rock storing a lesser amount of the strain energy after the excavations phase, but induced by the external disturbances in the far-field region
such as blasting, caving, and adjacent tunneling, etc. Based on this awareness, rockburst phenomena under two different conditions can be categorized into two major classes (depicted in Figure 1):

Class I: the strainbursts or excavation-induced rockbursts occurred during process of the excavation
Class II: the impact-induced rockbursts occurred after the excavation.

Strainbursts (or stress-induced rockbursts) occur during the excavation phase and are induced by the redistribution of excavation-induced stress. They include tunnel burst (induced by tunnel excavation), stope burst (induced by stope excavation) and pillar burst (induced by pillar excavation). The seismic site and source for strainbursts are the same: at, or near, the excavation boundaries (for tunnel burst and stope burst) or at the pillar face (for pillar burst). Impact-induced rockbursts take place at the excavation boundaries and are initiated by far-field seismic waves, and could be further classified into three types: rockbursts induced by blasting or excavation; rockbursts induced by roof collapse; and rockbursts induced by fault slip. The dynamic nature of this kind of event will be dealt with specifically in the Section 5 of this paper.

3 ROCKBURST STUDY

It was known to all that indoor rockburst experiments play an important role in understanding its formation mechanisms, calibration of numerical models, evaluation of mechanical parameters, and identification of the stress state where a dynamic event may be initiated. The primary goal for researchers who were engaged in the physical
modeling of rockburst phenomena is to reproduce the stress states in the laboratory in a faithful manner, to simulate the conditions under which a dynamic event may occur. Great efforts were made in developing tri-axial or true-tri-axial devices to achieve this end, involving work done by Mogi (1967), Crawford & Wylie (1987), Chang & Haimson (2000), Chen & Feng (2006), Haimson (2006), Lee & Haimson (2011), for example. Although some degree of success was achieved with these studies, they did not, however, reproduce conditions for testing rock specimen analogous to the in situ event, i.e. from a stationary or equilibrium state, transferred to the critical state and then attaining the final chaotic state where a large volume of the fractured rock is ejected. This Section presents the research achievements to accomplish these goals carried out in the State Key Laboratory for Geomechanics and Deep Underground Engineering (LGDUE) at the China University of Mining & Technology Beijing (CUMTB) involving the development of the strainburst testing machine and the impact-induced testing machine based on the above rockburst classifications (Class I and Class II).

3.1 Studies on strainburst

3.1.1 Strainburst testing machine

The strainburst testing machine, developed by He (2006), is shown in Figure 2; its main task is to simulate the stress-induced rockburst phenomena (Class I rockburst in Figure 1, Patent No. ZL 2007 1 0099297.1). Figure 2a is the schematic of the main unit of the testing machine, a modified true-tri-axial apparatus (MTTA). The MTTA can provide dynamic loading/unloading independently in three principal directions (He et al., 2010). Load in the minimum principal stress direction (horizontal) can be unloaded abruptly on one face and displacement constraint condition is maintained on the opposite face, simulating the stress condition for rock mass at the excavation surface. Its major technical specifications are also shown in Figure 2(a).

![Figure 2 Strainburst testing machine; (a) schematic of the testing machine, and (b) photograph taken in the laboratory for an overview of the testing machine and the peripheral monitoring instruments.](image-url)
Figure 2b is a photograph showing an overview of the strainburst testing machine. In addition to the MTTA, the testing machine is equipped with a hydraulic control system and monitoring instruments such as those for force monitoring, acoustic emission (AE) monitoring, and high-speed digital camera recording. The AE monitoring system manufactured by PAC (Physical Acoustics Corporation, USA) was used with two polarity transducers mounted on the two sides of the specimen (the intermediate principal direction, in Figure 2a). The resonance frequency is 150 kHz, the fairly flat response ranges from 0–400 kHz; the pre-amplification is 40 dB, gain amplification is 10 times, and the total amplification is 1000 times; the data acquisition rate was set to 1 MHz. AE events were monitored over 0–512 kHz of the frequency specimen. The recording speed of the high-speed camera was 1000 frames per second under full resolution.

3.1.2 Stress paths for instantaneous and delayed rockbursts

A strainburst is self-initiated due to the stresses in the near-face region. That is, the self-initiated rockbursts occur when the stresses near the boundary of an excavation exceed the rock mass strength, and failures proceed in an unstable or violent manner (when the stored strain energy in the rock mass is not dissipated during the fracturing process). The design of the MTTA can perform loading/unloading independently in three principal directions, which provide flexibilities for realized varied stress paths analogous to those at, or near, the surface of underground excavations or mine stopings. Typically, stress paths for the three types of the self-initiated rockbursts (Figure 1) can be designed.

Figure 3a shows the stress path for instantaneous rockbursts. The stress path was designed to resemble static loading and dynamic loading due to excavation at the excavation boundaries. The load is first increased proportionally and slowly to attain the hydrostatic stress state ($\sigma_1 = \sigma_2 = \sigma_3$) marked by letter A, under the convention of $\sigma_1 > \sigma_2 > \sigma_3$ for the principal stresses. Secondly, $\sigma_1$ and $\sigma_2$ were increased step by step until approaching the virginal stress state marked by B. After that, this stress state was maintained for a certain time to allow the equilibrium state to be attained inside the rock specimen, and then $\sigma_3$ was suddenly removed from one surface of the specimen (Figure 2a) while keeping $\sigma_1$ and $\sigma_2$ at constant. Thus the sample is at the possible

![Figure 3 Stress paths](image-url)
occurrence state of rockburst (the first unloading marked by C). If the rock sample does not fail after around 30 minutes of the first unloading (He et al., 2010), the loading process is resumed. Typically, the stress paths in Figure 3 have three cycles of the loading/unloading, assuming that rockburst occurs at the third cycle.

Figure 3b shows the stress for delayed rockbursts. The major difference between 3a and 3b lies in the relationship between $\sigma_1$ and $\sigma_3$ at unloading. In the stress path for instantaneous rockbursts (Figure 3a), $\sigma_1$ is kept constant when unloading $\sigma_3$, and rockburst occurs after the unloading with a very small time lag (delayed rockburst mechanism). In the stress path for delayed rockbursts (Figure 3b), $\sigma_1$ increases at unloading and rockburst occurs undergoing a period of time, $\Delta t$, after unloading $\sigma_3$. For the instantaneous rockbursts at the critical stress state undergoing the stress path, $\sigma_1$, is equal to, or larger than, the unconfined compressive strength (UCS) of the rock mass. When $\sigma_3$ approaches zero instantaneously, the excessive potential energy stored in the highly stressed rock mass will be released and converted into kinematic energy, carrying the rock fractures into the excavation space. For the delayed rockburst, no failure occurs when $\sigma_3$ approaches zero instantaneously and $\sigma_1$ at a low level (less than the UCS). It is the excavation that causes the dramatic increase in $\sigma_1$ at unloading and rockburst will happen when $\sigma_1$ is sufficiently high. For a reflection of the stress concentration, $\sigma_1$ is increased to the level of 1.2–1.3 times the UCS.

### 3.1.3 Stress paths for pillar bursts

Figure 4 shows the stress path for pillar bursts. This stress path simulates the stress redistribution existing in a coal pillar during the mining phase. The load is first increased proportionally and slowly to attain the hydrostatic stress state ($\sigma_1 = \sigma_2 = \sigma_3$) marked by letter A. Secondly, $\sigma_1$ and $\sigma_2$ were increased step by step until approaching the virginial stress state marked by B. After that, this stress state was maintained for a certain time to allow the equilibrium state to be attained inside the rock specimen. Then the major principal stress was increased, simulating the stress concentration due to the decreasing of the cross-sectional section perpendicular to the vertical direction. At the same time, the minimum principal stress was decreased with a small stress increment,
−Δσ₃, simulating the mining-induced unloading on the pillar’s lateral direction (marked by C). It was assumed that the pillar-like specimen undergoes three cycles of the loading/unloading (denoted by C, D, and E) and the pillar burst occurs at the third cycle (marked by E, the critical state). The pillar burst also exhibits a delayed burst mechanism with a time lag by Δt.

Pillars were designed and remained when using the pillar mining method in underground coal mines. Progressively reduction of the cross-sectional area during face stoping can result in the concentration of stress in the vertical direction while setting the lateral face free, leading to the rockburst event. Pillar design plays a significant role in these events, i.e. increase in pillar size will effectively limit the transfer of abutment stresses to the longwall face and decrease the rockburst potential (Barton et al., 1992).

Actually, the stress paths for pillar bursts are closely related to the mine design and more complex than that for the former two types of rockbursts. The methodology for the design of a stress path for the pillar burst will be dealt with in detail late in the document, along with the pillar burst criterion.

### 3.1.4 Experimental results for strainburst

Up to now, more than 300 rockburst experiments have been conducted employing the strainburst testing machine with rock samples of different rock types cored from different countries, including Italy, Canada, Iran, Singapore, and China. As an example, rockburst experiments on the granite from Laizhou (Shandong Province, eastern China) are presented. The cored rock blocks were machined into cubical specimens with a dimension of 150×60×30 mm. X-ray diffraction analysis of the granite was carried out. The major minerals are quartz (27%), feldspar (68%), and clay minerals (5%) with mica as most of the content. During the test, the stress path for the instantaneous rockburst (Figure 3a) was followed.

Figure 5a shows the measured stress path for the Laizhou granite sample. The virginal in situ stresses (σ₁, σ₂, σ₃) are 101, 60 and 30 MPa, respectively. The sample underwent two cycles of the loading/unloading and rockburst occurred at the second unloading with the critical state of stress at 129, 59, 0 MPa, respectively. That is, the polaxial strength for rockburst is σ₁ = 129 MPa. Figure 5b shows the AE energy rate and accumulated AE energy rate monitored during the experiment. The accumulative

![Figure 5](image-url)
AE rate increases during the test and increases suddenly at unloading. Similarly, the AE energy rate has a high level at every unloading. Both the cumulation and distribution of AE energy have higher levels at the critical stress state, manifested by the dynamic nature of the event.

Figure 6 shows a selection of photographs of the unloading surface of the test rock specimen recorded by the high-speed camera during the rockburst experiment. Figure 6a shows the surface at the intact state. Figures 6b–f show that there were rock grains and fragments ejected from the upper area of the surface for the first time 11 microseconds after the unloading. Figures 6g–m show a large rock fracture split from the upper left area of the surface one second later. Figures 6n–x show the man-made rockburst event during the test. From these photographs we can observe the ejection and expulsion of rock fractures on the upper region of the exposed surface. The photographs in Figure 6 demonstrate that the strainburst event at the excavation boundaries can be reproduced very well in the laboratory using our innovative rockburst testing machine and designed stress path.
3.2 Study on impact-induced burst

3.2.1 Impact-induced rockburst testing machine

Figure 7a shows the schematic of the main unit for the impact-induced rockburst testing machine (Patent No. ZL 200610113003.1). The main unit is actually a dynamic true-tri-axial apparatus (DTTA) which can accommodate a cubical specimen of 110×110×110 mm with a tunnel-like hole inside. Each of the loading devices for DTTA consists of a loading plate, a pressure cell, and a loading rod, and all the loading devices can produce the wave-formed dynamic loads independently in the three perpendicular directions. As reviewed above, a rockburst event at the excavation surface can also be triggered by a remote seismic source such as blasting, a roof fall, and adjacent caving, etc. The DTTA, developed by Professor He, was designed for creating the dynamic stress states analogous to those in real situations. Figure 7b shows a photograph of the overview of the impact-induced testing machine including the main unit and the peripheral controlling and monitoring instruments, which are the servo-controlled stress wave loading device (beyond the figure), the data monitoring system, and the imaging system.

3.2.2 Stress paths for impact-induced bursts

The DTTA is capable of producing the dynamic stress wave in any, or all, of the principal directions, providing flexibilities for the investigator to design different the static–dynamic combinations of the principal stresses \((\sigma_1, \sigma_2, \sigma_3)\). Figure 8 shows a typical stress path for the impact-induced rockbursts in which \(\sigma_1\) is designed as a squared-formed stress wave and \(\sigma_2\) and \(\sigma_3\) are stationary.

This stress path is designed to simulate caving or blasting-induced impact on the country rock mass. With the programmed computer code, the servo-controlled dynamic loading device of the DTTA can simulate stress waves generated by different sources such as by site excavation, blasting, caving, earthquakes, mechanical
tunneling, etc. At present, sixteen kinds of the stress wave forms can be implemented in the testing machine. These are the ramp wave; sine wave; triangle wave; sawtooth wave; square wave; white noise; Gaussian noise; cycle random noise; ramp and circular wave; ramp and noise wave; circular and noise wave; ramp and circular and noise wave; loading single pulse; uninstall single pulse; Laplace pulse; and uninstall Laplace pulse.

3.2.3 Results

Employing the impact-induced rockburst testing machine, more than thirty experiments on the tunnel-like model were accomplished including the sandstone model, the limestone model, mudstone model, artificial-analogue model, and granite model. The experimental results regarding the granite model are presented here as an illustrative case. The tested granite tunnel-like model has a dimension of 110×110×110 mm with a tunnel-like hole inside. The routine analysis and tests are also performed on the granite (description is omitted) and a UCS of 68 MPa is used as a strength reference here for the model. The measured stress states and the loading path are shown in Figure 9. At the stationary loading stage, the stresses (σ₁, σ₂, σ₃) were increased proportionally and slowly to attain the hydrostatic stress state firstly, and then attain the virginal stress state of the simulated prototype of 20.7, 4.3 and 2.5 MPa, respectively, as was done in the strainburst experiment.

During the dynamic loading process (Figure 9), σ₁ (vertical direction) was modulated as a stress wave with an amplitude of 0.1 mm and frequency of 0.5 Hz, and σ₂, σ₃ are stationary. During the first two episodes of the applied stress waves, no rock fracturing or ejection occurred. In the third episode of the stress wave (at an averaged stress level of 26.6 MPa), ejection of rock grains took place. During the fourth episode of the wave loading (at an average stress level of 29.2 MPa, the critical stress for σ₁), rockburst occurred. Figure 10 shows photographs showing the rockburst process. Figures 10a and 10b show rock splitting on the left side wall and floor. Figures 10c and 10d shows the violent ejection of the rock fractures from the tunnel face during the fourth wave loading and Figures 10e and 10f show the final state of the face after the event.

Figure 8 Stress paths for impact-induced rockbursts.
Figure 9 The measured stress paths in the impact-induced rockburst experiment.

Figure 10 Photographs showing the process of impact-induced rockburst.
4 ROCKBURST CRITERION

Research on empirical equations for the determination of stress-strength behavior of a rock mass, including the discontinuity pattern, has been a very attractive topic in rock engineering, and numerous empirical equations have been proposed in the literature. Hoek and Brown introduced the most popular empirical approach to determine the strength of rock materials and rock masses (Hoek & Brown, 1980). The proposed approach by Hoek and Brown, known as the Hoek–Brown (H–B) empirical failure criterion, has been in the center of rock mechanics practice since 1980 (Sonmez & Gokceoglu, 2006). This section presents the empirical rockburst criteria based on insight into the rockburst mechanisms obtained in the rockburst experiments introduced above.

4.1 Study on impact-induced burst

The rockburst criteria for the three types of the strainbursts (see Figure 1), viz. the instantaneous rockbursts, the delayed rockbusts and the pillar bursts, are presented in this subsection with references to the H–B criterion.

4.1.1 Instantaneous rockburst criterion

Figure 11a shows the instantaneous rockburst criterion and the bursting path in the $\sigma_1$–$\sigma_3$ space. Point A represents the virginial stress state $(\sigma_1, \sigma_2, \sigma_3)$. $\sigma_c$ and $\sigma_c'$ are the UCS and the long-term peak strength for the country rocks, respectively. Instantaneous rockburst occurs under the condition where rapid release of the minimum principal stress, $\sigma_3$, and the maximum principal stress, $\sigma_{1c}$, is larger than the UCS, $\sigma_c$. These theoretical analyses were verified by the rockburst experiments (He et al., 2007, 2010, 2012a, 2012b). Any point falling into the area between the H–B curve and the UCS (marked by Zone 1) represents the stress state that may initiate a rockburst event.

![Figure 11](image-url) (a) The instantaneous rockburst criterion, and (b) energy relation between the uni-axial compression and true-tri-axial compression by suddenly unloading the confining pressure.
The experimentally obtained knowledge on the strainbursts leads to the following theoretical formulation of the energy relationship between the uni-axial compressive tests and the true-tri-axial unloading tests (Figure 11b). The blue line is the complete stress and strain curve of $\sigma - \varepsilon$ typically found in the UCS tests. The right-angled triangle drawn in a black line is an idealized curve of $\sigma_1 - \varepsilon_1$ found in true-tri-axial unloading tests. The shaded area below the $\sigma - \varepsilon$ curve represents the energy consumed during the uni-axial loading process in the pre-peak region. The area of the triangle minus this area represents the energy stored in the country rocks (shaded area between the $\sigma_1 - \varepsilon_1$ curve and $\sigma - \varepsilon$ curve) which is releasable during the dynamic event. The releasable energy is achieved due to the high level of $\sigma_1$ under the confinement at depth where the polyaxial strength $\sigma_{1c}$ is much higher than the UCS. The amount of the releasable energy (or seismic energy) could be estimated by the area encompassed by the triangle $\Delta OAC$ in Figure 11b, and be expressed mathematically by:

$$\Delta E = \int_0^{\varepsilon_{1c}} \sigma_1 d\varepsilon_1 - \int_0^{\varepsilon_c} \sigma d\varepsilon \approx \text{area}(\Delta OAC)$$  \hspace{1cm} (1)$$

Where $\Delta E$ is the releasable energy; $\sigma_{1c}$ the polyaxial strength obtained in the rockburst tests; $\sigma_c$ the UCS; $\varepsilon_c$ the peak strain at the peak stress in the UCS test; and $\varepsilon_{1c}$ the peak strain at $\sigma_{1c}$ in the rockburst test. Thus, the generalized rockburst criterion can be written as:

$$\Delta E > 0$$  \hspace{1cm} (2)$$

### 4.1.2 Delayed rockburst criterion

Figure 12a shows the delayed rockburst criterion and the bursting path in the $\sigma_1 - \sigma_3$ space. Point B represents the virginal stress state ($\sigma_1, \sigma_2, \sigma_3$). Under this condition, the rockburst may not occur at the unloading, $\sigma_3$; as a result $\sigma_1$ is lower than the UCS, $\sigma_c$. 

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Figure 12 (a) The delayed rockburst criterion, and (b) energy relation between the uni-axial compression and true-tri-axial compression by suddenly unloading the confining pressure.
At or near the excavation surface, rockbursts may be initiated as $\sigma_1$ increases (the tangential stress concentration due to the excavation) to a level larger than UCS and the rockburst criterion in Equation 2 is met. This kind of stress path is manifested by the rock response, such that rockburst occurs usually in a period of time after the free surface was created. The theoretical formulation of the energy relationship between the uni-axial compressive tests and the true-tri-axial unloading tests is given in Figure 12b, and the releasable energy and rockburst criterion are expressed by Equations 1 and 2.

4.2 Impact-induced rockburst criteria

The impact-induced rockburst, as classified in Section 1, consists of three types of rockbursts, viz. induced by blasting, by roof collapse, and by fault slip. Besides the rock strength, wavelength was also considered in their criteria as the dynamic nature.

4.2.1 Physical model for the impact-induced rockbursts

Figure 13 shows a tunnel of diameter $D$ in the path of a plane seismic wave of wave length. When a seismic wave propagates in an elastic continuum, a point or particle of this continuum oscillates around its stationary or equilibrium position. A particle is prevented from flying off by the atomic bond strength which increases as the particle moves away from its equilibrium position. On the other hand, a particle on the free boundary of an opening may fly off into the opening if the atomic bond is broken due to excessive acceleration of this particle. Similarly, rock blocks on the free boundary of an opening which are separated from the surrounding rock mass by joints and fractures can be carried or ejected into the opening by seismic waves. This seismic wave is assumed to be sinusoidal with positive (compressive) and negative (tensile) pulse. The tunnel will undergo a dynamic stress state under the condition that the tunnel diameter is much less than the wave length (McGarr et al., 1981; Roberts & Brummer, 1988), that is:

$$D\lambda^{-1} \ll 1$$

(3)

Figure 13 Cylindrical tunnel in the path of a propagating plane seismic wave (Xiaoping Yi, 1993).
4.2.2 Delayed rockburst criterion

Figure 14a shows the criterion for impact-induced rockbursts and the bursting path in the $\sigma_1-\sigma_3$ space. Point B represents the virgin state ($\sigma_1, \sigma_2, \sigma_3$) at which the stress wave oscillates. Different from the static loading illustrated in Figures 11 and 14, the dynamic loading in Figure 15 is a rate-dependent process and can also result in an increase in the tangential stress at the excavation surface, i.e. the increase in the major principal stress. The dynamic rockburst strength is hereby termed as $\sigma_{1d}$ in comparison with the static rockburst strength $\sigma_1$ in the above section. The released energy $\Delta E$ can also be estimated using the method illustrated in Figure 14b and Equation 1 by substituting $\sigma_1$ with $\sigma_{1d}$. The necessary and sufficient condition for initiating the induced-types of rockbursts should follow the energy criterion expressed by Equation 2 and the dynamical condition ($D\lambda^{-1} << 1$) expressed by Equation 3 all together:

$$\Delta E > 0 \quad \text{and} \quad D\lambda^{-1} << 1 \quad (4)$$

As to the specific rockburst criterion for induced rockbursts, the differences lie in the configuration of the dynamical stress waves. That is, no matter what the type of seismic source – blasting, caving, roof collapse, and fault slip – it can be represented by adjusting the magnitude, the wave length, and the wave type. Therefore, a specific rockburst criterion could be formulated.

5 SUMMARY

A new concept was introduced into the classification of rockbursts according to their initiation mechanisms and results of indoor experimental methods. This classification of rockbursts into two general categories, viz. stress-induced rockbursts and impact-induced rockbursts, contributes a great deal to the development of state-of-the-art
rockburst testing machines, and the establishment of a framework for the systematic rockburst studies undertaken by the author’s research team.

The innovative work in developing the ‘strainburst testing machine’ and ‘impact-induced rockburst testing machine’ creates a new era at which in-depth and comprehensive investigations into the rockburst phenomena can be made in the laboratory. The artificially produced rockburst phenomena of different types in the novel testing machines can provide us with a convenient way of observing the rockburst process with various advanced monitoring techniques, which was originally unlikely in field.

The stress paths proposed in this paper, corresponding to the rockbursts in the new classification systems, are closely analogous to those at, or near, the surface of underground excavations. The corresponding real rockburst phenomena can be reproduced in the laboratory in the new testing machines using these stress paths and the related testing procedures.

Rockburst criteria for the stress-induced and impact-induced rockbursts are proposed based on experimental investigations both in the laboratory and in the field. The rockburst criteria take into account both the static and dynamic stress states, and are have general applications in rockburst prediction and rockburst control design.

REFERENCES