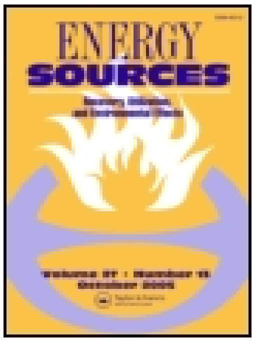

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# Research on the relationship between coal burst tendency and rockburst risk of coal seam

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**ABSTRACT**
The burst tendency and the risk of rock burst are of great significance in the research of coal mine, which is the basis for the prediction and prevention of rock burst. In order to avoid the confusion of two basic concepts, their essential properties and differences are discussed in detail. In this paper, a prediction model of rock burst in circular roadway based on disturbance response instability theory is proposed, and the critical stress formula of burst is derived to obtain the relationship between the burst tendency and the rockburst risk. The results show that the burst tendency is a necessary condition and an important index to evaluate the strength of the rockburst risk. The risk of rock burst is the possibility and harm degree of rock burst in coal seam with burst tendency. A new identification index of burst tendency and a new evaluation index of rock burst risk are put forward, which provides a new method for the risk evaluation and provides theoretical guidance for prevention and control.

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**KEYWORDS**
Rock burst; burst tendency; rockburst risk; disturbance response instability; critical stress

## Introduction

With the gradual increase of mining depth and area, rock burst is becoming more and more serious, which has become the main obstacle of mine safety production (Pan 2018a). It is an important safeguard to predict the location, type, and damage level of rock burst in the mining process of working face, and to formulate corresponding prevention and control measures (Singh 1989). The tendency and the risk of rock burst are two important indexes and often be used in the forecasting and prevention. At present, the mechanism of rock burst is not completely clear, and the relationship between them is not given in theory, which makes the two concepts easily confused. In the process of mine rock burst risk prediction, due to the confusion of the concepts, and the diversity of index evaluation system, the results of rock burst risk prediction are often significantly different, which has a great influence to management cost.

In the aspect of research on the burst tendency , many countries in the world have done a lot of research (Li and Cheng 2014; Sears and Heasley 2009; Wang, Xu, and Wei 1999)· South Africa, the former Soviet Union, Poland, Germany, and other countries put forward a variety of indicators to determine the burst tendency, which can be summarized into four aspects: energy concentration and release of coal and rock mass, failure time, deformation and stiffness. Typical ones among them include elastic energy index, impact energy index, effective impact energy index, bending energy index, dynamic failure time, elastic deformation index, creep compliance coefficient, brittleness coefficient, limit energy ratio and limit stiffness ratio, etc. (Mou et al. 2013; Qi, Peng, and Li 2011; Song, Ji, and Sun 2015; Su, Gao, and Yuan 2014; Su, Yuan, and Zhai 2013). The study of coal burst tendency in China is nearly 30 years later than that of the main rock burst disaster countries in the world, but it has developed rapidly. At present, a number of practical methods and indexes for the

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evaluation have been established already ((GBT 25217.1-2010); (GBT 25217.2-2010); (MT/T174-2000); Qi and Dou 2008). The burst tendency indexes stipulated in the national standard include uniaxial compressive strength, elastic energy index, impact energy index, and dynamic failure time (Lei, Qi, and Jie 2004; Mao 2000; Zhou 1985)˙

In the field of rockburst risk research, related researchers around the world put forward a variety of risk assessment and prediction methods. Mainly include drilling cuttings, surrounding rock deformation, conventional mine pressure observation method, the geological dynamic division method, the electromagnetic radiation method, acoustic emission method, micro seismic monitoring system, charge radiation method, computer numerical simulation, similar material simulation method, the comprehensive index method, probability index diagnosis method, the fuzzy hierarchy index method, etc. (Shao, Zhao, and Shao 2013; Sun 2009).

In the process of rock burst management, some people mistakenly confuse the relationship between burst tendency and rockburst risk due to unclear concepts. They think that the coal seam with burst tendency has rockburst risk, and the burst tendency is equal to the rockburst risk; or the risk level of rockburst risk assessment is regarded as the occurrence probability or damage degree of rock burst, and they think that the area with weak rockburst risk will not have greater destructive rock burst. The deficiency in cognition lead to the establishment of the impact of the ground pressure prevention measures exist safety hazards. Based on the theory of rock burst disturbance response instability, this paper expounds the concept and relationship between burst tendency and rockburst risk, and points out the important role of them in prediction and prevention.

## Theory of rock burst disturbance response instability

Rock burst in coal mine is a kind of dynamic disaster caused by sudden and rapid destruction of coal and rock mass such as roadway, coal pillar and mining face (Pan 1999; Pan, Zhao, and Ma 2005; Zhao 1994). Its essence is deformation and instability of underground space structure system composed of coal and rock mass near mine roadway or mining face under the action of mining load (Pan 2018b). The factors affecting the stability of underground space structure can be divided into internal and external factors. The internal cause is the inherent property of underground space structure, which mainly includes the geometric structure of underground mining space and the lithology of coal and rock body, which plays a decisive and controlling role on the stability of underground space structure. The external cause is the rock mass stress exerted on the underground space structure system, mainly including additional stress caused by mining and far-field mine earthquake.

In order to clarify the mechanism of rock burst, the roadway was simplified into a circular tunnel of radius $a$and a two-dimensional circular tunnel model was established, as shown in Figure 1.It is assumed that the support resistance of the inner wall of the roadway is $p_s$, which is affected by the rock stress $P$ at infinite distance. The axisymmetric plane strain problem is considered when gravity is ignored and unit width is taken along the direction of tunnel axis for analysis.

Equilibrium equation

$$\frac{d\sigma_r}{dr}+\frac{\sigma_r-\sigma_\theta}{r}=0 \tag{1}$$

Geometric equation

$$\varepsilon_r=\frac{du}{dr}\,\varepsilon_\theta=\frac{u}{r} \tag{2}$$

In the formula, $u$ is the radial displacement; $\sigma_r$, $\sigma_\theta$is the radial stress and tangential stress; $\varepsilon_r$, $\varepsilon_\theta$is the radial strain and tangential strain.

When the load $P$ is small, the surrounding rock is in an elastic state, and the stress-strain relationship is as follows.

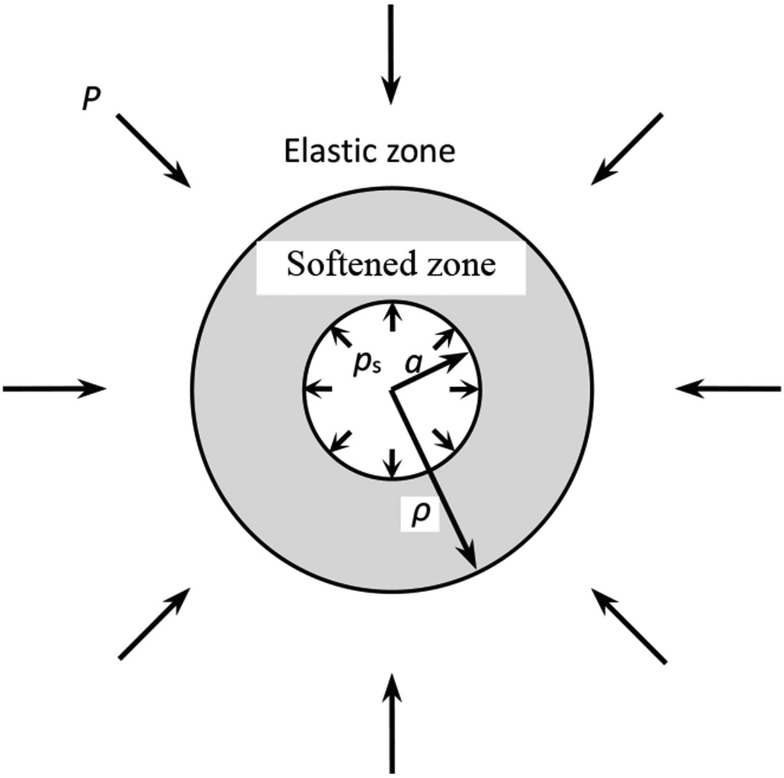

**Figure 1.** Mechanical model of roadway surrounding rock – support system.

$$\begin{cases} \sigma_r = \bar{E}(\varepsilon_r + \bar{\mu}\varepsilon_\theta) \\ \sigma_\theta = \bar{E}(\varepsilon_\theta + \bar{\mu}\varepsilon_r) \\ \sigma_z = \bar{E}\bar{\mu}(\varepsilon_r + \varepsilon_\theta) \end{cases} \tag{3}$$

$\bar{E} = \frac{E(1-v)}{(1+v)(1-2v)}$,$\bar{v} = \frac{v}{1-v}$,$E$,$v$is elasticity modulus and Poisson's ratio of surrounding rock.

From (1)~(3), at the roadway wall support $\sigma_r = p_s$ and in the far field $\sigma_r = P$, the component of stress is obtained as follow.

$$\begin{cases} \sigma_r = P - (P - p_s)\frac{a^2}{r^2} \\ \sigma_\theta = P + (P - p_s)\frac{a^2}{r^2} \\ \sigma_z = 2vP \end{cases} \tag{4}$$

If there is no support resistance, $p_s = 0$,so

$$\sigma_r = P\left(1 - \frac{a^2}{r^2}\right),\ \sigma_\theta = P\left(1 + \frac{a^2}{r^2}\right),\ \sigma_z = 2vP \tag{5}$$

Stress intensity $\bar{\sigma} = P\sqrt{3\frac{a^4}{r^4} + (1-2v)^2}$. From $\bar{\sigma}_{\max} = \sigma_c$,$\sigma_c$is uniaxial compressive strength. Elastic limit load $P_e = \frac{\sigma_c}{2\sqrt{1-v+v^2}}$ can be obtained.

When $P > P_e$, the plastic softening zone appears around the roadway, and suppose the radius of the softening zone is$\rho$. In softening region $a \le r \le \rho$, assuming that volume is incompressible, known$\bar{\varepsilon}(\rho) = \varepsilon_c$,then radial displacement $u = \frac{\sqrt{3}}{2}\frac{\varepsilon_c\rho^2}{r}$ and strain component $\varepsilon_r = -\frac{\sqrt{3}}{2}\frac{\varepsilon_c\rho^2}{r^2}$, $\varepsilon_\theta = \frac{\sqrt{3}}{2}\frac{\varepsilon_c\rho^2}{r^2}$ are obtained.

Mohr – Coulomb yield criterion is adopted.

$$\sigma_\theta = m\sigma_r + \sigma_c \tag{6}$$

In the previous formula,$m = \frac{1+\sin\varphi}{1-\sin\varphi}$,$\varphi$is the internal friction Angle of coal and rock materials. Substitute equation (6) into the equilibrium equation, as $\sigma_r(a) = p_s$, we get the stress component:

$$\sigma_r = \left(p_s + \tfrac{\sigma_c}{m-1}\right)\left(\tfrac{r}{a}\right)^{m-1} - \tfrac{\sigma_c}{m-1},\ \sigma_\theta = \left(p_s + \tfrac{\sigma_c}{m-1}\right)\left(\tfrac{r}{a}\right)^{m-1} - \tfrac{\sigma_c}{m-1},\sigma_z = \tfrac{m+1}{2}\left(p_s + \tfrac{\sigma_c}{m-1}\right)\left(\tfrac{r}{a}\right)^{m-1} - \tfrac{\sigma_c}{m-1}.$$

In elastic areas $r \geq \rho$,$\sigma_r = P - (P - q_r)\frac{\rho}{r^2}$,$\sigma_\theta = P + (P - q_r)\frac{\rho^2}{r^2}$,$\sigma_z = 2\nu P$.In the above formula, $q_r$ is the radial stress at the interface $r = \rho$ of elastic zone and softening zone.

At the junction of elastic zone and softening zone $r = \rho$, $q_r = \frac{2P-\sigma_c}{m+1}$ can be obtained from $\sigma_\theta(\rho) = m\sigma_r(\rho) + \sigma_c$, and the radius of softening zone can be obtained from the continuous condition of radial stress.

$$\rho = a\left[\frac{1}{m+1}\frac{(m-1)P + \sigma_c}{(m-1)p + \sigma_c}\right]^{\frac{1}{m-1}} \tag{7}$$

Formula (7) shows that the radius of the softening zone increases with the increase of load, and indicate that the above analysis can only reflect the stable deformation law of surrounding rocks of the roadway, which cannot reflect the phenomenon that the system instability occurs the rock burst (Pan, Geng, and Li 2010).

In the softening zone, the equivalent strain $\bar{\varepsilon} = \frac{2}{\sqrt{3}}\frac{B}{r^2}$ is obtained from the geometric relation and the condition of volume incompressibility. At the interface $r = \rho$ between the softening zone and the elastic zone, the coal and rock materials in the elastic zone just reach the peak strength, and the corresponding strain is $\varepsilon_c$.This position is in three-dimensional stress state. According to the general method to generalize uniaxial strain to triaxial strain in plastic mechanics, then the equivalent strain $\bar{\varepsilon} = \varepsilon_c$,

Substitute it into $\overline{\overline{\varepsilon}}\frac{2}{\sqrt{3}}\frac{B}{r^2}$ get $B = \frac{\sqrt{3}}{2}\rho^2\varepsilon_c$, so

$$\bar{\varepsilon} = \varepsilon_c\frac{\rho^2}{r^2} \tag{8}$$

Assuming that damage evolution occurs in the softening zone, the damage variable $D$ is linearly related to the equivalent strain $\bar{\varepsilon}$, namely $D = D_1 + D_2\bar{\varepsilon}$. When $\bar{\varepsilon} = \varepsilon_c$, $\bar{\sigma} = \sigma_c$, $D = 0$.when $\bar{\varepsilon} = \varepsilon_u$, $\bar{\sigma} = 0$, the damage reaches the critical value $D = D_{cr}$, where $\varepsilon_u$ is the strain when the stress decreases to zero in the softening stage (see Figure 2).According to this, $D_1 = -\frac{D_{cr}\varepsilon_c}{\varepsilon_u - \varepsilon_c}$, $D_2 = \frac{D_{rc}}{\varepsilon_\mathrm{u} - \varepsilon_c}$ can be obtained,

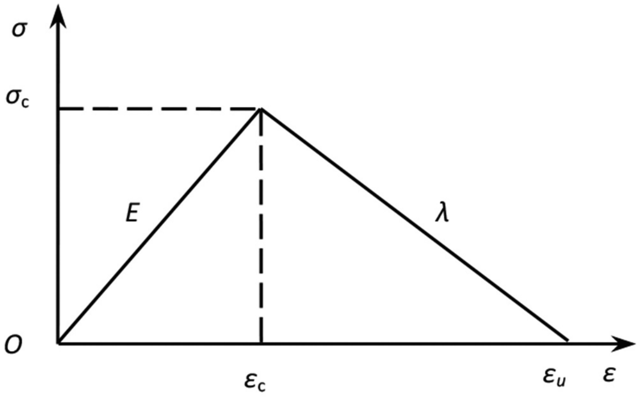

Figure 2. Bilinear stress-strain relationship of coal and rock.

so$D = \frac{D_{cr}}{\varepsilon_{\mathrm{u}} - \varepsilon_c}(\bar{\varepsilon} - \varepsilon_c)$. Suppose the softening modulus is $\lambda$, then $\varepsilon_u - \varepsilon_c = \frac{\sigma_c}{\lambda}$, set the damage threshold $D_{cr} = 1$, then get

$$D = \frac{\lambda}{E}\left(\frac{\rho^2}{r^2} - 1\right) \tag{9}$$

Considering material damage in softening zone, effective stress components $\tilde{\sigma}_r = \frac{\sigma_r}{1-D}, \tilde{\sigma}_\theta = \frac{\sigma_\theta}{1-D}$ are considered. $\tilde{\sigma}_\theta = m\tilde{\sigma}_r + \sigma_c$is obtained by replacing the stress in Mohr-Coulomb yield criterion with effective stress. So

$$\sigma_\theta = m\sigma_r + (1 - D)\sigma_c \tag{10}$$

After substitute equation (9) into equation (10), substitute into the equilibrium equation, and get

$$\frac{d\sigma_r}{dr} - (m - 1)\frac{\sigma_r}{r} = \left(1 + \frac{\lambda}{E}\right)\frac{\sigma_c}{r} - \frac{\lambda\sigma_c}{Er^3}\rho^2 \tag{11}$$

The solution of the above equation is

$$\sigma_r = Qr^{m-1} + \frac{\lambda\sigma_c}{E(m+1)}\frac{\rho^2}{r^2} - \left(1 + \frac{\lambda}{E}\right)\frac{\sigma_c}{m-1} \tag{12}$$

In the above equation, Q is the integral constant.

From the boundary condition $\sigma_r(a) = p_s$, we get $Q = \left[p_s - \frac{\lambda\sigma_c}{E(m+1)}\frac{\rho^2}{a^2} + \left(1 + \frac{\lambda}{E}\right)\frac{\sigma_c}{m-1}\right]\frac{1}{a^{m-1}}$, so

$$\sigma_r = \left[p_s - \frac{\lambda\sigma_c}{E(m+1)\frac{\rho^2}{a^2}\left(1 + \frac{\lambda}{E}\right)\frac{\sigma_c}{m-1}}\left(\frac{r}{a}\right)^{m-1} + \frac{\lambda\sigma_c}{E(m+1)\frac{\rho^2}{r^2}\left(1 + \frac{\lambda}{E}\right)\frac{\sigma_c}{m-1}}\right] \tag{13}$$

According to the continuous condition of radial stress at $r = \rho$,then

$$\frac{P}{\sigma_c\frac{m+1}{2}\left[\frac{p_s}{\sigma_c\left(1+\frac{\lambda}{E}\right)\frac{1}{m-1}}[]\left(\frac{\rho}{a}\right)^{m-1}\frac{\lambda}{2E}\left(\frac{\rho}{a}\right)^{m+1}\left(1 + \frac{\lambda}{E}\right)\frac{1}{m-1}\right]} \tag{14}$$

If the far-field stress disturbance is considered, the criterion of disturbance response caused by rock burst can be obtained as follows:

$$\frac{\rho_{cr}}{a\sqrt{1 + \frac{E}{\lambda} + \frac{E}{\lambda}(m-1)\frac{p_s}{\sigma_c}}} \tag{15}$$

In the formula, $\rho_{\mathrm{cr}}$ is the critical softening zone radius. It is also called critical depth problem.

Substituting (15) into equation (14), get the critical stress $P_{\mathrm{cr}}$when rock burst occurs.

$$\frac{P_{\mathrm{cr}}}{\sigma_c} = \frac{1}{m-1}\left\{\frac{\lambda}{E}\left[1 + \frac{E}{\lambda} + \frac{E}{\lambda}(m-1)\frac{p_s}{\sigma_c}\right]^{\frac{m+1}{2}} - \frac{\lambda}{E} - 1\right\} \tag{16}$$

From the above analysis, whether rock burst in roadway is determined by the mechanical properties of coal and rock, such as uniaxial compressive strength $\sigma_c$, elastic modulus E, softening modulus $\lambda$, angle t of internal friction of coal and rock material $\varphi$ and other mechanical properties of coal and rock, support resistance $p_s$ of roadway, radius of roadway softening zone$\rho$ and rock stress P.

The factors affecting the stability of surrounding rock-support system can be divided into three categories: control quantity, disturbance quantity and influence quantity. The relationship between each main control factor and roadway surrounding rock – support system is shown in Figure 3.

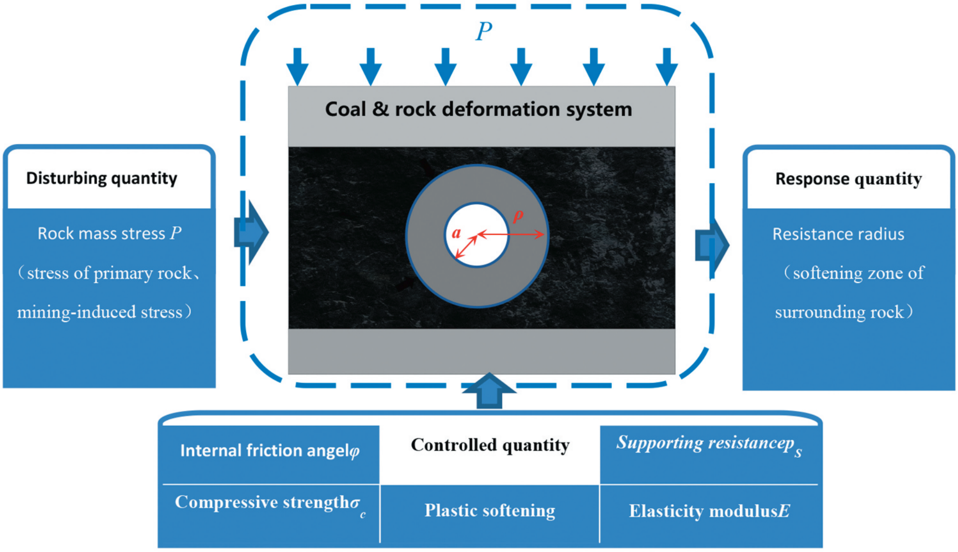

**Figure 3.** Relationship between main control factors and roadway surrounding rock – support system.

As can be seen from Figure 3, $\sigma_c$, $E$, $\lambda$, $\varphi$ in the control quantity is an inherent attribute of coal and rock mass, independent of the control quantity and the influence quantity, but affected by $p_s$.

The reason is that roadway support transforms the plane stress state near roadway surrounding rock into a triaxial stress state. Under the triaxial stress state, the compressive strength of coal and rock increases with the increase of confining pressure, and the bursting liability decreases with the increase of confining pressure (Pan 2018a).

Therefore, under the effect of roadway support resistance, the stability of roadway surrounding rock support system is greatly improved, that is, the critical stress $P_{\mathrm{cr}}$ increases.

It can be seen from this that the control quantity is the internal factor that affects the stability of surrounding rock-support system of roadway.

Disturbance quantity mainly refers to the external forces acting on the surrounding rock support system of roadway, such as original rock stress, mining stress and dynamic load generated by mine earthquake. Its value directly determines whether the roadway will have rock burst or not. That is, as long as the $P$action on the roadway surrounding rock-support system is greater than $P_{\mathrm{cr}}$, the roadway surrounding rock-support system will be unstable, and rock burst will occur.

The response quantity refers to when the radius $\rho$ of softening zone is approximately equal to that of $\rho_{\mathrm{cr}}$, that is, the roadway surrounding rock-support system is in a critical instability state, and even a small disturbance amount will lead to the occurrence of rock burst. $\rho$ is a controllable quantity, and its size can be adjusted actively by blasting and increasing roadway support resistance, so as to increase $P_{\mathrm{cr}}$ and improve the stability of roadway surrounding rock-support system.

## The concept and function of burst tendency and risk

### *The burst tendency of coal and rock*

The burst tendency refers to the nature of coal and rock mass with accumulated deformation energy and produces impact failure. It is the intrinsic property of coal and rock mass, and its numerical value determines how hard it is of rock burst in coal seam. Bursting liability of coal and rock is mainly used to measure the elastic energy stored in coal and rock mass, and the ability to release elastic energy instantaneously when brittle failure occurs. According to the theory of rock burst disturbance response instability, coal rock burst liability belongs to the controlled quantity of roadway surrounding rock-support system and is a necessary condition for occurring rock-burst. If there is no burst tendency of coal and rock, that's ideal elastic-plastic material, and there will be no rock burst in mining process, and there is no need to predict and prevent it.

The theory of rock burst disturbance response instability reveals the mechanism. However, due to its simplification of the parameters of roadway surrounding rock-support system, only the compressive strength and elastic modulus are used to reflect the bursting liability of it. As a matter of fact, due to the different types of rock-burst and its disaster causing factors, the evaluation indexes of the bursting liability will be various, which may need to be determined by one or a group of indexes, or the correlation between indexes or comprehensive evaluation (Zhang, Lu, and Chen 2017).

The identification of coal burst tendency is mainly to evaluate the property of coal rock prone to rock burst under certain conditions by studying and understanding the mechanical properties of coal and rock itself. At present, laboratory test method is mainly used at present. Based on the experimental results of stress-strain curve of coal and rock, various evaluation indexes of coal burst tendency are directly or calculated. The appraisal of coal burst tendency mainly evaluates the attributes of this kind of coal rock which tends to occur rock burst under certain conditions through the study and understanding of its mechanical characteristics. At present, the main method is laboratory test (Wang, Pan, and Feng 2001). Based on the results of the stress-strain curve of coal rock obtained from the experiment, the evaluation indexes of coalburst tendency are directly or calculated. Because the mechanism of rock burst is not completely clear up to now, according to different research objects, different test and analysis methods, relevant scholars have put forward a number of indicators for authenticating burst tendency (Pan, Geng, and Li 2010). According to physical connotation, they can be divided into four categories: energy index, deformation index, time index, and intensity index (Zhang, Lu, and Chen 2017).

The energy index is based on the energy dissipation in the process of deformation, and the elastic energy storage and plastic energy dissipation capacity of coal and rock in the process of mining. It is taken as the standard to evaluate the burst tendency of coal and rock. The specific indicators include: elastic energy index, impact energy index, effective impact energy index, bending energy index, energy release index, residual energy emission speed index; impact energy velocity index, etc. The last three indexes consider the time effect of energy release, and judge the dynamic effect of coal and rock failure according to the amount of energy conversion per unit time.

From the deformation ability of coal and rock mass, the more brittle the coal is, the smaller the plasticity is. And the more elastic deformation energy stored in the deformation process is, the smaller the plastic deformation energy is, and the higher the burst tendency is. Deformation indexes mainly include Index of brittleness of strength, Index of brittleness coefficient of deformation, elastic deformation index, creep compliance coefficient and stiffness ratio index, and so forth.

The time index reflects the intrinsic law of burst tendency from the aspect of time, and reflects the intensity of burst tendency of it by the time from strength limit to complete collapse. The time from the strength limit to complete disintegration is the dynamic failure time. The shorter the dynamic failure time, the stronger the bursting liability is.

The strength index is based on the uniaxial compressive strength index to evaluate the impact propensity. A large number of experimental data of stress-strain curve show that the higher the strength of coal and rock, the less plastic it is, and the greater the elastic deformation energy stored in the process of rock deformation, the smaller the plastic deformation and damage dissipation energy, and the shorter the dynamic failure time, so the higher the burst tendency.

The identification result of coal and rock burst tendency is an important basis for predicting and preventing (Qi, Peng, and Li 2011). Relevant regulations such as " Coal Mine Safety Regulations ", " Detailed Rules for The Prevention and Control of Coal Mine Rock burst " and have clearly stipulated the identification methods and institutions of bursting liability, which makes the coal burst tendency appraisal unity and perfect further. However, a large number of field practice and theoretical research results show that there are still the following problems in the current identification method and index evaluation method of burst tendency:

(1) Due to the complexity of the structure and failure process of the rock materials themselves, and the existing experimental testing standard system is not systematic and perfect enough. On the other hand, the burst tendency index obtained by laboratory sample test has large dispersion, which result in value difficulty and need to be improved (Pan, Geng, and Li 2010).

(2) There is a big difference between the mechanical properties of coal and rock obtained from the testing of samples in the laboratory and the properties in the working face site. The samples used for laboratory testing are basically intact obtained in the field, and their joints and fractures are of low development degree and high strength, which cannot truly reflect the mechanical properties in the working face. Although the relationship between the mechanical properties of it has been studied, the test data in laboratory cannot reflect the natural characteristics in working face.

(3) Each index of burst tendency only evaluates the strength of coal seam unilaterally, and the boundary of dividing the strength are fuzzy, leading to large or contradictory dispersion of evaluation results, and the evaluation results of each index are difficult to be unified. The comprehensive evaluation method ignores the weight of each index in the evaluation, which easily leads to the underestimation and reduce the objective accuracy (Pan, Wang, and Liu 2014).

In view of the existing problems in the identification, the identification of coal burst tendency needs to be improved in the following aspects according to its laboratory, theoretical and actual site. (1) Searching for the index with high accuracy and sensitivity can accurately and comprehensively reflect the degree of coalburst tendency such as energy storage, failure time, deformation and rigidity (Jin and Xian 1993). (2) The identification method of coalburst tendency is practical and reliable, which can be quickly and conveniently measured. (3) Unify the testing technical conditions of appraisal institutions, such as mechanical parameters equipment stiffness, to ensure the uniformity of burst tendency appraisal results. In addition, according to the instability theory of rock burst disturbance response, it is known that it is caused by deformation instability of surrounding rock system (Xu et al. 2019).

The current burst tendency index only considers the mechanical properties of it, ignoring the influence of the characteristics (such as coal and rock structure, occurrence environment, etc.) of surrounding rock spatial structure on the stability of the system. Therefore, in order to improve the accuracy and reliability of coal seam impact proneness index, and establish the correlation model between each index and the spatial structure. To measure the coal seam impact propensity comprehensively, a scientific index which can reflect the energy storage and dissipation process, combine the time effect and strength characteristics, and comprehensively consider the spatial structure characteristics of surrounding rock is put forward.

## The influence of coal and rock burst tendency grade on rock burst

The strength of coal rock bursting liability can be divided into three grades: no bursting liability, weak bursting liability and strong bursting liability. Based on the statistics of coal rock bursting liability in China’s coal mines with bursting pressure, it is found that 88% of coal rocks with bursting pressure have bursting liability, among which 47% of it have strong bursting liability and 53% of it have weak bursting liability (Jiang, Pan, and Jiang 2014; Lan, Qi, and Pan 2011).The above data show that the coal rock has bursting liability is one of the important conditions for the occurrence of rock burst.

Brittleness is one of the inherent properties of coal and rock under mechanical failure. According to the current classification standard of burst tendency, the coal rock with no burst tendency also has the ability to accumulate deformation energy and produce impact failure. Therefore, according to the theory of disturbance response instability, rock burst will also occur when the original rock stress increases to a certain degree. Therefore, there are 12% coal mines with rock burst, and the coal seam is identified as non-bursting liability, but it still occurs.

From a large number of on-site failure data of rock burst, it is found that the range and intensity of rock-burst failure increased with the decrease of bursting liability of coal and rock. Such as Hongyang No.3 Coal Mine of Shenyang Coking Coal Co., Ltd, the buried depth of 702 working face is about 1100 m, and the coal seam has weak burst tendency. There has been a serious rock-burst accident on November 11, 2017, resulting in large area floor heave, roof fall and obvious displacement of coal side in 220 m roadway. A total of 296 working face of Junde Coal Mine in Hegang is buried at about 400 m, and the coal seam has strong burst tendency, On March 22, 2006, a rock burst accident occurred, which caused serious deformation of 35 m roadway support. The reason is that the weaker the bursting liability of coal seam is, the stronger the ability of surrounding rock-support system to resist external interference is, the larger the critical load will be. When rock burst occurs, the more work the original rock stress does, the more impact energy will be released.

## *Risk of rock burst*

Rock burst hazard refers to the possibility in coal seams with bursting liability and its harm degree (Execution Notes of Coal Mine Safety Regulations 2016; Wang, Wang, and Liu 2014), it is not only related to the bursting liability of coal and rock, but more importantly affected by the original geological conditions such as geological structure and ground stress, as well as mining factors such as the layout of working face, mining mode, mining method and the size of the goaf, that is, it is significantly affected by the disturbance amount of surrounding rock system.

The risk of rock burst is of great significance in the study of rock burst, only on the basis of the risk assessment of rock-burst, can the corresponding prevention and control measures be taken for the dangerous area. According to the instability theory of rock-burst disturbance response, the occurrence mainly depends on the stress of rock mass. Therefore, when evaluating the risk of rock burst, it is necessary to consider not only the bursting liability and geological conditions of coal seam, but also the change of mining stress field caused by working face layout, mining method, mining way and other factors such as the size of goaf (Zhou 1985). By using various observation and monitoring methods, the volume, range and magnitude of mining stress of high-stress ones in the excavation space as well as their variation rules can be obtained.

The risk assessment of rock burst is based on the inherent law of rock burst to identify and confirm the risk factors existing in the surrounding rock system.

Based on the comprehensive analysis of various factors affecting the mining process of a coal seam or a mining area, the possibility of the occurrence of rock-burst in a mining area is comprehensively analyzed (Wang, Wang, and Liu 2014). According to the accuracy of evaluation results, it can be divided into qualitative evaluation method and quantitative evaluation method (Lei, Qi, and Jie 2004); according to the size of the evaluation area, it can be divided into regional risk evaluation and local risk evaluation; according to the number of indicators used in evaluation, it can be divided into single evaluation method and comprehensive evaluation method; according to the monitoring methods and evaluation methods, it can be divided into rock mechanics method, geophysical method, empirical analogy method, dynamic method of surrounding rock, etc. (Gu, Wang, and Gu 2011; Jin, Wang, and Liu 2013; Zhou 2014).

The advantages of rock mechanics method, geophysical method and surrounding rock dynamic method are simple to operate, but they are easily affected by environment and conditions. The monitoring range of rock mechanics method and surrounding rock dynamic method is small, and when it is used to judge the rockburst risk, the critical index varies in the value of different coal seams, which requires the expert's knowledge and experience to judge, and the evaluation result is also the qualitative result, usually occurs (the probability is 100%) or does not occur (the probability is 0). The advantage of conventional method of observation of mineral pressure, comprehensive index method, possibility index diagnostic method and other empirical classification methods is that on the basis of comprehensive identification and confirmation of the risk factors existing in the system, the severity of each risk factor is “graded”, and an evaluation result is obtained through simple mathematical operation. However, due to the strong subjectivity, there are sometimes large deviations due to the artificial division scale, which to some extent damages the objectivity of the evaluation results. Moreover, as the limitation of theory and technology, there are still many deficiencies in the understanding of the disaster factors and risks caused.

The assessment method of coal seam to have a holistic view, in the basis of the research on the impact of coal and rock orientation, according to the mechanism occurred in analysis of mining geological conditions and mining technical condition, the influence of mining segment and instrumental determination of rock mass stress change rule. And set up a comprehensive index evaluation model, it is the main direction of risk assessment.

### *The rockburst risk level plays an important role for the prevention and control*

A large number of rock burst data also show that there is a critical depth at which rock burst occurs frequently. The rock burst may occur, when the mining depth is less than this value. However, it is sporadic. When mining at a depth that greater than this, rock-burst will occur frequently and the intensity is also increasing. Generally, the stronger the bursting liability, the shallower the critical depth. Therefore, under the same conditions of coal and rock bursting liability, different areas of roadway or working face have different rock burst risks due to different stress distribution. The greater the stress of rock mass is, the greater the disturbance is, the higher therockburst risk is. Based on the statistical analysis of the buried depth of some Chinese rock-burst roadways, it is found that the coal seams with a depth of 200 m or less (except under the influence of large geological structures) are basically free from rock-burst, and the buried depth of more than 77.2% of the roadways is more than 400 m. The results show that, when the coal seam depth is shallow and the original rock stress is low, even if the coal and rock have burst tendency, the rockburst risk is still small, and rock burst is not easy to occur. Therefore, the result of rockburst risk assessment is an important basis for the prediction and prevention. The coal mine Safety Regulations and The Rules for the Prevention and Control of Coal Mine Rock Burst have made corresponding requirements with different grade of rockburst risk.

## The relationship between rockburst risk and bursttendency

According to the above analysis in this paper, the identification results of bursting liability can not be directly used to evaluate the risk and strength, and the bursting liability index is only an index to evaluate the stability of surrounding rock of working face, which is the basis for evaluating the rockburst risk (Wang, Wang, and Dai 2020). Whether the coal seam with high tendency has rockburst or not depends on geological conditions, crustal stress and other factors.

In addition to the burst tendency, the risk of coal seam impact is mainly determined by the thickness of stratum, geological structure and other geological conditions on the working face. The exploitation mode, roadway layout in the mining area, mining sequence of the working face and other mining conditions, as well as the external factors such as the high rock stress, mining stress and dynamic load generated by the mine earthquake. Even if the coal seam is identified as weak or no burst tendency. However, due to the influence of occurrence environment, mining depth, mining sequence and mining technology, the load acting on the surrounding rock system is relatively high and close to the critical stress of instability, then the coal seam will have a greater rockburst risk and a higher probability of rock burst.

For example, the coal seams with rock-burst in Quantai mine of Xuzhou, No. 10 Mine of Pingdingshan and Daanshan mine in Beijing are all weak and non impact prone coal seams in the laboratory (considering that the determination of coal burst tendency in the laboratory is only for uniaxial test of samples, which fails to directly reflect the burst tendency in working faces, the coal

**Table 1.** Statistical table of destructive rock burst in Laohutai Mine from 1997 to 2016.

| year | 1997 | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|---|---|---|---|---|---|
| times | 70 | 49 | 51 | 124 | 239 | 136 | 88 | 61 | 42 | 20 |
| year | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
| times | 6 | 4 | 3 | 5 | 1 | 2 | 2 | 1 | 2 | 0 |

strata in these mines may have weak impact dip). However, rock burst still occurs due to the influence of coal-rock structure, geological abnormal conditions, stress state and mining influence (Jiang, Pan, and Jiang 2014). It shows that even if the coal burst tendency is weak, but the rock stress is high, then the rockburst risk is also strong. According to the statistics of 47 km deep wells in China (5 of which are under construction), 31 are rock burst mines. Through the survey found where did not happen rock-burst, the rock strength is low, no impact is weak or propensity to coal and rock. It indicates that face buried depth has important effects on rockburst risk, but the occurrence of rock burst mainly depends on the joint action of control variables such as the burst tendency and the disturbance of the stress.

For example, the rock-burst occurs when the mining distance is 300 m deep from the surface in Laohutai Mine in Fushun. The occurrence times of rock-burst in the past 20 years are counted as shown in Table 1. It can be seen that with the increase of mining depth, the degree and frequency of rock-burst damage increase, the destruction and frequency on the rise. Especially in the 2000 ~ 2006, the mine rock bursts occur frequently. In 2006, after the stopping of 83,001, the last first stratified working face, all the protective layer mining was completed, the occurrence times and the impact strength were reduced significantly.

It is found that the characteristics of coal seam bursting in Laohutai Mine are as follows: coal seam No. 3 and No. 4 with strong bursting liability, coal seam No. 5 with weak bursting liability is not easy to produce bursting liability.

With the increase of mining depth, the frequency of rock burst increases. Geological structural zones, such as near faults and syncline axis, are prone to rock-burst. The gob-surrounded pillar area is a serious area of rock burst.

In the fully mechanized coal caving face, the first stratified rock burst appears strongly, while the second stratified (pressure relief zone) rock burst frequency and intensity are weakened. Rock burst occurs frequently at the beginning of working face mining, when the goaf is “square” and near the end of mining. It can be seen that the rock burst mainly occurs in the high stress concentration area. Before 2006, the rock-burst increased gradually, mainly because the stress increased gradually with the increase of mining depth, which led to the increase of rock burst year by year. After 2007 because of the hierarchical mining fully after the mining of coal seam, form a protective layer, reduced the stress of the lower, and therefore the rock-burst decreases, but rock burst still occurs from time to time in the local stress concentration area of the working face. This case further illustrates that rock stress is the decisive factor affecting the rockburst risk.

In a word, there are essential differences between the risk and tendency. The coal seam with burst tendency does not necessarily have rockburst risk, but the coal seam with rockburst risk must have certain burst tendency. The burst tendency is only a basic condition for the coal seam to have the rockburst risk, that is, the necessary condition for the occurrence of rock burst. Therefore, to evaluate the rockburstrisk of coal seam and working face, the burst tendency identification should be carried out first. If the coal seam has no burst tendency, it is not necessary to take the rock-burst prediction and prevention measures. If the identification result of burst tendency is weak or strong, it is necessary to carry out rockburst risk assessment. As the burst tendency is affected by laboratory test error, heterogeneity and unclear conversion relationship between coal sample and large scale of working face, the coal seam with no burst tendency, if there is dynamic phenomenon such as impact, it should also be regarded as the coal seam with weak burst tendency and carry out rockburst risk assessment.

## Evaluation index and risk assessment method of burst tendency based on instability theory of rock burst disturbance response

### A new evaluation index of burst tendency

Based on the instability theory of rock burst disturbance response, formula (16) can be further simplified into the following formula without considering the roadway support resistance$p_s$

$$P_{\mathrm{cr}} = \frac{\sigma_c}{2}\left(1 + \frac{E}{\lambda}\right) \tag{17}$$

It can be seen from Formula 17 that$/E$ has an important influence on critical stress and is an important control quantity index that affects the stability of roadway surrounding rock-support system. Therefore, it can be used as an index to identify the strength of coal seam bursting liability, which is called burst tendency index K.

$$K = \frac{}{E} \tag{18}$$

The coal burst tendency index K and uniaxial compressive strength $\sigma_c$ of 24 rock burst mines in China are calculated. The critical instability load is calculated according to formula (16), as shown in Table 2. The critical instability load is further calculated, which will be compared with the analysis to evaluate the risk of rock burst in the working face.

### A new assessment method of rockburst risk

According to the study of 5.1, the critical stress can be obtained through the burst tendency index $P_{\mathrm{cr}}$ and uniaxial compressive strength $\sigma_c$ of coal seam. According to the theory of rock burst disturbance response instability, if the rock mass stress P acting on the roadway surrounding rock is greater than or equal to the critical stress $P_{\mathrm{cr}}$, then rock burst will occur. Based on this, this paper proposes a new rockburst risk evaluation method, the critical stress index method, which uses $P/P_{\mathrm{cr}}$ as the index to evaluate the rockburst risk and calls it the critical stress index .

$$K_P = \frac{P}{P_{\mathrm{cr}}} = \frac{2}{(1 + E/\lambda)}\frac{P}{\sigma_c} \tag{19}$$

In the practical application, $P_{\mathrm{cr}}$ can be obtained by testing the mechanical parameters of coal and rock, and P can be calculated by ground stress measurement, working face buried depth, numerical simulation and other methods. Therefore, this method can be used to evaluate the rockburst risk level of working face simply and quickly.

According to a large number of literature data and field survey data, combined with the relevant specification requirements, the relationship between the magnitude of the critical stress index and the grade of the irockburst risk is preliminarily determined in Table 3.

That is, when $P/P_{\mathrm{cr}}$ >0.8 has strong rockburst risk; when 0.65 < $P/P_{\mathrm{cr}}$< 0.8 has moderate rockburst risk; when 0.5 <$P/P_{\mathrm{cr}}$<0.65 has weak rockburst risk; and when $P/P_{\mathrm{cr}}$<0.5 has no rockburst risk.

In the process of using the critical stress index method, it should be noted that it is difficult to obtain the rock mass stress directly. However, according to the instability theory of rock burst disturbance response, rock mass stress $P$ can be obtained from Equation (14). That is, the radius $\rho$of the softening zone of the roadway was measured by cuttings, borehole observation or other geophysical methods, and substituted into Equation (14) to obtain the rock mass stress $P$. At the same time, according to Equations (15) and (17), another index to evaluate the rockburst risk – critical radius index $K_\rho$ is proposed, namely the radius $\rho$/of the softening zone of roadway surrounding rocks critical softening zone radius $\rho_{\mathrm{cr}}$. This index only needs to grasp the coal and burst tendency index K, uniaxial compressive strength $\sigma_c$ and other mechanical parameters, as well as the actual radius $\rho$ of the

**Table 2.** Burst tendency index and critical stress of some Chinese rock-burst mines.

| Mine | Longfeng Mine | Tianchi Mine | Taozhuang Mine | Meitougou Mine | Tangshan Mine | Nanshan Mine | Junde Mine | Fuli Mine |
|---|---|---|---|---|---|---|---|---|
| $\lambda/E$ | 1.05 | 1.35 | 2.00 | 2.38 | 1.14 | 3.33 | 3.45 | 4.76 |
| $\sigma_c$/MPa | 9 | 12 | 18 | 14 | 10 | 16.12 | 16 | 18.2 |
| $P_{cr}$ | 8.775 | 10.44 | 13.5 | 9.94 | 9.4 | 10.478 | 10.32 | 11.011 |
| Mine | Tanshan Mine | Jixian Mine | Daoqing Mine | Longjiabao Mine | Xingfu Mine | Wulong Mine | Taiji Mine | Tangshan Mine |
| $\lambda/E$ | 4.55 | 2.00 | 1.59 | 0.80 | 3.03 | 0.81 | 1.69 | 0.88 |
| $\sigma_c/MPa$ | 16.84 | 18.57 | 4.91 | 10.4 | 22.13 | 6 | 10.14 | 14.74 |
| $P_{cr}$ | 10.2724 | 13.9275 | 4.00165 | 11.7 | 14.71645 | 6.69 | 8.0613 | 15.7718 |
| Mine | Fangshan Mine | Muchengjian Mine | Pingmei 8 Mine | Dongtan Mine | Ji 3 Mine | Xinzhouyao Mine | Tongjialiang Mine | Meiyukou Mine |
| $\lambda/E$ | 0.91 | 1.96 | 2.78 | 1.49 | 5.00 | 2.38 | 3.45 | 3.85 |
| $\sigma_c/MPa$ | 18.35 | 27.37 | 7.79 | 14.5 | 13.27 | 26 | 14.54 | 23.98 |
| $P_{cr}$ | 19.2675 | 20.66435 | 5.2972 | 12.1075 | 7.962 | 18.46 | 9.3783 | 15.1074 |

**Table 3.** Classification of rockburstrisk indicators.

| Strong rockburst risk | Moderate rockburst risk | Weak rockburst risk | No rockburstisk |
|---|---|---|---|
| >0.8 | 0.65 ~ 0.8 | 0.5 ~ 0.65 | <0.5 |

softening zone of the roadway on site, to calculate therockburst risk at this position of the roadway, which can greatly improve the efficiency of rockburst risk assessment.

## Conclusions

The stability of coal rock deformation system is controlled by the mechanical properties of itself, roadway support and other control variables, the disturbance of rock stress and the radius of softening zone of surrounding rock. The control quantity directly affects the critical stress of coal rock deformation system, but whether the rock burst occurs in the process mainly depends on whether the rock mass stress can exceed the critical stress or not. The closer the rock mass stress is to the critical stress, the higher the risk level of rock burst will be. The burst tendency refers to the nature of coal and rock mass with accumulated deformation energy and impact failure, which is the inherent property. Its value determines the difficulty of rock burst, and is the necessary condition to have rock burst.

Rockburst risk is the possibility and risk degree of rock burst in coal seam with burst tendency, and it is the external factor controlling the stability of surrounding rock system. There are essential differences between the risk and the tendency.

The assessment of burst tendency is the basic condition for the risk assessment of rock burst. Only it has burst tendency should the risk assessment be carried out. The rockburst risk grade mainly depends on the joint action of the bursttendency and rock mass stress. Under the same external conditions, the stronger the tendency is, the greater the rockburst risk is.

A new rockburst risk assessment method is proposed, index of bursting tendency K and a new rockburst risk assessment method, that's Critical stress index method. It can be used to evaluate the rockburst risk level of working face simply and quickly. However, it is difficult to accurately predict the location and energy of the focal point in the process of roof rupture or fault dislocation for roof rupture and fault-dislocation, so further research is needed to increase the impact load value of this kind of mine earthquake.

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