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Research Article

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Research on evaluation method of rockburst proneness based on energy principles

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Abstract: The study of rockburst criterion is the key to predict whether rockburst occurs or not. First of all, based on the energy principle and taking the rock strength and overall failure criterion as the benchmark, the rockburst proneness criterion of rock mass unit under compression and tension was established. The criterion took into account the integrity factors, mechanical factors, brittleness factors and energy storage factors in the process of rockburst inoculation, and three rockburst classification thresholds (2, 11 and 110) for four grades of none, weak, moderate and severe rockburst were proposed. Second, Taking the typical rockburst disaster as examples, the rationality of the existing classical rockburst criterions and the rockburst proneness criterion proposed in this paper were tested, and the results showed that this criterion had good engineering applicability. Finally, the numerical simulation analysis of rockburst disaster in 2\textsuperscript{nd} diversion tunnel of Jinping II hydropower station was carried out by using this criterion. The results were basically consistent with the actual situation, which verified the accuracy and effectiveness of the rockburst proneness criterion proposed in this paper. The research results can provide reference for the
evaluation and prediction of rockburst disaster in deep underground engineering.

Keywords: Energy principle; Rockburst proneness criterion; Rockburst classification thresholds; Rockburst disaster; Numerical simulation analysis

1 Introduction

Since the first rockburst occurred in the South Stafford tin mine in the United Kingdom in 1738, many countries and regions have experienced rockburst disasters worldwide, such as South Africa, India, Japan, the United States, France, Switzerland, etc. (Feng et al. 2012, Ma et al. 2015, Wei et al. 2020). The earliest recorded coal-burst in China occurred in the Shengli Coal Mine of Fushun in 1933 (Zhang and Fu, 2008). After that, rockburst frequently occurred in traffic tunnels, hydraulic tunnels and other underground cavern projects in China. Rockburst is a dynamic instability phenomenon of sudden burst caused by the instantaneous release of elastic deformation energy accumulated in rock mass in the process of underground engineering excavation, which is often accompanied by rock ejection or throwing, strong vibration, huge sound and air waves, etc. (Feng et al. 2019). Rockburst has strong suddenness, locality, concealment and harmfulness, which greatly threatens the safety of on-site construction personnel and mechanical equipment, and brings serious challenges to the design and construction of deep engineering (Roohollah and Abbas, 2018).

Therefore, with the vigorous development of deep underground engineering construction in the world, it is urgent to continuously study the mechanism of rockburst, accurately grasp the law of rockburst inoculation and evolution and the possibility of rockburst occurrence, and accurately predict the strength of rockburst activities. This is of great theoretical significance and engineering application value to ensure the safety and healthy development of underground engineering.
At present, rock mechanics workers and engineering technicians at home and abroad have carried out in-depth research on rockburst criterion and rockburst classification from theoretical analysis, numerical simulation, field monitoring and test under the guidance of deep rock mass mechanics and nonlinear dynamic science theory, and put forward corresponding prediction and evaluation indexes based on their respective assumptions. In the study of rockburst criterion and rockburst classification theory, many experts and scholars have proposed dozens of classical rockburst criteria and intensity classification successively, such as E. Hoek criterion, Russnes criterion, Turchaninov criterion, Kidybinski energy criterion, Motycaka energy ratio method, Barton criterion, Erlangshan highway tunnel criterion and Gu-Tao criterion, etc. (Hoek and Brown 1997; Russnes 1974; John and Neville 1974; Kidybinnski 1981; Zhang et al. 2017; Barton et al. 1974; Xu and Wang 1999; Gu et al. 2002) In the field monitoring research, scholars have achieved some fruitful research results, such as microseismic monitoring method, acoustic emission monitoring method, microgravity method, acoustic wave detection method, infrared thermal imaging method and so on (Wu 1993; Chen et al. 2010; Zhang et al. 2012; Zhang et al. 2018; Zhang et al. 2020). In the aspect of experimental study on rockburst criterion, some experts at home and abroad have also carried out some research. Karchevsky (2017) proposed a calculating quantity algorithm through experimental research, and took this algorithm as a standard to distinguish the possibility of rock fracture in coal seam. Li et al. (2018) proposed failure criterion of rock strength based on energy mutation. Li et al. (2019) put forward a rockburst dynamic criterion based on dynamic and static energy index. Gong et al. (2020) advanced a rockburst proneness classification standard based on the failure results and phenomena of rock samples tested in laboratory tests. With the rapid
development of computer technology, numerical analysis method emerges as the times require and
becomes more and more perfect. Based on energy theory, scholars have propounded different
numerical indexes of rockburst criteria, such as Energy release rate (ERR), Excess shear stress (ESS),
Burst potential index (BPI), Local energy release density (LERD), Local energy release rate (LERR),
Relative energy release index (RERI), Unit time relative local energy release index (URLERI), etc.
(Cook 1965; Ryder 1988; Mitri 1999; WILES 1998; Su 2006; Qiu et al. 2014; BIENIAWSKI 1967)
The above achievements greatly promote the development of the rockburst criterion research.
However, due to the complex conditions and many influencing factors of rock burst, the existing
rock burst criterions only consider one or two of the influencing factors, resulting in its theoretical
research far behind the engineering practice, and there are still deficiencies in engineering
applicability. In view of this, this study attempts to establish a rockburst proneness criterion and
based on energy principle on the basis of fully collecting, summarizing and deeply analyzing the
existing rockburst criterions at home and abroad, so as to provide basic scientific basis and important
theoretical support for rockburst prediction.

2 Energy conversion mechanism of deformation process of rock under stress

The deformation and failure of rock is mainly driven by energy. From the energy point of view,
when the rock is deformed under the action of external force, assuming that the physical process
has no heat exchange with the outside world, the total input energy generated by the external force
is $U$. According to the principle of energy conservation, the expression of $U$ can be obtained (Xie et
al. 2005):
\( U = U^d + U^e \)  

Where \( U^d \) is the dissipated energy of the rock, which is used to form the internal damage and plastic deformation of the material, as shown in the blank area surrounded by the curve in Fig. 1; \( U^e \) is the releasable elastic strain energy of the rock, as shown in the shadow area surrounded by the curve in Fig. 1.

The expression of \( U^e \) is

\[
U^e = \frac{1}{2} \sum \left( \sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu \left( \sigma_1 \sigma_2 + \sigma_2 \sigma_3 + \sigma_3 \sigma_1 \right) \right)
\]

Where \( \sigma_1, \sigma_2, \sigma_3 \) is the three principal stresses corresponding to the maximum value of element strain energy; \( E \) is the elastic modulus; and \( \nu \) is the Poisson's ratio.

Based on the energy transformation in the process of rock deformation, the difference between dynamic and static failure of rock is explained. The rock is disturbed by the dynamic load to form high stress, which leads to the aggravation of damage of some rock units in a very short period of time and the gradual decrease of strength; the stored elastic strain energy of most rocks rapidly reaches the limit value. \( U^0 \) represents the energy required when the rock mass is broken. When \( U^e = U^0 \), \( U^e \) completely releases and rock mass undergoes static failure; When \( U^e > U^0 \), the rock mass is damaged dynamically, and the energy difference \( \Delta U \) (\( \Delta U = U^e - U^0 \)) constitutes the kinetic energy of splitting rock mass, which induces rockburst.

3 Rockburst proneness criterion based on energy principle

3.1 Shortcomings of existing rockburst criterions

The existing rockburst accident cases show that rockburst mostly occurs in brittle rock mass
under the conditions of lithologically medium-hard to hard, good integrity, dry and high geostress.

At present, the rockburst criterion for underground engineering mainly considers the following indicators: maximum principal stress of cavern ($\sigma_1$), maximum tangential stress of cavern ($\sigma_0$), radial stress of cavern ($\sigma_1$), uniaxial compressive strength of rock ($\sigma_c$), tensile strength of rock ($\sigma_t$), elastic energy index of rock ($W_e$), integrity coefficient of rock mass ($K_v$) and lateral pressure coefficient ($\lambda$), etc.

Through in-depth analysis of existing rockburst criterions, it is known that (1) Most rockburst criteria are expressed by radial stress and tangential stress (or maximum tangential stress). Coordinate transformation is needed when using numerical simulation software to predict and evaluate rockburst risk in underground engineering excavation process, so the application is quite complicated (Xu et al. 2007; Guo et al. 2015). (2) The evaluation index of rockburst criterion is single, only one or two factors are considered, and the influencing factors of rockburst are not fully considered. (3) According to the definition of rockburst, the surrounding rock stress is one of the necessary conditions to induce rock burst (Wang et al. 1998), and the surrounding rock in the rockburst area is mostly in the three-dimensional stress state, but the existing rockburst criteria are mostly expressed by the maximum principal stress or the maximum tangential stress and the two-dimensional stress state. (4) Most rock burst classifications are more general and the discriminant indexes used are also different.

### 3.2 Establishment of rockburst proneness criterion

To establish rockburst criterion based on energy principle, it is necessary to clarify the energy evolution law in the process of rock deformation and failure. In this study, based on the rock strength and overall failure criterion (Xie et al. 2005), the rockburst criteria and rockburst classification
standards for rock mass units under compression and tension are given respectively.

3.2.1 Compression condition \( (\sigma_1 > \sigma_2 > \sigma_3 \geq 0) \)

A large number of underground engineering practice shows that the stress state of surrounding rock before underground cavern excavation is mostly three-dimensional compression (Fig. 2(a)). When the rock mass fails as a whole, the elastic strain energy in the principal stress \( \sigma_i \) direction is proportional to the energy release rate, which is distributed according to the minimum compressive stress difference. Assuming that the energy release rate \( G_i \) is expressed as:

\[
G_i = K_i (\sigma_1 - \sigma_i) U^e \quad (i = 1, 2, 3)
\]

(3)

Where \( K_i \) is the material constant.

(a) Compression condition  
(b) Tension condition

It can be seen from Eq. (3) that the maximum energy release rate occurs in the direction of the minimum compressive stress \( \sigma_3 \), i.e.

\[
G_3 = K_3 (\sigma_1 - \sigma_3) U^e
\]

(4)

This further shows that the hydrostatic pressure state will not cause the overall failure of rock mass. According to the above analysis, the energy release rate can meet the following requirements when rockburst occurs:

\[
G_i = K_i (\sigma_1 - \sigma_i) U^e \geq G_c
\]

(5)

Where \( G_c \) is the critical strain energy release rate of rockburst under compression state, which is the material constant and can be determined by laboratory rock mechanics test (uniaxial compression test). Let \( \sigma_1 = \sigma_c \) and \( \sigma_2 = \sigma_3 = 0 \), bring them into Eq. (5), it can be obtained by combining Eq. (2):

\[
G_c = K_c \frac{\sigma_c^3}{2E}
\]

(6)
Further considering the influence of rock mass integrity coefficient ($K_v$) on inducing rockburst, combining Eqs. (3)–(6), a rockburst proneness criterion (RPC_c) based on the energy principle (triaxial compression state of rock mass) is established:

$$\text{RPC}_c = K_v \cdot \frac{G_i}{G_c} = K_v \cdot \frac{(\sigma_1 - \sigma_3)2E\sigma_i^e}{\sigma_3^2} = K_v \cdot \frac{\sigma_1 - \sigma_3}{\sigma_3} \cdot \frac{\sigma_i \cdot 2E\sigma_i^e}{\sigma_3^2} = K_v \cdot (\sigma_1 - \sigma_3)\frac{\sigma_i}{\sigma_3} \cdot \frac{2E\sigma_i^e}{\sigma_3^2}$$  \hspace{1cm} (7)

It can be seen from Eq. (7) that: (1) RPC_c analysis model reflects the integrity factor ($K_v$), mechanical factor ($\sigma_1 - \sigma_3$), brittleness factor ($\sigma_i/\sigma_3$) and energy storage factor ($U_e/\sigma_3^4$) of rockburst incubation process; (2) RPC_c is the product of main stress in mathematical expression, which is easy to understand, use and operate; (3) RPC_c not only considers the stress state ($\sigma_1, \sigma_2, \sigma_3$) of surrounding rock and the integrity of rock mass, but also reflects the influence of rock mechanical parameters ($\sigma_c, \sigma_t$) and deformation parameters ($E, v$).

### 3.2.2 Tension condition ($\sigma_3 < 0$)

Tensile stress often occurs in the surrounding rock mass during excavation and unloading of underground engineering, which is also a stress state leading to the overall failure of rock mass. When there is at least one tensile stress in the principal stress ($\sigma_i$) of rock element (Fig. 2(b)) and the overall failure of rock mass occurs, the elastic strain energy is proportional to the energy release rate in the direction of principal stress, and it is distributed according to the principal stress value.

Assuming that the energy release rate expression is:

$$G_i = K_c \sigma_i U_e^i \hspace{1cm} (i = 1, 2, 3)$$  \hspace{1cm} (8)

By analogy with compression condition, it can be seen from Eq. (8) that the maximum energy release rate occurs in the direction of the maximum tensile stress $\sigma_3$, i.e

$$G_3 = K_c \sigma_3 U_e^3$$  \hspace{1cm} (9)

The energy release rate can meet the following requirements when rockburst occurs:
where $G_t$ is the critical strain energy release rate of rockburst under tension state, which is the material constant and can be determined by laboratory rock mechanics test (uniaxial tensile test).

Let $\sigma_3=\sigma_1$ and $\sigma_1=\sigma_2=0$, bring them into Eq. (10), it can be obtained by combining Eq. (2):

$$G_t = K_v \frac{\sigma_3^3}{2E}$$

Further considering the influence of rock mass integrity coefficient ($K_v$) on inducing rockburst, combining Eqs. (8)–(11), a rockburst proneness criterion (RPC) based on the energy principle (tension state of rock mass) is established:

$$\text{RPC}_t = K_v \cdot \frac{G_t}{G_c} = K_v \cdot \frac{2E\sigma_t^4}{\sigma_t^3} = K_v \cdot \frac{\sigma_t^2}{\sigma_c} \cdot \frac{\sigma_3}{\sigma_t} \cdot \frac{2EU^e}{\sigma_t^2}$$

By analogy with compression condition, it can be seen from Eq. (12) that when rock mass is in tensile state, RPC$_t$ also reflects the integrity factor ($K_v$), mechanical factor ($\sigma_3/\sigma_3$), brittleness factor ($\sigma_t/\sigma_t$) and energy storage factor ($U^e/\sigma_t^2$) of rockburst incubation process.

In order to determine the threshold value of the rockburst proneness criterion, based on the division of the elastic energy index threshold value and the rockburst potential threshold value (Zhang et al. 2011; Shang et al. 2013), the measured rockburst data of Tiantaishan tunnel (Table 1) (Guo et al. 2015) are taken as simulation samples for analysis, and the results are shown in Table 2 (Guo et al. 2015; Ministry of Water Resources of the People’s Republic of China 2014).

| Table 1 | Measured data of rockburst of Tiantaishan tunnel |
|---------|--------------------------------------------------|
| Table 2 | Simulation results of rockburst of Tiantaishan tunnel |

Considering that the probability of the boundary index of different factors reaching the maximum value at the same time is small, in order to facilitate practical application, the boundary indexes of RPC are set to 2, 11 and 110. Therefore, the rockburst proneness criterion and its intensity...
classification are as follows:

\[
\text{RPC} = \begin{cases} 
< 2 & \text{None rockburst} \\
2 - 11 & \text{Weak rockburst} \\
11 - 110 & \text{Moderate rockburst} \\
> 110 & \text{Severe rockburst} 
\end{cases}
\]  
(13)

### 3.3 Analysis and evaluation of rockburst proneness criterion

In order to further verify the rationality and superiority of the rockburst proneness criterion proposed in this paper, taking rockburst disaster of typical engineering as examples (Table 3), E. Hoek criterion, Russenes criterion, Erlangshan highway tunnel criterion, Gu-Tao criterion and the rockburst proneness criterion proposed in this paper were tested respectively. The results were compared with the actual rockburst intensity grade, as shown in Table 4 and Fig. 3.

1. (1) E. Hoek criterion

\[
\frac{\sigma_{\text{max}}}{\sigma_c} = \begin{cases} 
0.34 & \text{None rockburst} \\
0.42 & \text{Weak rockburst} \\
0.56 & \text{Moderate rockburst} \\
> 0.70 & \text{Severe rockburst} 
\end{cases}
\]  
(14)

2. (2) Russenes criterion

\[
\begin{align*}
\frac{\sigma_{\beta}}{\sigma_c} &< 0.2 & \text{None rockburst} \\
\frac{\sigma_{\beta}}{\sigma_c} &\geq 0.2 - 0.3 & \text{Weak rockburst} \\
\frac{\sigma_{\beta}}{\sigma_c} &\geq 0.3 - 0.55 & \text{Moderate rockburst} \\
\frac{\sigma_{\beta}}{\sigma_c} &> 0.55 & \text{Severe rockburst}
\end{align*}
\]  
(15)

3. (3) Erlangshan highway tunnel criterion

\[
\begin{align*}
\frac{\sigma_{\beta}}{\sigma_c} &< 0.3 & \text{None rockburst} \\
\frac{\sigma_{\beta}}{\sigma_c} &\geq 0.3 - 0.5 & \text{Weak rockburst} \\
\frac{\sigma_{\beta}}{\sigma_c} &\geq 0.5 - 0.7 & \text{Moderate rockburst} \\
\frac{\sigma_{\beta}}{\sigma_c} &> 0.7 & \text{Severe rockburst}
\end{align*}
\]  
(16)

4. (4) Gu-Tao criterion

\[
\begin{align*}
\frac{\sigma_c}{\sigma_1} &> 14.5 & \text{None rockburst} \\
\frac{\sigma_c}{\sigma_1} &\geq 5.5 - 14.5 & \text{Weak rockburst} \\
\frac{\sigma_c}{\sigma_1} &\geq 2.5 - 5.5 & \text{Moderate rockburst} \\
\frac{\sigma_c}{\sigma_1} &< 2.5 & \text{Severe rockburst}
\end{align*}
\]  
(17)
It can be seen from Table 4 and Fig. 3: (1) the total number of moderate and severe rockbursts determined by E. Hoek criterion, Russenes criterion and Erlangshan highway tunnel criterion is relatively close, and the number of weak rockburst determined by E. Hoek criterion is slightly higher than that determined by Russenes criterion and Erlangshan highway tunnel criterion; (2) the rockburst grade determined by the Gu-Tao criterion is mainly concentrated in the moderate rockburst, and the total number of weak and severe rockbursts is relatively close, which indicates that the determination accuracy of Gu-Tao criterion is slightly lower than that of E. Hoek criterion, Russenes criterion and Erlangshan highway tunnel criterion; (3) the total number of weak and moderate rockbursts determined by the rockburst proneness criterion in this paper is close to the actual situation, but its performance in the determination of severe rockburst grade is weak. By comprehensive comparison, the accuracy of the criterion presented in this paper is obviously higher than that of the other four criterions, and it is basically consistent with the actual occurrence of rockburst on the whole, which has good engineering applicability.

In summary, the rockburst proneness criterion established in this study is of clear significance, simple and practical, which can reasonably and quantitatively determine the occurrence and intensity grade of rockburst geological disasters in the process of deep underground engineering construction. It comprehensively considers the integrity factors, mechanical factors, brittle factors and energy storage factors in the process of rockburst inoculation. This criterion is more targeted for rockburst prediction and evaluation, and it has good engineering applicability.
4 Numerical simulation analysis

In this section, relying on the 2\textsuperscript{nd} diversion tunnel of Jinping II Hydropower Station, the feasibility of numerical simulation of rockburst process was verified by three-dimensional discrete element software (3DEC), and the accuracy and applicability of the rockburst proneness criterion proposed in this paper were tested. Then, numerical simulation analysis on the inoculation mechanism and evolution law of rockburst geological disasters in deep underground engineering under three-dimensional stress conditions was carried out to study the dynamic response law of surrounding rock of deep underground engineering under excavation disturbance.

4.1 Calculation model and boundary constraint conditions

The 2\textsuperscript{nd} diversion tunnel of Jinping II Hydropower Station was excavated from east to west. When the excavation reached the K11+027–K11+046 section, an severe rockburst occurred from the north wall to the spandrel (Fig. 4) (Zhou et al. 2015). The depth of rockburst pit is about 2 m. Through field investigation, it is not found that there is a control structural plane in this section, and the surrounding rock is fresh and complete, which is mainly T\textsubscript{2b} marble. The section size of 2\textsuperscript{nd} diversion tunnel is shown in Fig. 5. According to the field monitoring results, the ground stress level of the tunnel section was high, which was shown in Table 5.

![Fig. 4](image1)

**Fig. 4** Rockburst location of 2\textsuperscript{nd} headrace tunnel

![Fig. 5](image2)

**Fig. 5** Section size of 2\textsuperscript{nd} headrace tunnel

![Table 5](image3)

**Table 5** Ground stress grade of 2\textsuperscript{nd} headrace tunnel

According to the Saint-Venant principle and the influence range of tunnel excavation, the calculation model was established with 90 m transverse length, 80 m vertical height and 50 m longitudinal width. The numerical model is shown in Fig. 6 and the arrangement of monitoring
In the dynamic calculation, in order to make the dynamic energy of the system absorb quickly and achieve convergence, Rayleigh damping was used, the minimum critical damping ratio was 0.05, and the minimum center frequency was 500 Hz. The upper boundary of the calculation model was the stress constraint boundary condition, and the vertical load of 51.46 MPa (field measurement) was applied. The lower boundary, front and rear boundary and left and right boundary of the calculation model were all displacement constraint boundary conditions. The peripheral boundary of the model was set as a static boundary, and dampers were set in the normal and tangential directions of the model to reduce or eliminate the elastic wave reflection generated by the simulation calculation, which provided the constraint effect equivalent to the infinite site for the calculation model.

**Fig. 6** Numerical model

![Numerical model](image1)

**Fig. 7** Monitoring point arrangement of 2nd headrace tunnel

### 4.2 Action form of blasting load

Since rockburst is a complex process generated instantaneously, detonating the pre-buried explosive in the cavern will instantly generate irresistible high temperature and high pressure gas, which expand rapidly in the interior of the cavern. The blast shock wave generated acts on the inner wall of the cavern and rapidly attenuates to stress wave. The whole process is very short and the duration is only a few milliseconds. Because the explosion mechanism and its influencing factors are extremely complex, it is difficult to quantitatively determine the details of the explosion process. In the numerical analysis, the blasting load is often assumed to be a triangular shock wave (Zhou et al. 2020), and the expression of the blasting load history curve of the triangular function is shown in Eq. (18). Through the secondary development of three-dimensional discrete element software,
the dynamic load is applied by using FISH programming language, which is applied to the tunnel excavation profile by using APPLE command.

\[
p(t) = \begin{cases} 
0 & t < 0, t > t_d \\
\frac{t - t_r}{t_d - t_r} p_m & 0 \leq t \leq t_r \\
\frac{t_d - t}{t_d - t_r} p_m & t_r \leq t \leq t_d 
\end{cases}
\]  

(18)

Where \( p(t) \) is the blasting load pressure value at any moment; \( p_m \) is the peak blasting load, \( p_m = 60 \) MPa; \( t_r \) is the time when the blasting load rises to the peak, \( t_r = 0.3 \) ms; \( t_d \) is the time for the positive pressure of the blasting load, \( t_d = 1 \) ms.

4.3 Constitutive relation and yield criterion

In the numerical simulation, the selection of the constitutive model needs to have a high degree of conformity with the mechanical properties of engineering materials. The Mohr-Coulomb yield criterion, which describes the mechanical behavior of hard rock, is adopted for the constitutive relation of the model to truly reflect the stress condition of surrounding rock (Peng 2008). The failure envelope of the criterion corresponds to the shear yield function and the tensile stress yield function, which is a flow rule related to the tensile failure.

The physical and mechanical parameters of surrounding rock refer to the inversion results of ground stress and mechanical parameters of rock mass of Jinping Project Group, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, as shown in Table 6, where \( c_m \) is the peak value of cohesion, \( c_r \) is the residual value of cohesion, \( \phi_0 \) is the initial value of friction angle, \( \phi_m \) is the peak value of friction angle, and \( \psi \) is the dilatancy angle. The rock lithology is assumed in the numerical calculation: the rock is homogeneous, isotropic continuum, which conforms to Mohr-Coulomb strength criterion, and the material parameters meet Mohr-Coulomb constitutive model.
4.4 Analysis of numerical simulation results

The middle position of the rockburst area (near K11+037) was selected for analysis. In the numerical simulation, the FISH programming language embedded in 3DEC software was used to write calculation functions for Eq. (2), Eq. (7) and Eq. (12), and the change process of all calculation block units was monitored. In this section, the rockburst proneness would be evaluated according to the numerical simulation results and the prediction evaluation indexes.

4.4.1 Analysis of energy release evolution process

According to the numerical simulation results, the distribution state of elastic strain energy density was shown in Fig. 8, the contour nephogram of principal stress difference was shown in Fig. 9, and the space-time distribution of elastic strain energy density was shown in Fig. 10. From the above figure, it could be seen that the maximum principal stress difference was mostly concentrated in the right spandrel, side wall and arch bottom of the cavern after excavation. According to the rock mechanics theory, the energy storage limit of rock mass at the maximum principal stress difference will increase significantly. Combined with the cloud map of the elastic strain energy density distribution, it was found that the surrounding rock masses close to the empty surface of the cavern under the disturbance of dynamic excavation had different degrees of elastic strain energy release phenomenon, and the amount of elastic strain energy release gradually decreased with the increase of the distance to the center of the tunnel. The elastic strain energy release of surrounding rock at the right spandrel, side wall and arch bottom of the cavern was the largest, which further indicated that the gentle acceleration process of rock fracture evolution around the cavern is also the process of energy accumulation and dissipation in the surrounding rock. The stress of surrounding rock was

Table 6 Physical and mechanical parameters of surrounding rock
highly concentrated, which increased the energy accumulation. When the storage energy of
surrounding rock exceeded the energy storage limit of rock mass, the excess energy was released
rapidly in the form of kinetic energy, resulting in rockburst or large deformation failure of rock mass.

The rockburst simulation was shown in Fig. 11. It could be seen from Fig. 11 that the largest
rockburst pit of the tunnel was located at the right side wall and spandrel of the tunnel face, which
was close to the field situation, and the depth of the largest rockburst pit was about 2 m, as shown
in Fig. 12. According to the failure shape of the tunnel, the numerical simulation results were
basically consistent with the shape of the actual rockburst pit (Fig. 13), which verified the rationality
of the prediction and evaluation of the rockburst criterion in this paper, and could meet the
requirements of dynamic tracking of the rockburst process.

Fig. 8 Distribution of elastic strain energy density (unit: J/m$^3$)

Fig. 9 Contour nephogram of principal stress difference (unit: Pa)

Fig. 10 Space-time distribution of elastic strain energy density

Fig. 11 Rockburst simulation

Fig. 12 Rockburst areas in situ

Fig. 13 Tunnel section outline

4.4.2 Distribution characteristics of rock burst energy index

The nephogram of the boundary value distribution of rockburst proneness criterion was shown
in Fig. 14. From Fig. 14, it could be seen that the rockburst criterion RPC boundary value at different
locations of the tunnel section showed a completely different change rule. Details were as follows:
at the right spandrel position of the cavern, the RPC boundary value reached the maximum 121.23;
at the junction of the spandrel and the side wall on both sides of the cave, the RPC boundary values
were mostly concentrated between 40 and 85, which could release some elastic strain energy and had the possibility of moderate rockburst; at the left spandrel of the cavern, the RPC boundary values were mostly concentrated between 95 and 120, and there was a possibility of severe rockburst. This shows that the surrounding rock accumulates a large number of elastic strain energy under the influence of high stress. When the surrounding rock strength exceeds the ultimate strength of the rock mass, the surrounding rock occurs brittle failure and instantaneous releases a large number of elastic strain energy, and then the rockburst phenomenon of rock block spalling, ejection and even throwing occurs.

Taking the arch foot on the right side of the cavern as the center of the circle and rotating counterclockwise for one round, the RPC boundary value of the cavern cross section (0°–360°) of the section K11+037 was obtained, as shown in Fig. 15. According to the analysis of Fig. 15, the maximum value of RPC boundary value appeared on the surrounding rock surface of the cavern spandrel (about 70°–85°). When the angle was 0°–90°, the boundary value of RPC was 12–96, and there was a possibility of weak to severe rockburst. When the angle was 90°–180°, the boundary value of RPC was 30–95, and there was a possibility of moderate to severe rockburst. When the angle was 180°–240°, the boundary value of RPC was 25–70, and there was a possibility of moderate rockburst. When the angle was 240°–360°, the boundary value of RPC was 45–90, and there was a possibility of moderate to severe rockburst. From the above analysis, it could be seen that the RPC boundary value obtained by numerical simulation was consistent with the case of severe rockburst in practical engineering.

Fig. 14 Nephogram of the boundary value distribution of RPC

Fig. 15 RPC thresholds of the cavern cross section (0°–360°) of the section K11+037
5 Conclusion

(1) Based on the energy principle and taking the rock strength and overall failure criterion as the benchmark, we established the rockburst proneness criterion of rock mass unit under compression and tension and proposed three rockburst classification thresholds for four grades of none, weak, moderate and severe rockburst.

(2) Taking the typical rockburst disaster as examples, the rationality of the existing classical rockburst criterions and the rockburst proneness criterion proposed in this paper were tested, and the results showed that this criterion was simple and practical and had good engineering applicability, which took into account the integrity factors, mechanical factors, brittleness factors and energy storage factors in the process of rockburst inoculation.

(3) Numerical simulation analysis of rockburst disaster in 2# diversion tunnel of Jinping II hydropower station was carried out by using this criterion. The results were basically consistent with the actual situation, which verified the accuracy and effectiveness of the rockburst proneness criterion proposed in this paper.

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Disclosure statement

The authors declare that they have no conflicts of interest.
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Fig. 1 Stress-strain relation curve of rock
(b) Tension condition

Fig. 2 Loading condition
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Fig. 15 RPC thresholds of the cavern cross section (0°–360°) of the section K11+037
| No. | Position/m | Level of rockburst | Evaluation results of different evaluation methods |  |
|-----|------------|-------------------|-----------------------------------------------|---|
|     |            |                   | $K_u$  | Rockburst proneness | $\sigma_c/\sigma_{max}$ | Rockburst proneness | $R$  | Rockburst proneness |
| TSE5 | 108        | Weak              | 3.1   | Weak                | 8.1                   | Weak               | 0.8  | None                |
|      | 150        | Moderate          | 2.7   | Weak                | 7.3                   | Weak               | 2.7  | Weak                |
|      | 271–350    | Weak              | 2.7   | Weak                | 8.4                   | Weak               | 1.5  | None                |
|      | 500–550    | Moderate          | 2.8   | Weak                | 4.7                   | Weak               | 7.6  | Weak                |
| TSE6 | 350        | Weak              | –     | –                   | 7.4                   | Weak               | 1.4  | None                |
|      | 500        | Moderate          | –     | –                   | 5.1                   | Moderate           | 11.6 | Moderate            |
### Table 2: Simulation results of rockburst of Tiantaishan tunnel

| No. | Position/m | $\sigma_i$/MPa | $\nu$ | $K_u$ | $\sigma_c$/MPa | $\sigma_t$/MPa |
|-----|------------|----------------|------|-------|----------------|----------------|
|     |            | $\sigma_1$     | $\sigma_2$ | $\sigma_3$ |                |                |
| 108 |            | 16.15          | 8.14  | 4.27  |                |                |
| TSE5| 150        | 19.23          | 10.51 | 3.16  | 0.28           | 0.68           |
|     | 271–350    | 20.22          | 12.53 | 3.58  |                | 169.52         |
|     | 500–550    | 40.57          | 24.12 | 12.36 |                | 192.15         |
| TSE6| 350        | 23.65          | 10.87 | 4.02  | 0.28           | 0.68           |
|     | 500        | 35.86          | 21.44 | 15.61 |                | 184.27         |

Annotation: $K_u$ is the deformation brittleness coefficient; $\sigma_{max}$ is maximum principal stress of surrounding rock; $\sigma_c/\sigma_{max}$ is surrounding rock strength ratio.
Table 3 Initial data of rockburst disaster of typical engineering

| No. | Engineering                                      | Buried depth/m | \(\sigma_1\)/MPa | \(\sigma_2\)/MPa | \(\sigma_3\)/MPa | \(\sigma_{\text{max}}\)/MPa | \(\sigma_c\)/MPa | Kv         |
|-----|-------------------------------------------------|----------------|-------------------|-------------------|-------------------|--------------------------|----------------|------------|
| 1   | Jinping I hydropower station                    | 400            | 9.00              | 8.44              | 4.50              | 18–70                    | 50–70          | 0.34–0.72  |
|     |                                                |                | 35.00             | 17.50             | 10.80             |                          |                |            |
| 2   | Jinping II hydropower station                   | 1200–2500      | 38.00             | 32.40             | 19.00             | 55–108                   | 110–120        | 0.76       |
|     |                                                |                | 71.00             | 67.50             | 35.50             |                          |                |            |
| 3   | Diversion tunnel for TianshengqiaoII hydropower station | 130–760   | 25.80             | 12.90             | 3.51              | 30                       | 88.7           | 0.75       |
|     |                                                |                | 25.80             | 20.52             | 12.90             |                          |                |            |
| 4   | Diversion tunnel for Taipingyi hydropower station | 400          | 31.40             | 15.70             | 10.80             | 62.6                     | 130–180        | 0.75       |
| 5   | Qinling railway Tunnel                          | 1600           | 20.00             | 18.75             | 10.00             | 105                      | 95–130         | 0.75       |
|     |                                                |                | 40.00             | 37.50             | 20.00             |                          |                |            |
| 6   | Shandong Linglong gold mine                     | 1000           | 50.00             | 27.00             | 25.00             | 82–114                   | 138–197        | 0.75       |
|     |                                                |                | 60.00             | 30.00             | 27.00             |                          |                |            |
| 7   | Erlangshan highway tunnel                       | 770            | 53.70             | 26.85             | 20.79             | 41.46                    | 64.9           | 0.75       |
|     |                                                |                | 34.33             | 21.33             | 17.17             |                          |                |            |
| 8   | Tongling Dongguashan copper mine                | 790–850        | 34.33             | 22.95             | 17.17             | 105.5                    | 132.2          | 0.75       |
|     |                                                |                | 57.20             | 28.60             | 10.80             |                          |                |            |
| 9   | Underground caverns of Pubugou hydropower station | 250–320  | 27.30             | 13.65             | 8.64              | 42–54                    | 82.3–207.5     | 0.80       |
|     |                                                |                | 21.10             | 10.55             | 6.75              |                          |                |            |
| 10  | Diversion tunnel for Yuzixi I hydropower station | 250–600 | 45.00             | 22.50             | 16.20             | 90                       | 170            | 0.80       |
|     |                                                |                | 30.00             | 15.00             | 6.75              |                          |                |            |
| 11  | Tai-Jin expressway Cangling tunnel              | 300–756        | 59.50             | 29.75             | 8.10              | 48.9                     | 150            | 0.75       |
|     |                                                |                | 59.50             | 29.75             | 20.41             |                          |                |            |
| No. | $\sigma_t$/MPa | E.Hoek criterion | Russenes criterion | Erlangshan highway tunnel criterion | Gu-Tao criterion | The criterion of this paper |
|-----|----------------|-------------------|-------------------|-----------------------------------|-----------------|-----------------------------|
|     | Threshold      | Grade of rockburst | Grade of rockburst | Grade of rockburst                  | Threshold      | Grade of rockburst          |
| 1   | 5.0            | 0.36 Weak         | Moderate          | Weak                              | 5.56           | Weak                        |
|     |                | 1.40 Severe       | Severe            | Severe                            | 1.43           | Severe                      |
|     |                |                   |                   |                                   | 0.4            | None                        |
| 2   | 5.0–6.0        | 0.50 Moderate     | Moderate          | Moderate                           | 2.89           | Moderate                    |
|     |                | 0.46 Weak         | Moderate          | Weak                              | 1.55           | Severe                      |
|     |                | 0.34 Weak         | Weak              | Weak                              | 3.44           | Severe                      |
|     |                | 0.34 Weak         | Weak              | Weak                              | 3.44           | None                        |
|     |                |                   |                   |                                   | 98.8           | Moderate                    |
| 3   | 3.7            | 0.34 Weak         | Weak              | Weak                              | 3.44           | Severe                      |
|     |                | 0.34 Weak         | Weak              | Weak                              | 3.44           | None                        |
| 4   | 9.4            | 0.35–0.48 Weak-Moderate | Weak-Moderate | Weak                             | 4.14–5.73     | Moderate-Severe             |
|     |                |                   |                   |                                   | 6.2            | Weak                        |
| 5   | 7.0            | 1.11 Severe       | Severe            | Severe                            | 4.75–6.50     | Weak-Moderate               |
|     |                | 0.81 Severe       | Severe            | Severe                            | 2.38–3.25     | Moderate                    |
|     |                |                   |                   |                                   | 61.7           | Moderate                    |
| 6   | 7.0–10.0       | 0.59 Moderate     | Severe            | Moderate                           | 2.76           | Moderate                    |
|     |                | 0.42 Weak         | Moderate          | Weak                              | 3.94           | Moderate                    |
|     |                |                   |                   |                                   | 31.2           | Moderate                    |
| 7   | 8.0            | 0.64 Moderate     | Severe            | Moderate                           | 1.21           | Severe                      |
|     |                |                   |                   |                                   | 56.6           | Moderate                    |
| 8   | 16.4           | 0.80 Severe       | Severe            | Severe                            | 3.85           | Moderate                    |
|     |                |                   |                   |                                   | 2.4            | Weak                        |
| 9   | 5.9            | 0.20–0.51 Severe  | Severe            | Severe                            | 3.01–7.60     | Moderate                    |
|     |                | 0.26–0.66 Severe  | Severe            | Severe                            | 3.90–9.83     | Moderate                    |
|     |                |                   |                   |                                   | 8.1            | Weak                        |
| 10  | 11.3           | 0.53 Weak-Moderate | Weak-Moderate     | Weak-Moderate                     | 3.78           | Weak-Moderate               |
|     |                | 0.53 Weak-Moderate | Weak-Moderate     | Weak-Moderate                     | 5.67           | Weak-Moderate               |
|     |                |                   |                   |                                   | 2.4            | Weak                        |
| 11  | 8.0            | 0.33 Moderate     | Moderate          | Moderate                           | 2.52           | Moderate                    |
|     |                | 0.33 Moderate     | Moderate          | Moderate                           | 2.52           | Moderate                    |
|     |                |                   |                   |                                   | 68.3           | Weak                        |
Table 5 Ground stress grade of 2nd headrace tunnel

| Buried depth/m | $\sigma_x$/MPa | $\sigma_y$/MPa | $\sigma_z$/MPa | $\tau_{xy}$/MPa | $\tau_{yz}$/MPa | $\tau_{zx}$/MPa |
|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| 1900          | -48.54        | -49.97        | -51.46        | -3.23         | -5.82         |               |
Table 6 Physical and mechanical parameters of surrounding rock

| $E$/GPa | $\nu$ | $c_m$/MPa | $c_r$/MPa | $\phi_0$/$(^\circ)$ | $\phi_m$/$(^\circ)$ | $\psi$/$(^\circ)$ |
|---|---|---|---|---|---|---|
| 18.9 | 0.23 | 15.6 | 7.4 | 25.8 | 39.0 | 10.0 |
Figures

Figure 1
Stress-strain relation curve of rock

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Figure 8
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Figure 9
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Figure 10

Space-time distribution of elastic strain energy density
Figure 11

Rockburst simulation

Figure 12

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Rockburst areas in situ

Figure 13

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Nephogram of the boundary value distribution of RPC

Figure 15

RPC thresholds of the cavern cross section (0°–360°) of the section K11+037