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# A Review of Rock Burst's Experimental Progress, Warning, Prediction, Control and Damage Potential Measures

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*Investigation*

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*Damage potential*

## Abstract

Rock burst is the most attractive and hot research area in geomechanics, mining, and civil engineering due to the increasing depth of mines and construction of deep underground structures. It has also been a severe problem in ground control measures in the last few decades. Many studies have been done by different researchers in order to minimize the hazards of rock burst and to provide a safe mining/working environment. It is important to review the current advancement of rock burst prediction and its preventive measures. This paper reviews the experimental progress of rock burst warning, prediction, control measures, and potential damage measures. Different effective methods of rock burst prediction and control are also described.

## 1. Introduction

The rock burst occurrence has been reported in China, South Africa, Canada, Australia, Chile, Sweden, India, Poland, France, America, Britain, Germany, Russia, Ukraine, Japan, South Korea, Pakistan, and twenty other regions/countries [1]; the history of rock burst in China and other countries dates back to 280 years ago. It has become a transient and complex static-dynamic process, and has attracted attention in rock science, underground excavations, supports design in hard rock-mines, geomechanics, and mostly in coal mines at deep levels.

In order to understand the rock burst mechanism, its prediction, assessment, and prevention, and its intensity, damage potential, and impacts, a lot of research works have been carried out in the form of laboratory tests, field experiments, and computer-based technologies. With the passage of time, the mitigation techniques have been improved and the theories have been modified to find solutions for this world-wide rock burst problem. Rock burst is a severe and complex problem in every country where the mines are very deep. It has also attracted attention in geotechnical engineering [2-4]. Sound research works in rock mechanics are revolving around rock burst, and the researchers are doing their best to predict it and to control this problem. This section of the paper will show the research progress made by several experts and researchers from all over the world. In the recent decades, the rock burst phenomenon has been investigated through experiments on the basis of different proposed theories.

## 2. Experimental progress

Experimental studies have been conducted by some experts on rock burst using the uniaxial compression tests, multi-mode tests (combined uniaxial and biaxial static-dynamic tests), true tri-axial loading and unloading tests, and conventional tri-axial unloading tests. The acoustic emission (AE) technology has been introduced and used in rock mechanics to investigate the rock failure and rock burst phenomenon [5-7]. True tri-axial equipment has been modified and re-introduced

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with a unique characteristic of unloading the samples during a test on one surface; it was used to understand the strain burst process and simulate the results obtained [8]. Bolts and anchors have been designed and considered as an efficient measure for rock burst control due to their performance in the reinforcement of rock-coal and to hold retained reinforced rock-coal mass. Supports have also been monitored and investigated by different experts such as "Cone bolt" and "Roofex" [7, 9]. Laboratory experiments have been conducted to investigate the rock burst mechanism. The *in-situ* stress state has been investigated, and also generation of the 3D stress state has been analysed and discussed [10]. An experimental scenario is mentioned in Figure 1. The plate structure evolution is correlated with the structural response of the rock, and is divided into three types [Figure 2].

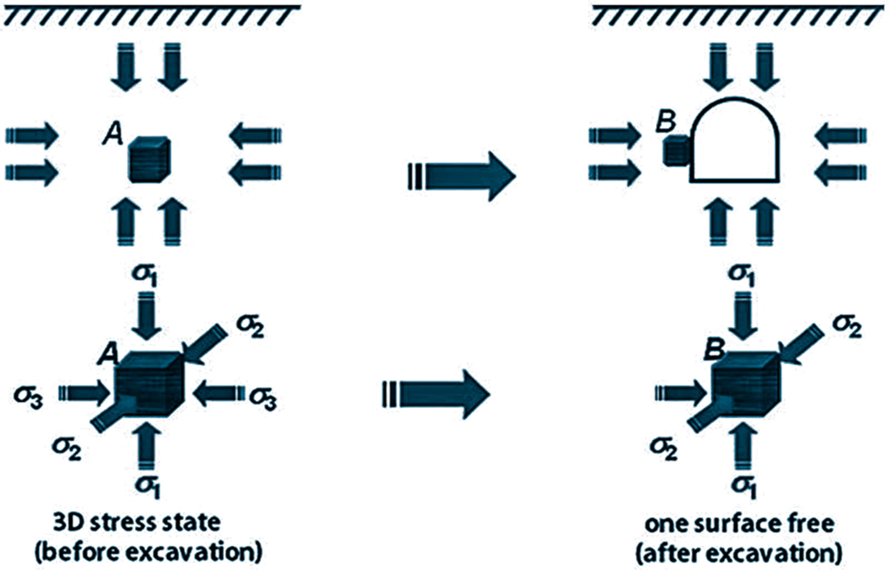


**Figure 1. Stress excavation-induced rock burst [10].**

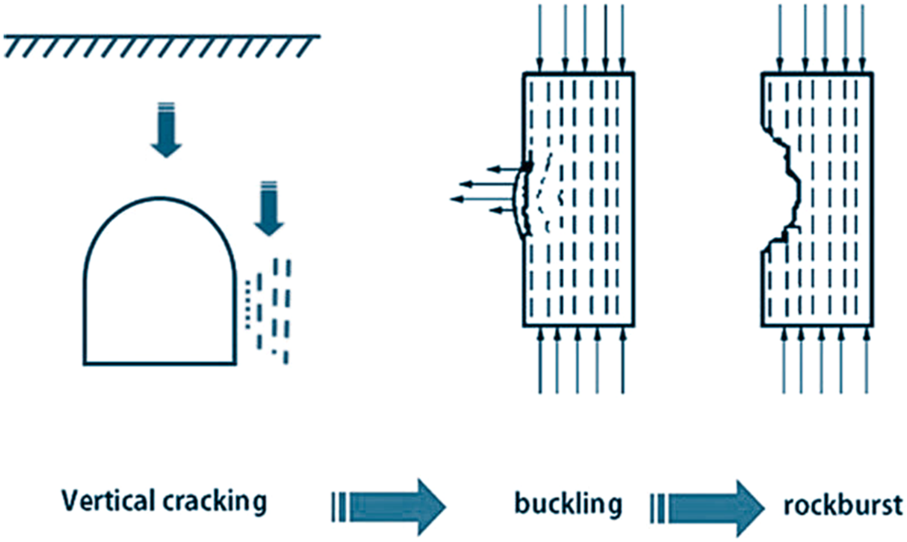


**Figure 2. Structural changes after rock burst [10].**

Laboratory modelling of the rock burst phenomenon under a severe deep ground condition was the major achievement of the State Key Laboratory for Geomechanics and Deep Underground Engineering (SKLGDUE) at the China University of Mining and Technology, Beijing. A "Deep Underground Rock Burst Analogue Test Machine (DURATM) was designed in 2006 (Figure 3).

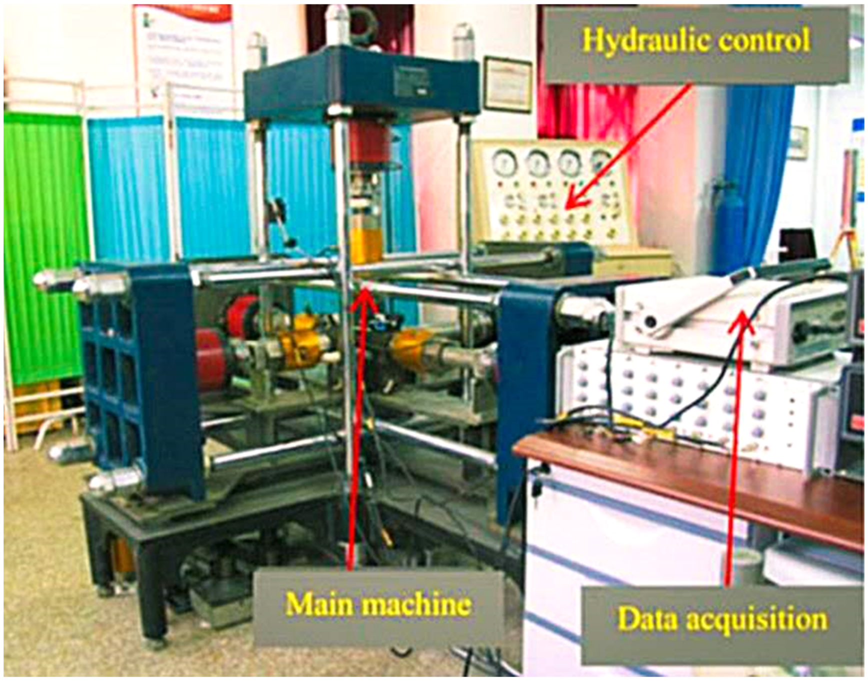


**Figure 3. DURATM simulation of rock burst process at deep levels (CUMT-BEIJING) [10].**

DURATM is a unique system with specific characteristics. In these experiments, it was important that one surface of the sample should be unloaded immediately and the other surface should be free, which was crucial for the simulation of the *in situ* rockburst condition, and the design of a single face unloading device was a great achievement of SKLGDUE at CUMT, Beijing [Figure 4].

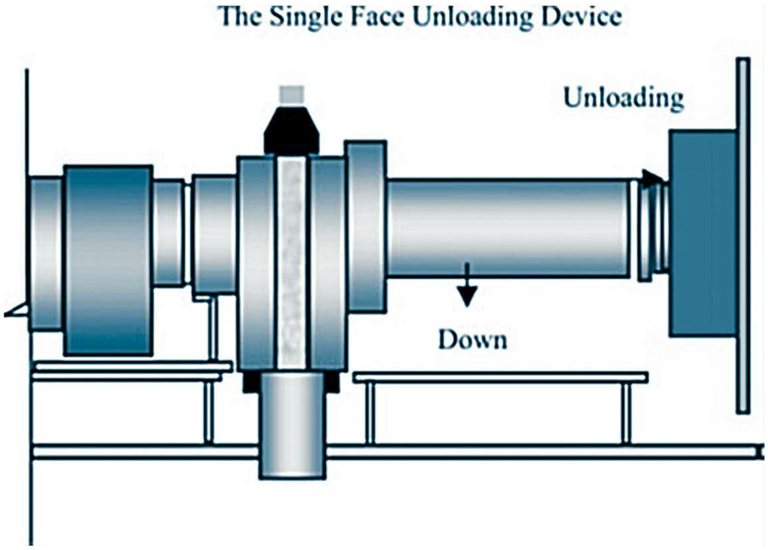
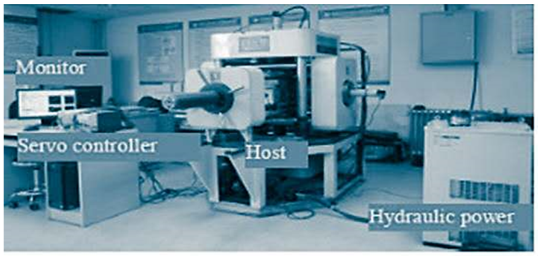


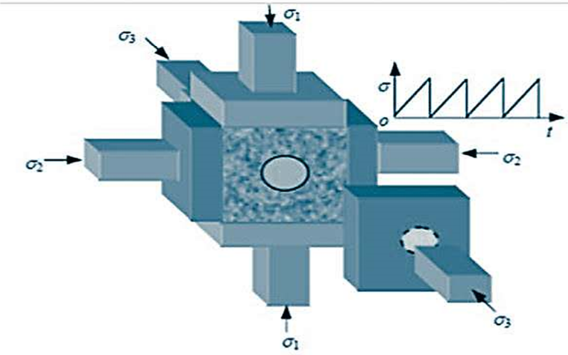
**Figure 4. The single face unloading device [10].**

In 2006, 200 tests were conducted using DURATM at SKLDGUE; the samples were brought from different countries, and different types of tests were conducted; the rock burst tests were most important among them. In 2011-12, a new apparatus for rock burst experiments in laboratory was introduced and designed. It was developed to simulate the impact-induced rock burst. Instantaneous burst, delayed burst, and pillar burst were simulated by this system. A representation of the system is given in Figure 5. For the static and dynamic tests, CRLD (constant resistance large deformation bolts) were developed. CRLD, with its working principles, is given in Figures 6 and 7 [10]. Apart from this, the testing systems for the static and dynamic stress-state tests were developed and used [11]. On the basis of the types and classification of rock burst, an experimental study was conducted, and a variety of laboratory tests were performed to understand the rock burst mechanism. In 2015, Zhou carried out the buckling rock burst test on a granite specimen to analyze the failure characteristics [12]. In 2018, Li conducted a spallation failure test on a granite sample through a modified Hopkinson pressure bar, and a crack propagation in the form of semi-sinusoidal waves was observed by a high-speed camera [13]. Dyskin and Germanovich conducted an experiment to evaluate the causes of slab-type rock burst, and their results proposed that excavation promoted the primary fractures, and free surface was responsible for crack propagation in the parallel direction of rock-wall, and rock burst occurred [14]. Li also carried out a test on the same material to find out the causes of rock burst by tunnel excavation, and from the results obtained, he proposed that the tunnels in the fields were under the spalling and drum-type tensile failure [15]. Gong reproduced the buckling rock burst process through an experiment (a 3D loading test by a true tri-axial test system) [16].

Laws of failure of rock burst were analyzed through an experiment using the true tri-axial test system [17].



An overview of the system



Loading principle of tunnel-like specimens

**Figure 5. New deep rock non-linear mechanical system [10].**

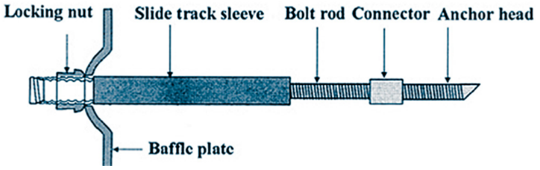


**Figure 6. Constant resistance large deformation bolt [10].**

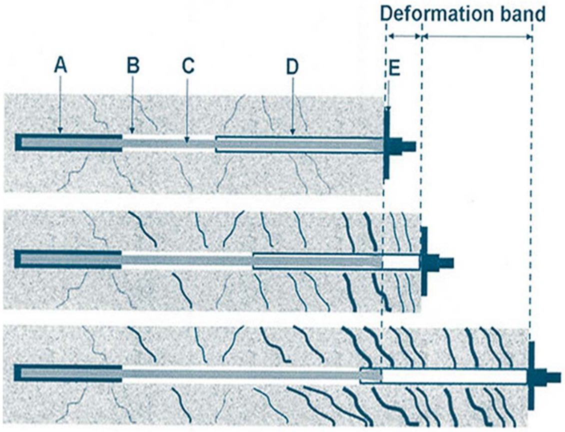


**Figure 7. Supporting principle for a constant resistance, large deformation bolt. (A). Elastic deformation stage (B). Structural deformation stage (C). Ultimate deformation stage. [10].**

Zuo conducted various experiments on a combination of different rocks and analyzed the dynamic effect of stress [18]. The evolution laws of temperature field and displacement field were verified by conducting an experiment on an instable model to analyze the failure process (by the non-contact monitoring method) [19]. An indoor physical test was conducted in 2018, and the model of inclusion rock burst was proposed; the whole process of rock burst was reproduced in laboratory to study the rock burst mechanism. This study was very fruitful for the prevention and control of rock burst [20].

## 3. Warning, prediction, and control measures

As rock burst is accompanied by a sudden and violent ejection of rock or coal, and so it is almost difficult to minimize deformation and failure initiation in a highly stressed rock or coal [21]. “Warning” means the indication of rock burst risk in high stressed zones, and it is the first step towards rock burst prediction. Several researchers have adopted different warning methods about rock burst. “Rock burst warning” is an indication towards the location, intensity, and probability of a rock burst. It does not indicate the time of rock burst occurrence. In 2017, the Chinese researchers proposed the warning measures for rock burst in deep metal mines, and the results obtained were used for further investigations [22]. Rock burst creates a spatial fractal behavior during the distribution process [23]. According to the Chinese researchers, monitoring the micro-seismic events and energy distribution during these events is a fundamental step towards warning. They have proposed a correlation between the rock burst intensity and micro-seismicity. The higher the energy, the larger are the event numbers and the higher is the rock burst tendency and the greater are the rock burst intensities [24].

Several measures have been used to prevent and restrict failure of rock or coal. The preventive measures can help to avoid or minimize the impact of rock burst. In Poland, the research on rock burst is more advanced. Poland has developed an efficient monitoring system, which has been installed in all rock burst prone mines. This monitoring system works on the method of micro-seismic events, drilling chip, and efficient prediction. The ARAMIS M/E micro-seismic monitoring system and the ARES-5/E earth-sound monitoring systems have been developed in Poland, and these systems are used around the world. A passive seismic tomography has been effectively used for the prediction of the rock burst hazard [25]. In China, there are several monitoring systems that are helpful to predict rock burst as the more cases of rock burst occurred, so different monitoring methods such as micro-seismic monitoring events, electromagnetic radiation, drilling chips, and ground sounds are used [26-30]. Rock burst is accompanied by induced dynamic and static stress according to the principle of superposition. In 2014, Limning Dou and Zonglong Mu suggested that in order to predict rock burst occurrence, the static and dynamic stress states should be monitored. According to these researchers, the dynamic stress is monitored on the basis of the breaking laws of coal-rock. The micro-seismic method, CT/EMR, and the earth sound technology were used to monitor the whole process. The static stress was monitored through drilling cutting monitoring and the elastic wave CT test. The static1dynamic stress method was used for the prediction of rock burst [31]. The zoning and leveling forecasting method [32] has been proposed by Dou and He in order to predict the rock burst danger. According to them, the prediction method includes an early prediction and a real time prediction. They used a comprehensive index to predict danger. They also proposed different forecasting methods, and rockbursts were predicted on four scales in dangerous areas. The prediction scale is given in Figure 8 [33]. The CT technology was used in China to predict the rock burst danger; Wang have studied and used the CT and EMR technologies in Chinese coal mines [34-36].

A “novel technology” has been used for controlling the hard and thick roofs. This technology was effective with broad applications such as time-saving, labor-saving and safety. Researchers have conducted sound analyses on burst intensities through the burst resisting mechanism by hard rock fracturing (roof fracture) [37, 38]. Many prediction methods such as the fuzzy-based evaluation method distance discriminant analysis, support vector machine (SVM) extension theory-based method, rough-set-based method, numerical simulation method, and unascertained method have been suggested by many researchers; every method has its own limitations. BP (back-propagation) and RBF (radial basis function) have also been used [39-47]. In the recent years, the ANN-based method has been used by various researchers to predict rock burst. This method has been considered as an efficient and intelligent method for rock burst prediction [48-49]. PNN (probabilistic neural network) has been introduced by Specht and Donald, and used by a number of researchers to predict the rock burst classification as well as fault diagnosis [50-55].

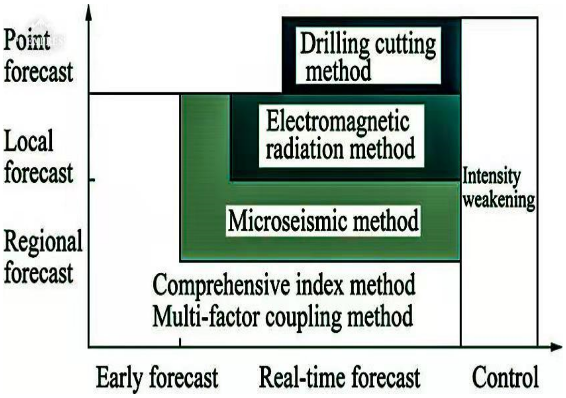


**Figure 8. Prediction of rock burst danger [31].**

Since rock burst is a complex phenomenon, therefore, a comprehensive analysis has been performed by different researchers; the individual indices were determined, and then a comprehensive index was presented. Figure 10 [56] illustrates the comprehensive analysis of different factors for rock burst prediction and pre-warning from a stress-strain curve. Based on the comprehensive index, the degree of rock burst is identified and the controlling measures are given in Table 1.

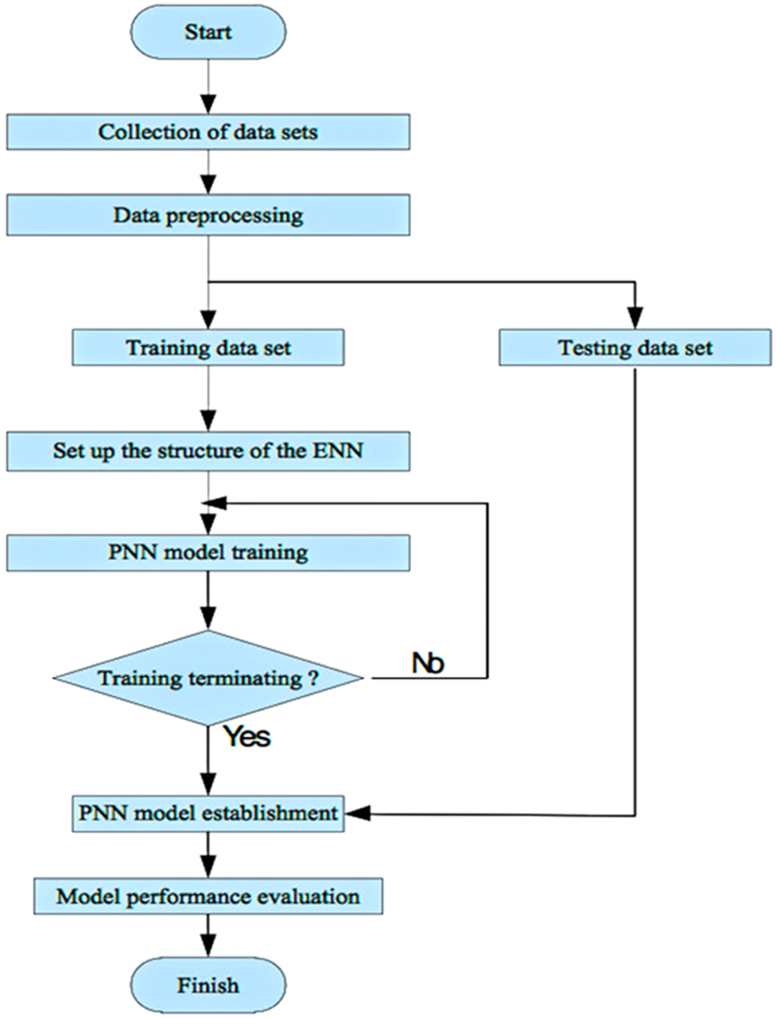


Figure 9. The design process of PNN modeling for prediction of rock burst [42].

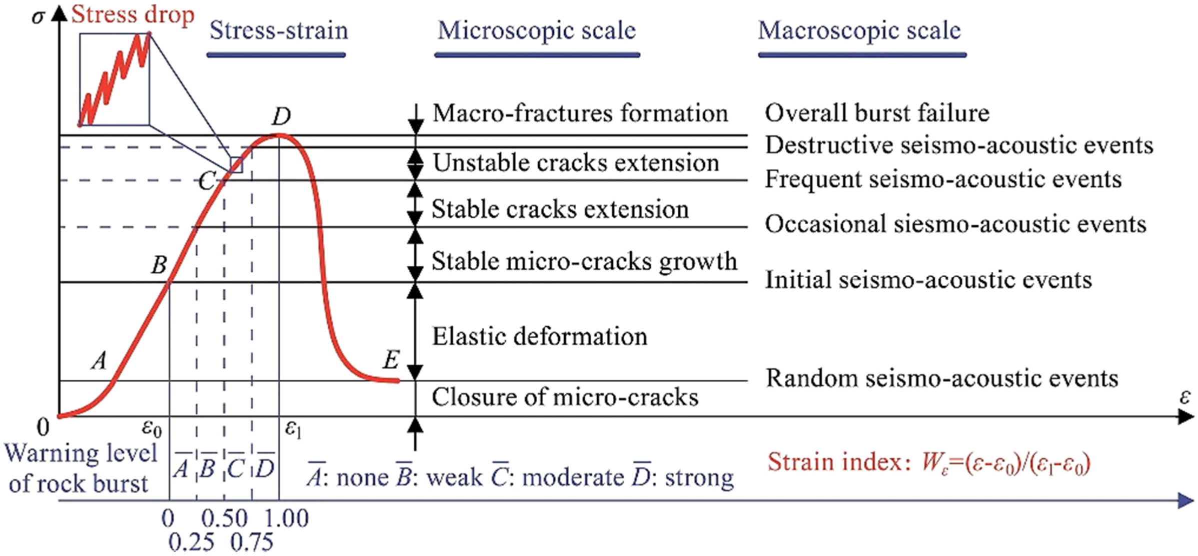


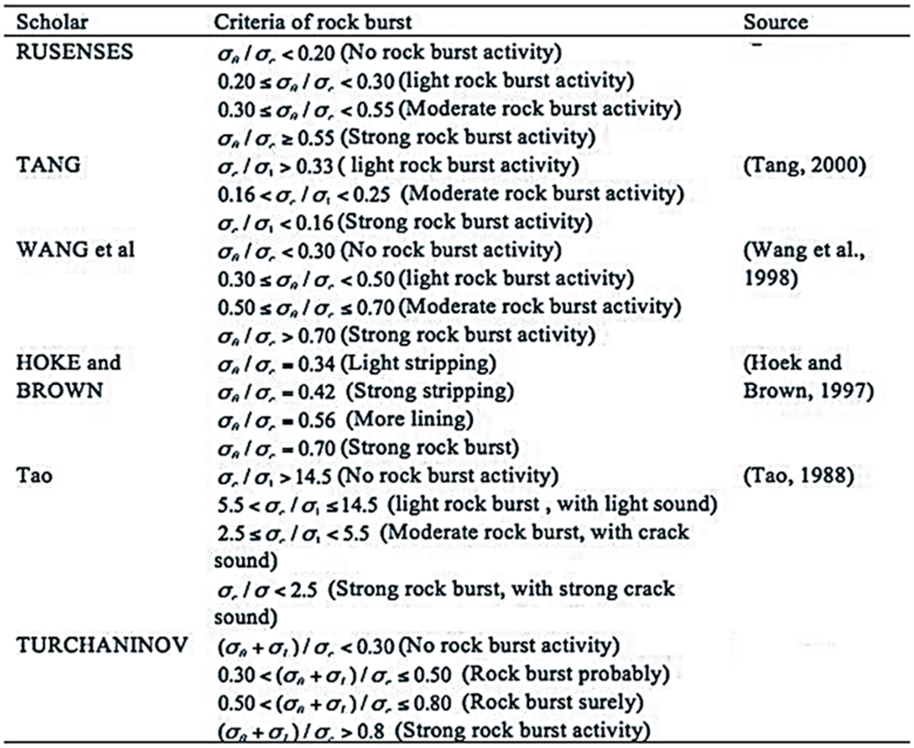
Figure 10. Stress-strain and seismo-acoustic events for rock under different loading stages. [56].

**Table 1. Prediction of rock burst danger [56].**

| Danger degree | Danger state | Comprehensive index | Controlling measures |
|---|---|---|---|
| A | No | < 0.25 | Managing the mining area normally and conducting the designing and mining the same as that without rock burst danger. |
| B | Weak | 0.25-0.5 | Providing monitoring and pressure releasing equipment.<br>Forming monitoring and controlling plans.<br>Conducting monitoring and pressure measures and check validity. |
| C | Medium | 0.5>0.75 | In addition to measures taken as weak danger, reasonably allocating roadways and chambers, reasonably selecting mining, and supporting parameters. |
| D | Strong | >0.75 | In addition to the measures taken as a medium danger, pre-mining pressure releasing measures should be conducted comprehensively and check their validity.<br>If rockburst danger cannot be eliminated, mining activities should terminate or be re-designed. |

Different researchers have selected different parameters to evaluate the rockbursts index criteria. The approaches were different on the basis of rockbursts intensities. Field stresses were used to define the rockbursts intensities. The criteria listed in Table 2 were proposed early and used for further research works.

**Table 2. Warning and prediction about rock burst occurrence [57-60].**



| Scholar | Criteria of rock burst | Source |
|---|---|---|
| RUSENSES | $\sigma_\theta / \sigma_c < 0.20$ (No rock burst activity) | - |
| | $0.20 \leq \sigma_\theta / \sigma_c < 0.30$ (light rock burst activity) | |
| | $0.30 \leq \sigma_\theta / \sigma_c < 0.55$ (Moderate rock burst activity) | |
| | $\sigma_\theta / \sigma_c \geq 0.55$ (Strong rock burst activity) | |
| TANG | $\sigma_c / \sigma_1 > 0.33$ ( light rock burst activity) | (Tang, 2000) |
| | $0.16 < \sigma_c / \sigma_1 < 0.25$ (Moderate rock burst activity) | |
| | $\sigma_c / \sigma_1 < 0.16$ (Strong rock burst activity) | |
| WANG et al | $\sigma_\theta / \sigma_c < 0.30$ (No rock burst activity) | (Wang et al., 1998) |
| | $0.30 \leq \sigma_\theta / \sigma_c < 0.50$ (light rock burst activity) | |
| | $0.50 \leq \sigma_\theta / \sigma_c \leq 0.70$ (Moderate rock burst activity) | |
| | $\sigma_\theta / \sigma_c > 0.70$ (Strong rock burst activity) | |
| HOKE and BROWN | $\sigma_\theta / \sigma_c = 0.34$ (Light stripping) | (Hoek and Brown, 1997) |
| | $\sigma_\theta / \sigma_c = 0.42$ (Strong stripping) | |
| | $\sigma_\theta / \sigma_c = 0.56$ (More lining) | |
| | $\sigma_\theta / \sigma_c = 0.70$ (Strong rock burst) | |
| Tao | $\sigma_c / \sigma_1 > 14.5$ (No rock burst activity) | (Tao, 1988) |
| | $5.5 < \sigma_c / \sigma_1 \leq 14.5$ (light rock burst , with light sound) | |
| | $2.5 \leq \sigma_c / \sigma_1 < 5.5$ (Moderate rock burst, with crack sound) | |
| | $\sigma_c / \sigma < 2.5$ (Strong rock burst, with strong crack sound) | |
| TURCHANINOV | $(\sigma_\theta + \sigma_l) / \sigma_c < 0.30$ (No rock burst activity) | |
| | $0.30 < (\sigma_\theta + \sigma_l) / \sigma_c \leq 0.50$ (Rock burst probably) | |
| | $0.50 < (\sigma_\theta + \sigma_l) / \sigma_c \leq 0.80$ (Rock burst surely) | |
| | $(\sigma_\theta + \sigma_l) / \sigma_c > 0.8$ (Strong rock burst activity) | |

In Table 2, $\sigma_\theta$ denotes the tangential stress of the surrounding rock, MPa, $\sigma_c$ denotes the axial stress of the rock surrounding the excavation, MPa, $\sigma_I$ represents the *in-situ* stress of the area, and MPa, $\sigma_1$ is the uniaxial compressive strength (UCS) of the rock in MPa.

Dong has proposed a set of equations for the prediction of rock burst on the basis of energy, and this set of equations have been used by various researchers to evaluate the comprehensive indices through different approaches [42, 61].

$$W_{qx} \geq 1.5 \tag{1}$$

$$\sigma_1 \geq \text{б}_c / \sqrt{\alpha Wqx} \tag{2}$$

$$\alpha = 1 + \xi^2 - 2\mu\xi \tag{3}$$

$$\xi = \sigma_2 / \sigma_1 \tag{4}$$

$W_{qx}$ is the rock burst occurrence tendency index; $\sigma_1$ and $\sigma_2$ are the principle stresses around the surrounding rock; $\mu$ is the possion ratio, and $\xi$ is a ratio of the major stress.

Kidybinski gave an idea of energy index $W_{et}$, and proposed a new criteria for warning and prediction of rock burst [62].

**Table 3. Conditions and warnings** [62].

| Condition | Warninig/Prediction |
|---|---|
| $W_{et} < 2.0$ | No Rock burst |
| $2.0 \leq W_{et} \leq 5.0$ | Moderate Rock burst |
| $W_{et} \geq 5.0$ | Strong Rock burst |

The intensity weakening theory has been adopted and applied as a preventive measure for rock burst.

$$U = U_f = \iint \left[ jU_{rs}(\sigma_t, E_r)/j_t + jU_f(\sigma_t, E_f)/j_t + jU_{cr}(\sigma_t . E_c)/j_t \right] - U_{co} \quad (5)$$

where U is the accumulated elastic strain energy of the coal-rock mass at any time, Uf is the disturbance energy by mining-induced tremors, U0 is the difference between the initial accumulated and dissipated elastic strain energy of the coal-rock mass, Uj is the limited elastic stored energy of the coal-rock mass, Ut is the increment of accumulated elastic strain energy at any time t of coal-rock mass, and Ue denotes the released elastic energy by the relieve shot [31]. This theory was applied to the long wall mining method [Figure 11].

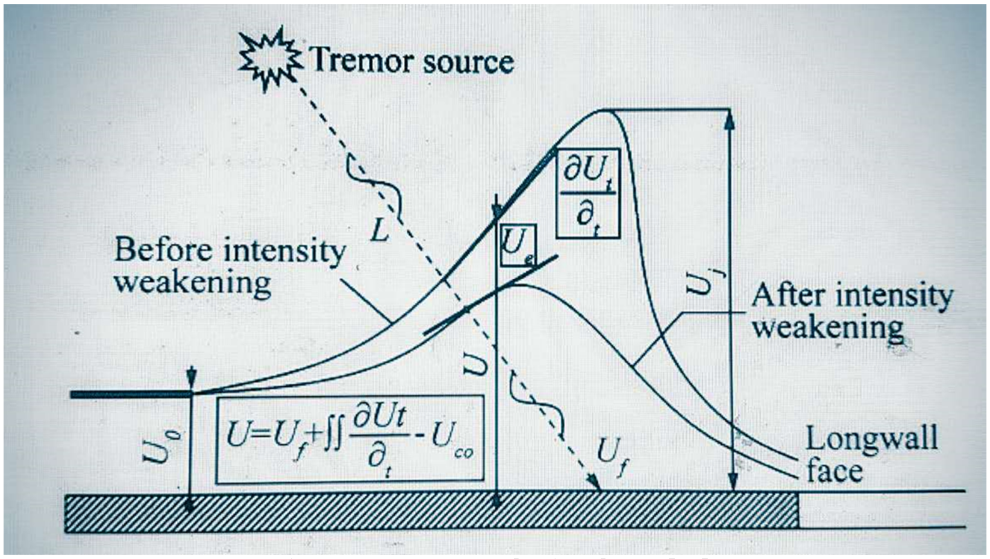


**Figure 11. Energy weakening theory [31].**

According to the above theory, the burst tendency can be reduced by weakening the coal-rock. Stress concentration can be reduced by transferring the peak stress into a deep area of coal-rock. The pressure measures can be taken in case of rock burst occurrence to release pressure in order to minimize the damage risk. In 2008, Singh proposed some ideal steps to control the rock burst occurrence and concluded that "the number of steps can be taken to minimize the occurrence of rock bursts in the seismically hazardous mine workings [63]. The mining operations should be planned to minimize the mining induced energy changes by optimizing the mining sequence and by avoiding the formation of high-stress areas. Rock support should be designed adequately, and the volumetric convergence may be controlled by partial extraction, back-filling, and small stopping-width" [64]. In 2015, A. Mazaira and P. Konicek published an article and proposed that lithology and stress concentration monitoring and investigations are the main steps to predict the risk zones. They proposed that it was necessary to predict the dangerous zones that had a tendency for rock bursts. Determination of the lithology and *in-situ* stress state are the basic steps involved to indicate the areas where rock or rock mass achieves a level of critical stress because a huge amount of strain energy can be stored in a hard rock mass, and this is done by using a comprehensive geological model. A correct prediction can minimize the risk and costs, and provides a safe environment for the workers. According to the stress approach, several mathematical indices, e.g. failure approach index (FAI) and excess shear stress (ESS) were used to evaluate and forecast the rock burst risk. Under an energy-balance approach, the methods used to predict rock burst risk were based on energy indices such as energy release rate (ERR), energy storage rate (ESR), strain energy storage index (WET), potential energy of elastic strain (PES) or strain energy density (SED) (i.e. the elastic strain energy in a unit volume of the rock mass, which is calculated by the uniaxial compressive strength of the rock and its unloading tangential modulus and burst potential index (BPI). Rock burst risk was also predicted using the rock brittleness index B (i.e. the ratio of uniaxial compressive strength to tensile strength of rock [65-73]. When the predictions were completed, then it was easy to take the control steps and preventive measures. According to the research studies, three different approaches or steps have been proposed for rock burst prevention: (I) optimization of the project layout scheme; (II) pre-conditioning of the rock mass; and (III) rock mass reinforcement and support [74, 75]. These approaches were felicitous for both the mining and civil works, even though there were important differences in their application to these fields, for instance, establishing the same prevention approaches but specifically focusing on mining excavations. Recently, numerical modelling has been used as a helping tool to evaluate the rock burst risk. Rock burst is a very complex phenomenon and cannot be predicted through a single parameter or factor. On the basis of the above-mentioned information, mining stresses and disturbances are responsible for rock burst occurrence; multi-factors were considered and studied for the prediction and control measures.

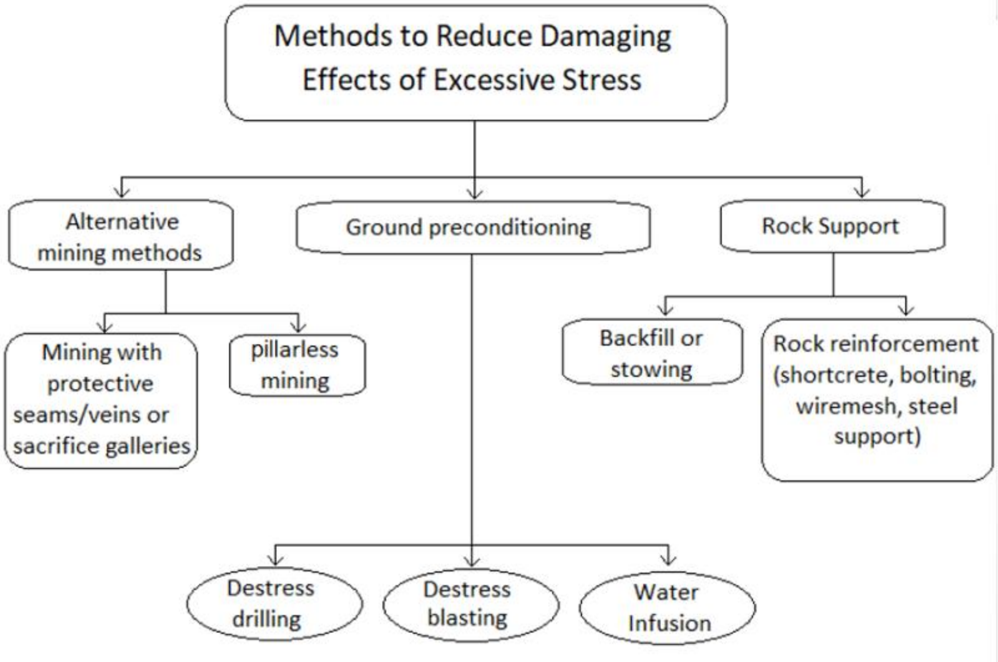


**Figure 12. Modified [76, 77].**

## 4. Damage potential measures

A sound research work related to the potential of rock burst has been conducted. In 1974, the Russnes's method was proposed, which classified the rock burst severity into four groups (none, weak, moderate, and severe, according to different basis such as noise, shape, and features of failure after rockburst) [78]. Tan has proposed a method that classified rock burst into four classes on the basis of *in-situ* laboratory tests and investigations, and considered the mechanical characteristics, the type and the shape of the failure, the intensity of destruction, and the sound of the rock burst [79]. In 1994, Brauner proposed a unique method (Brauner, 1994), which classified rock burst into three levels based on the intensity of destruction to the surrounding rock mass [80]. The Canadian team of Rockburst Research Program (CRRP) has also proposed a method (Kaiser, 1996) that is based on geometry, depth of damage zone inside the rock mass, observations and empirical criteria, and classifying the damage severity of rock burst into minor, moderate, and major [81]. In China, a research group working on the Code for Geological Investigations of Hydropower Engineering (CGIHE) has proposed a method to investigate the rock burst severity, which is a typical qualitative rock burst classification method. A new rock burst classification method has been suggested by Chen, which is based on the radiated energy from rock burst monitored with a micro-seismic method and the severity of surrounding rock damage for the quantitative prediction of rock burst severity [82, 83]. Due to the simplicity and flexibility of this method, it is mostly used for the prevention and control of rock burst in mining and geotechnical engineering fields, and these methods help for further studies and new methods. Different approaches are shown in Table 6. The researchers are working on the rock burst phenomenon in every respect because it is a major problem of mining and geotechnical fields globally. The above table describes the different approaches, mathematical equations, and parameters to predict the rock burst potential. It also describes the complete the scenario of various approaches from 1972 to 2017 [84-133].

**Table 4. Damage potential approaches [84-133].**

| Authors (year) | Index and/or equations | No rock burst | Light rock burst | Medium rock burst | Heavy rock burst | Serious rock burst |
|---|---|---|---|---|---|---|
| Turchaninov (1972) | $(\sigma_\theta + \sigma_L)/\sigma_c$ | ≤ 0.3 | 0.3–0.5 | 0.5–0.8 | > 0.8 | |
| Neyman (1972) | $W_{et} = E_e/E_p$ | < 2.0 | 2.0–3.5 | 3.5–5.0 | > 5.0 | |
| Hucka and Das (1974) | Brittleness of rocks<br>$B_1 = (\sigma_c - \sigma_t)/(\sigma_c + \sigma_t)$; $B_2 = \sin\varphi$ | | 10–5 | | | |
| Barton (1974) | $\sigma_c/\sigma_1$ | > 10 | 5–2.5 | < 2.5 | | |
| Barton (1974) | $\sigma_t/\sigma_1$ | > 0.66 | 0.66–0.33 | 0.33–0.16 | < 0.16 | |
| Russenes (1974) | Stress coefficient $\sigma_\theta/\sigma_c$ | ≤ 0.2 | 0.2–0.3 | 0.3–0.55 | > 0.55 | |
| Russenes (1974) | Stress coefficient $I_s/\sigma_\theta$ | > 0.20 | 0.15–0.20 | 0.083–0.15 | < 0.083 | |
| Hoek and Brown (1980) | $\sigma_\theta/\sigma_c$ | 0.34 | 0.42 | 0.56 | ≥ 0.7 | |
| Ryder (1988) | $ESS=\lvert\tau\rvert-\sigma_n\tan\varphi_d$ | <5 | 5–15 | >15 | | |
| Cook, (1966) | $ERR = \Phi_k/\Phi_0$ | < 3.5% | 3.5–4.2% | 4.2–4.7% | > 4.7% | |
| Tao (1988) | $AI = \sigma_c/\sigma_1$ | > 14.5 | 5.5–14.5 | 2.5–5.5 | ≤ 2.5 | |
| Tao (1988) | $\sigma_1/\sigma_c$ | < 0.069 | 0.069–0.180 | 0.180–0.400 | > 0.400 | |
| Hou (1989) | $H_{cr} = 0.318\sigma_c (1 - \mu)/(3 - 4\mu)\gamma$ | | | | | |
| Hou (1992) | $W_{qx}$<br>$\sigma_1 (\alpha W_{qx})0.5/\sigma_c$ | < 1.5<br>< 1 | 1.5–2.5<br>1–1.41 | 2.5–3.5<br>1.41–1.73 | > 3.5<br>> 1.73 | |
| Singh (1988) | Decrease modulus index | > 1 | 1–2 | < 1 | | |
| Singh (1988) | Burst proneness index | < 10 | 10–15 | > 15 | | |
| Li (1990) | $K_w = (\sigma_{max})2\lambda \cos\alpha/E$ | < 0.1 | 0.1–0.3 | 0.3–0.6 | > 0.6 | |
| Tan (1991) | Brittleness index $K_u = U/U_1$ | ≤ 3.5 | 3.5–5.0 | 5.0–7.0 | > 7 | |
| Xiao (1991) | $\omega = (\sigma_1/\sigma_{1cr})^2$ | < 1 | 1–2 | 2–5 | > 5 | |
| GB50218-94 (IYRWR 1995) | $K_v = (V_p/V_s)2$ | < 0.55 | 0.55–0.65 | 0.65–0.75 | > 0.75 | |
| Aubertin (1994) | Brittleness Index Modified (BIM) = $A_2/A_1$ | > 1.5 | 1.2–1.5 | 1.0–1.2 | | |
| Mitri (1996) | Energy-band failure index $PSF = e_4/e_c$ | | | | | |
| Palmström (1995) | Competency factor $C_g = f_\sigma\sigma c/\sigma\theta = RMi/\sigma_\theta$ | > 2.5 | 1.0 | –2.5 | 0.5–1.0 | < 0.5 |
| Peng (1996) | $H_{cr} = \sigma_t/[\gamma((1 + \lambda) + 2(1 - \lambda)\cos2\theta)]$ | | | | | |
| Peng (1996) | Rock brittleness coefficient $B_3 = \sigma_c/\sigma_t$ | > 40 | 40–26.7 | 26.7–14.5 | < 14.5 | |
| Wu and Zhang (1997) | $D_T$ | > 500 | 50–500 | ≤ 50 | | |
| Simon (1999) | $BPR = \lvert K_p/K_e$ | | | | | |
| Simon (1999) | $OBI = F_{ob}/F_{res}$ | | | | | |
| Wang (2009) | EMTDM $\sigma_\theta/\sigma_c$ | < 0.3 | 0.3–0.5 | 0.5–0.7 | ≥ 0.7 | |
| Mitri (1999) | BPI = (ESR/E) 100% | 100% | < 25% | 25–50% | 50–75% | 75%–1 > 1 |
| Yeryomenko (1999) | Rockburst-hazard criterion $K_1 = E_{se}/JQ$ | $< 10^{-5}$ | | $1.7 \times 10^{-4}$<br>$-3.5 \times 10^{-4}$ | $> 3.5 \times$<br>$10^{-4}$ | |
| Yeryomenk (1999) | $K2 = \rho_1/\rho_2$ | ≥ 1 | 0.5–1 | 0.1–0.5 | < 0.1 | |
| Feng (2000) | $k = 0.1(\sigma_c \times \varepsilon_f)/(\sigma_t \times \varepsilon_b)$ | < 3 | 3–5 | ≥ 5 | | |
| Tang (2000) | $H_{cr} = \sigma_c(1 - \mu)/[5(3 - 4\mu)\ \gamma]$ | | | | | |
| Wang and Park (2001) | $PES = \sigma_c^2/2E_u$ | ≤ 50 | 50–100 | 100–150 | 150–200 | > 200 |
| Pan and Li (2002) | $H_{cr} = \sigma_c(1 - \sin\varphi)\lambda 1[(1 + E/\lambda_1)^{1/(1 - \sin\varphi)} - E/\lambda_1 - 1]/2E\gamma\sin\varphi$ | | | | | |
| Tang and Wang (2002) | $k = (\sigma_c \times \varepsilon_f)/(\sigma_t \times \varepsilon_b)$ | < 20 | 20–75 | 75–130 | > 130 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Zhang (2003) | Brittleness index $K_u$<br>$Ku = U/U_1$ | ≤ 2 | 2–6 | 6–9 | > 9 | |
| Zhang (2003) | $B3 = \sigma_c/\sigma_t$ | < 10 | 10–18 | > 18 | | |
| Zhang ( 2003) | $\alpha = \sigma_c/\sigma_1$ | > 10 | 5–10 | 2.5–5 | < 2.5 | |
| Zhang (2003) | $\beta = \sigma_t/\sigma_1$ | | | | | |
| Heal (2006) | $EVP = E_1 E_2/E_2 E_4$ | < 50 | 50–85 | 85–105 | 105–140 | > 140 |
| Bukowska (2006) | $GEO_n = R_n W_n$ | < 60 | 60–71 | 72–112 | > 112 | |
| GB50487-2008 (National Standards Compilation Group of People's Republic of China, 2008) | $\sigma_c/\sigma_{max}$ | > 7 | 4–7 | 2–4 | < 2 | |
| Mitri (2007) | $PSF =(\sigma_1/UCS_{rm})$ | 100% | | | | |
| Li (2008) | RQD index | < 25 | 25–50 | 50–70 | > 70 | |
| Li (2008) | Stress index | <0.15 | 0.15-0.20 | 0.15–0.25 | >0.25 | |
| Li (2008) | Grade of surrounding rock | below | II–III | II–I | I | |
| Chen | $U/U_0$ | | 0.3 | 0.4 | 0.5 | ≥0.7 |
| Lu, J.Y, (Zhou, 2010) | $\sigma_\theta/\sigma_c \geq K_s\ \sigma_t/\sigma_c$ | 0.25 | 0.5 | 0.75 | 1.00 | |
| Lu, J.Y (Zhou, 2010) | $K_s$ | 0.30 | 0.40 | 0.45 | 0.60 | |
| Hosseini, (2010) | Normalized deviatoric stress $NDS=(\sigma_1-\sigma_3)/\sigma_c$ | ≤0.35 | 0.35–0.5 | 0.5–0.8 | 0.8–1.0 | >1.0 |
| Shan Z G (Zhou, 2010) | lithology criteria $\sigma_\theta/\sigma_c > K_s$ | | | | | |
| Qiu (2011) | $RVI = F_s F_r F_m F_g$ | | | | | |
| Tarasov and Randolph ( 2011) | Brittleness index $B_4 = (E_u - M)/M$ | | | | | |
| Castro (2012) | $BSR = (\sigma_1 - \sigma_3)/\sigma_c$ | .45–0.6 | 0.6–0.7 | > 0.7 | | |
| Shang (2013) | $P_{rb} = (K_v\ \sigma_\theta)/\sigma_t$ | < 1.7 | 1.7–3.3 | 0.3.3–9.7 | > 9.7 | |
| Zhang (2013) | $S = \tanh\{[0.1648(\sigma_\theta/\sigma_c)^{3.064} (B_3)^{-0.4625} (W_{et})^{2.672}]^{(1/3.6)}\}$ | < 0.25 | 0.25 | –0.50 | 0.5–0.75 | > 0.75 |
| He (2015) | Rockburst risk index $I_{RB} = H/\sigma_{RB}$ | < 0.6 | 0.6–1.2 | 1.2–2.0 | > 2.0 | |
| Yin (2014) | $D_S = W_{cf}\ \varepsilon_{sa}//\varepsilon_{fc}$ | < 10 | 10–20 | > 20 | | |
| Mutke (2015) | Weighted value of peak particle velocity (PPVW), m/s | ≤ 0.05 | 05–0.2 | . 0.2–0.4 | > 0.4 | |
| Mutke (2015) | AG-R = [(bm − b)/bm]·100% | < 0 | 0–25 | 25–50 | > 50 | |
| Zhang (2016) | Potential rockburst index $\Omega = (3 - \lambda_0)W_{et}\ \sigma_\theta/\sigma_c$ | < 0.4 | 0.4–1.05 | 1.05–2.5 | > 2.5 | |
| Zhao (2017) | $\sigma_c/\sigma_1$ | >5 | 4–5 | 2.5–4 | 1.5–2.5 | ≤ 1.5 |
| | $\sigma_\theta/\sigma_c$ | ≤ 0.2 | 0.2–0.5 | 0.5–0.7 | 0.7–0.9 | > 0.9 |
| | $\sigma_c/\sigma_v$ | > 10 | 5–10 | 3.3–5 | 2.5–3.3 | ≤ 2.5 |
| Zhou (2017) | $W_{et} = E_e/E_p$ | < 2.0 | 2.0–5.0 | 5.0–10.0 | >10.0 | ≤ 2.5 |

## 5. Conclusions

The previous experiments and strategies of rockburst prevention, control, monitoring, and prediction are discussed and mentioned in this paper. From the very beginning to the current era, there were many flaws in the previous approaches and methods, which were modified with the passage of time and requirements. Experiments were performed carefully to investigate the rockbursts phenomenon and its prediction and damage potential. The uniaxial compressive test, multi-mode tests, and tri-axial texts were conducted at laboratory to investigate the rockburst mechanisms. The experimental procedures and equipment were modified. The AE technology was introduced to investigate the rock failure. Laboratory modelling of the rock burst phenomenon under severe deep underground condition was the major achievement of SKLGDUE at the China University of Mining and technology, Beijing. Laboratory modelling of rock burst phenomenon under severe deep underground condition was the major achievement of SKLGDUE at the China University of Mining and technology, Beijing. Invention of DURATM and simulation of rock burst process at deep levels (CUMT-BEIJING) were a major success. Many prediction methods such as the fuzzy-based evaluation method have been suggested by many researchers. The PNP modelling process was established to predict rockburst. Dou Liniming and Mu Zonglong invented a new procedure to evaluate the rockburst prediction, prevention, and damage potential through the energy theory. At the end, a table is drawn carefully to summarize the rockburst danger and potential measure.

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# مروری بر پیشرفت‌های تجربی، هشدار، پیش بینی، کنترل و آسیب‌های احتمالی ناشی از انفجار سنگ

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## چکیده:

انفجار سنگ یک مسئله‌ی مهیج و قابل تأمل در معدنکاری و ژئومکانیک در پی افزایش عمق معادن و عمق قرار گیری سازه‌ی زیر زمینی است. همچنین انفجار سنگ یک معضل اساسی در مسائل مربوط به اقدامات کنترل زمین در چند دهه اخیر است. مطالعات بسیاری توسط محقیق پیرامون کاهش خطرات ناشی از انفجار سنگ و فراهم آوردن یک محیط عملیاتی امن در معادن زیرزمینی صورت گرفته است. بازبینی مزایای فعلی پیش بینی انفجار سنگ و اقدامات پیشگیرانه لازم برای آن، امری ضروری است. در این مطالعه پیشرفت تجربی در مورد هشدار برای انفجار سنگ، پیشبینی انفجار سنگ، اقدامات کنترلی و پتانسیل تخریب توسط انفجار سنگ بازبینی شده است. همچنین روش‌های مختلف پیش بینی انفجار سنگ و کنترل آن شرح داده شده است.

**کلمات کلیدی:** انفجار سنگ، تحقیق و بررسی، ایمنی کار، پیش‌بینی، پتانسیل آسیب.

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