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Study on rockburst tendency of deep underground engineering based on multi-factor influence

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ABSTRACT: Rockburst disaster seriously threatens the construction schedule and the worker's safety of underground engineering. Rockburst prediction has become one of the essential methods to ensure the normal development of engineering construction. To further understand the rockburst occurrence mechanism and predict rockburst more accurately, the typical rockburst criterion and factors are systematically summarized and analyzed, and the main factors reflecting the rockburst development process are screened and analyzed. Then comprehensively considering the main factors, based on the energy conversion and overall failure mechanism in the rock failure process, a new multi-factor rockburst tendency criterion is proposed by comprehensively considering the stress states of the rock unit. Finally, the rockburst criterion is applied to typical engineering cases. The rockburst section of the Sangzhuling tunnel is predicted by numerical simulation. The results show that: the rockburst criterion considering the mechanical, brittleness, integrity, and energy factor can comprehensively reflect the rockburst failure process; The predicted results are in good agreement with the actual grades in typical engineering cases; the simulation result of rockburst tendency prediction is consistent with on-site rockburst occurrence, which further verifies the effectiveness and engineering applicability of the criterion. The research results can provide a reference for rockburst prediction in deep underground engineering.

Keywords: Deep underground engineering; Rockburst; Rockburst tendency criterion; Multi-factor; Engineering verification

1 INTRODUCTION

With the development of the social economy, underground engineering is gradually attracting more and more attention. With the gradual increase of the buried depth in the underground construction, the stress environment of the surrounding rock is very complex. The rockburst disaster has become one of the crucial issues affecting the safety and progress of underground engineering construction (FENG et al, 2013; FENG et al, 2019). Rockburst is a dynamic instability geological disaster in high in-situ stress conditions due to excavation and unloading of the surrounding rock resulting in the instantaneous release of accumulated elastic strain energy to produce bursting, spalling, ejection, and other phenomena (ZHANG and FU, 2008; LI et al, 2019). Rockburst has strong temporality, uncertainty, continuity, and harmfulness, which causes a serious threat to the safety of construction workers and greatly hinders the normal progress of engineering (WEI et al, 2020). For example, in 2009, a strong rockburst occurred in the Headrace Tunnel of the Jinping II hydropower station in China, resulting in 7 deaths and the complete scrapping of TBM; in 2015, there was a strong rockburst at the N-J hydroelectric diversion tunnel in Pakistan, resulting in 3 deaths and damage to excavation equipment; Erlangshan Tunnel of Sichuan-Tibet Railway in China also encountered many landslides, rockburst, and other disasters during construction, resulting in huge economic losses and construction delay (FENG, 2017; FARADONBEH and TAHERI, 2019; WANG et al, 1999). Therefore, a thorough and systematic study of the disaster-causing mechanism and rockburst criterion can accurately and effectively predict rockburst occurrence and reduce the possibility of rockburst, which has important engineering implications to ensure the safety and normal progress of deep underground engineering construction.

To thoroughly study the rockburst disaster, many experts have conducted a series of studies on the rockburst inducement mechanism, criterion, and prediction. In terms of research on rockburst mechanisms, scholars have not yet formed a unified standard on rockburst inducement mechanism and rockburst classification. Ortlepp and Stacey (1994) divided the rockburst into strain type, buckling type, pillar type, shear fracture type, and fault slip type according to the focal mechanism. Hoek et al (1995). divided rockburst into strain type and fracture type according to the slip of the original fracture surface and the fracture of the total rock mass. Feng et al (2013). divided the rockburst into the immediate type and time delayed type according to the rockburst occurrence time, and divided the rockburst into strain type, strain structural plane sliding type and fracture sliding type according to the rockburst development mechanism. The above studies have contributed positively to the understanding of rockburst mechanism and classification. In terms of theoretical research on rockburst criteria, many scholars have presented corresponding rockburst criteria and intensity classification based on strength theory, stiffness theory, energy theory, et al. The commonly used stress criteria are mainly based on the tangential stress σ_θ or maximum principal stress σ_1 of surrounding rock, such as Russenes criterion, E. Hoek criterion, and Erlangshan criterion (RUSSENSE, 1974; HOEK and BROWN, 1997; XU and WANG, 1999). Most stress criteria have different critical stresses due to the specific engineering background. The brittleness criterion is a lithology-based tendency index, such as rock brittleness coefficient (B) and deformation brittleness coefficient (K_U) (LI et al, 2001; ZHANG et al, 2017), which is a more commonly used index for the evaluation of rockburst tendency. And the occurrence of rockburst is also the process of dynamic instability failure caused by the rapid release of stored energy in the surrounding rock, the analysis of rockburst from the energy perspective will be closer to its mechanism and essence. From the energy perspective, experts and scholars analyze the rockburst problem by comprehensively considering the characteristics of the surrounding rock, and presented some rockburst criteria based on energy principle, such as elastic energy index (W_{et}), energy impact index (R), residual elastic energy index (A_{ef}) (GOODMAN, 1980; KIDYBINSKI, 1981; GONG et al, 2018). The comprehensive factor criterion mainly integrates in-situ stress, rockburst tendency, and other factors. It has obvious advantages over the single factor criterion, such as the Jia Yuru criterion, Qinling tunnel criterion, and rockburst tendency index *RVI* (JIA and FAN, 1990; GU et al, 2002; QIU et al, 2011). In terms of test and numerical simulation of rockburst criteria, Sousa et al (2017). used digital mining technology to evaluate deep rockburst disaster. Based on dynamic numerical analysis, Sun et al (2022). used FLAC3D numerical simulation software to evaluate six kinds of rockburst prediction indexes in the diversion tunnel of Jinping II Hydropower Station, to provide an in-depth analysis of the evolution process and formation mechanism of rockburst. The occurrence of rockburst is a comprehensive result of multiple factors such as lithology, stress environment, energy storage, and integrity of surrounding rock. The existing rockburst empirical criteria only consider one or two affecting factors in the rockburst occurrence and have certain one-sidedness and limitations. Based on the research about the rockburst inducement mechanism and the advantages of the comprehensive factor criterion, the research on the rockburst criterion should gradually change to the trend of composite multi-parameter energy criterion, and the form of the rockburst criterion also tends to be simplified. In terms of rockburst prediction, many scholars have carried out qualitative or quantitative predictions of rockburst tendency based on various rockburst criteria established by the rockburst occurrence mechanism. Feng et al (1996). have systematically predicted the occurrence of rockburst in South Africa. Zhang et al (2013). established a comprehensive analysis and prediction system for rockburst and successfully applied it to the rockburst prediction of the Micangshan Highway Tunnel. Qu et al (2021). used different rockburst criteria to predict rockburst in the area of the Caoguoshan Tunnel. Rockburst tendency prediction is to predict the occurrence trend of rockburst by various criteria, which has the advantages of low cost and fast evaluation of rockburst prediction, but its accuracy is worse than that of field measurement. Therefore, the accuracy of rockburst prediction can be further improved by combining the numerical calculation method with rockburst criteria.

In this paper, some typical rockburst evaluation indexes and intensity classification are systematically summarized, and the rockburst affecting factors are sorted out and screened to obtain the main control factors affecting the rockburst development process: Mechanical factor (σ_θ / σ_{c}), Brittleness factor (σ_{c} / σ_{t}), Integrity factor (K_{v}), and Energy storage factor (U^{e} / U_0). Based on the energy conversion and overall failure mechanism in the rock failure process, and taking into account the rock unit with various stress conditions, a new multi-parameter rockburst tendency criterion *REC* is proposed. This criterion is applied to some typical engineering cases to verify the reasonableness of the criterion by comparing the results of the rockburst tendency evaluation with the actual rockburst situation on the site. The secondary development of the 3D discrete element numerical simulation platform was carried out, and the newly proposed criterion *REC* was successfully used for the rockburst prediction in the Sangzhuling Tunnel, further verifying the validity and engineering applicability of the *REC*. To provide a basic scientific basis and theoretical support for rockburst disaster evaluation and prediction.

2 ESTABLISHMENT OF ROCKBURST TENDENCY CRITERION

Rockburst is not determined by a single factor, which is related to each other and independent of each other. The influence degree and mode of different factors on rockburst are also different. A reasonable and accurate selection of factors affecting rockburst is the basis for the study of rockburst tendency prediction. This section first summarizes some of the typical rockburst criteria and intensity classification, and the main control factors in the rockburst development process are analyzed respectively. Based on the energy conversion and overall failure mechanism, the energy storage factor U^{e} / U_0 is considered as the main control affect factor inducing rockburst disaster, and a multi-parameter rockburst tendency criterion is proposed.

2.1 *Analysis of previous rockburst tendency criteria*

Existing rockburst engineering cases show that the following indexes are mainly considered for the rockburst tendency criterion of underground engineering: Maximum principal stress σ_1, Maximum tangential stress σ_θ, Radial stress σ_r, Uniaxial compressive strength σ_c, Tensile strength σ_t, Rock elastic energy index W_{et} (Φ_{sp} and Φ_{st} is the maximum stored elastic strain energy and loss strain energy), rock mass integrity coefficient K_v, releasable elastic strain energy U^e, rock limit stored energy U_0, actual energy of surrounding rock unit U and lateral pressure coefficient λ. According to the rockburst mechanism and occurrence process, experts and scholars have presented various hypotheses and rockburst tendency criteria through theoretical analysis, laboratory tests, numerical simulation, and other methods combined with different indexes, and provided on-site guidance, as shown in Table 1.

The following rockburst criteria and intensity classification are classified and analyzed to show that: (1) Most experts and scholars classify rockburst intensity into 3 grades (No, Moderate and Intense rockburst) or 4 grades (No, Weak, Moderate, and Intense rockburst), and the expression form of the proposed evaluation indexes is different due to the different affecting factors. (2) As can be seen from Table 1, the ratio of σ_1 or σ_θ to σ_c is more widely used, such as Gu-Tao criterion, Barton criterion, and Hoek criterion. In different engineering cases, the intensity classification standards are different due to the various geo-mechanical environment of the surrounding rock. (3) Traditional evaluation indexes of stress and brittleness only consider one or two factors, which cannot comprehensively reflect the rockburst development process. Therefore, many scholars attempt to establish an empirical evaluation system by selecting multiple main control factors that influence the rockburst development process as evaluation indexes, such as five-factor rockburst criterion and rockburst potential criterion P_{rb} (ZHANG et al, 2011; SHANG et al, 2013), some scholars further carried out a comprehensive evaluation of underground engineering rockburst based on this criterion combined with the appropriate mathematical model. (4) Stress condition is the triggering condition for rockburst and energy condition is the basic condition for rockburst (WU et al, 2018). As a dynamic instability phenomenon, the dissipation and release of energy are accompanied by rockburst occurrence. If the energy transfer and conversion process under the state of tensile and compressive stresses in the rock failure process can be considered, a rockburst evaluation index can be established that can comprehensively reflect the different main control factors in the rockburst development process. It may more truly and accurately reflect the failure law and rockburst tendency of surrounding rock under the excavation and unloading of deep underground engineering.

Table 1. Criteria for rockburst tendency and intensity classification

Name	Expression	Intensity classification				
		No	Weak	Moderate	Intense	Extreme
Gu-Tao (1994)	σ_c / σ_1	>14.50	5.50~14.50	2.50~5.50	<2.50	—
Barton (1974)	σ_1 / σ_c	—	—	0.2~0.4	>0.4	—
E.Hoek (1997)	σ_θ / σ_c	—	<0.34	0.34~0.42	0.42~0.56	0.56~0.70
Russense (1974)	σ_θ / σ_c	<0.20	0.20~0.30	0.30~0.55	≥0.55	—
Turchaniov (2008)	$\sigma_\theta+\sigma_r / \sigma_c$	≦0.3	0.3~0.5	0.5~0.8	>0.8	—
Erlangshan (1999)	σ_θ / σ_c	<0.3	0.3~0.5	0.5~0.7	>0.7	—
Kidybinski (1981)	$W_{et}=\phi_{sp} / \phi_{st}$	<2.0	2.0~3.5	3.5~5.0	≥5.0	—
J J Zhang (2011)	σ_1 / σ_c	<0.15	0.15~0.20	0.20~0.40	>0.40	—
	σ_θ / σ_c	<0.20	0.20~0.30	0.30~0.55	≥0.55	—
	σ_c / σ_t	<15	15~18	18~22	≥22	—
	W_{et}	<2.0	2.0~3.5	3.5~5.0	≥5.0	—
	K_v	<0.55	0.55~0.60	0.60~0.80	≥0.80	—
Y J Shang (2013)	$P_{rb}=(\sigma_\theta / \sigma_t)K_v$	<1.70	1.70~3.30	3.30~9.70	>9.70	—
W Z Chen (2009)	$K=U / U_0$	—	0.3	0.4	0.5	≥0.5
J Q Guo (2015)	$R_i=K_v \frac{\sigma_i}{\sigma_c} \frac{\sigma_c}{\sigma_t} \frac{2E_0 U^e}{\sigma_t^2}$	<3	3~10	10~110	>110	—

2.2 *Analysis of the main control factors of rockburst tendency*

The affecting factors of rockburst are roughly divided into the internal cause, external cause, and incentive cause. The external and incentive causes are local stress conditions and rockburst dynamic critical conditions, which affect the rockburst development process to a certain extent. Under the high in-situ stress condition in which deep underground engineering is located, the internal cause is the rock lithology, which has a significant influence on the occurrence of rockburst or not. Considering the influence of various factors on the rockburst tendency criterion, it is believed that rockburst is mainly controlled by four aspects (rock mechanics, brittleness, integrity, and energy storage) under the action of affecting factors. The main control factors that can reflect the rockburst tendency are analyzed respectively from the perspective of mechanical factor, brittleness factor, integrity factor, and energy storage factor:

(1) Mechanical factor: The rockburst occurrence is related to the stress of the surrounding rock in the tunnel. Russense (1974) carried out a point load test on the rock and transformed the test results into the combination of the uniaxial compressive strength and the tangential stress of the surrounding rock to establish the criterion (σ_θ / σ_c). The greater the value of the maximum principal stress σ_1 and the maximum tangential stress σ_θ in the surrounding rock, the greater the probability of a rockburst occurring and the higher the risk during construction. However, the adoption of the maximum principal stress σ_1 to reflect the stress level has limitations, the effect of excavation size on the secondary stress field is ignored and the probability of rockburst is underestimated. The maximum tangential stress σ_θ and the maximum principal stress σ_1 of the surrounding rock essentially reflect the same index, when the lateral pressure coefficient λ=1, the tangential stress at the vault, arch bottom, and sidewall of the tunnel is equal(σ_1=σ_2=σ_v) (SHANG and ZHANG, 2013). Therefore, σ_1 / σ_c can be replaced by σ_θ / σ_c, and the larger the ratio of σ_θ / σ_c, the stronger the rockburst tendency. The ratio of σ_θ to σ_c can more truly reflect the critical stress state when the rock fails.

(2) Brittleness factor: Lithology is a significant factor affecting the rockburst occurrence. Rockburst occurs mostly in hard and brittle rocks, while rockburst rarely occurs in soft rocks. Because of the high elastic modulus of the rock in deep underground engineering, a large amount of elastic strain energy has been accumulated in the rock before the tunnel excavation, the energy within the rock disturbed by excavation is easy to release and suddenly produces fragments and rock ejection, which occurs the rockburst phenomenon. Moreover, the higher the brittleness of the rock, the greater the elastic deformation and the smaller the plastic deformation during the rock deformation process. Therefore, it is necessary to establish a specific brittleness index to characterize the brittleness of the rock. The compressive and tensile strengths are the uniform criteria used by most scholars to measure the ultimate values of rock strength, which can describe lithology to a certain extent. In addition, the limit values of compressive and tensile strength can be easily obtained, which are suitable for engineering practice. It is reasonable to adopt the brittleness evaluation index σ_c / σ_t based on rock strength characteristics as one of the main control factors for the prediction of rockburst tendency.

(3) Integrity factor: The rock mass integrity is also one of the important indexes for evaluating whether rockburst occurs in engineering, which is mainly determined by the geometric and character characteristics of the structural plane. The integrity degree of rock mass is a classification factor for evaluating the basic rock mass quality index, and the method of a quantitative index can improve the accuracy and reliability of rock mass classification. Numerous studies have shown that the rock integrity coefficient K_v is an important physical parameter to describe the integrity of rock mass, which can be characterized by the rock quality index *RQD* or obtained as the square of the ratio of elastic longitudinal waves v_{pm} to shear waves v_{pr} in fresh rock mass (SHEN and CHEN, 2015). The higher the rock mass integrity coefficient, the stronger the rockburst tendency.

(4) Energy storage factor: Dissipation and release of energy are the fundamental conditions for the deformation and damage of rock mass. Energy dissipation causes damage to the rock, which reduces the rock strength, and energy release leads to the ejection of rock failure (XIE et al, 2005). It can be seen from the overall failure criterion that the magnitude relationship between the releasable strain energy U^e and the limit value of the surface energy U_0 is the main reference for the rock unit failure. Therefore, if both U^e and U_0 are considered as energy storage factors in the main control factors of rockburst tendency, combined with the law of energy conversion, to analyze the relationship between the static and dynamic failure of surrounding rock and energy under different stress states during rockburst incubation, it can better reflect the correlation between the stress state and rockburst tendency in the critical location of the excavation process in deeply buried underground tunnels.

2.3 *Multi-parameter rockburst tendency criterion based on energy principle*

2.3.1 *Analysis of rockburst mechanism based on energy principle*

(1) Energy conversion mechanism of the surrounding rock

According to the theory of energy conservation, considering the deformation of the rock unit under the action of external force, it is assumed that there is no heat exchange with the external during this deformation process, the energy U generated by the work of external force can be obtained as (XIE et al, 2005):

$$U = U^{\mathrm{e}} + U^{\mathrm{d}} \tag{1}$$

Where: U^{d} is the rock dissipation energy density, U^{e} is the rock releasable elastic strain energy, which the Equation is:

$$U^{\mathrm{e}} \approx \frac{1}{2E_0}\left[\sigma_1^2+\sigma_2^2+\sigma_3^2-2\nu(\sigma_1\sigma_2+\sigma_2\sigma_3+\sigma_1\sigma_3)\right] \tag{2}$$

Where: σ_1, σ_2, and σ_3 are the maximum principal stress, intermediate principal stress, and minimum principal stress, respectively. For the convenience of engineering application, E_0 and ν take the initial elastic modulus and the initial Poisson's ratio.

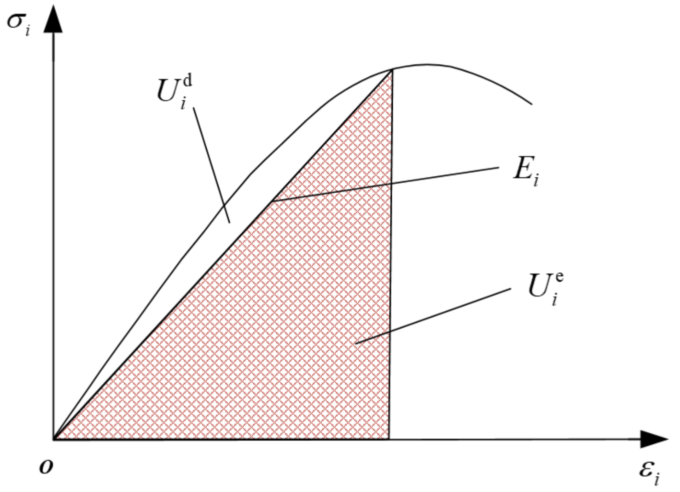


Figure 1. Stress-strain curves of rock unit failure

Figure 1 shows the stress-strain curve of the rock unit failure, σ_i and ε_i are the values of stress and strain corresponding to each point on the stress-strain curve respectively. the area U_i^{d} indicates the dissipation of the rock unit energy, and the shaded area U_i^{e} indicates the releasable stress energy stored in the rock unit, E_i is the unloading elastic modulus.

(2) Limit energy storage of rock under different stress paths

① State of tension

During the excavation and unloading process of underground construction, the rock unit often shows tensile failure($\sigma_3<0$), which is a stress state that can easily lead to the overall failure of the rock unit, and any tensile stress will promote the release of energy in the rock unit. Based on the rock strength and overall failure criterion, Guo et al (2015). concluded that the process of rockburst occurrence can be simply expressed by the state of tensile stress in the rock unit. When the energy release rate in the direction of any principal stress is greater than the critical energy release rate, the rockburst will occur. The elastic strain energy is distributed in the three principal stress directions according to the magnitude of the principal stress value, and the energy release rate G_i of the rock unit is:

$$G_i = K_i \sigma_i U^{\mathrm{e}} \geq G_{\mathrm{t}} \tag{3}$$

Where: K_i is the material constant (i=1,2,3), and G_{t} is the critical energy release rate of the rockburst occurrence (the material constant determined by the uniaxial tensile test). Suppose that $\sigma_3=\sigma_{\mathrm{t}}$, $\sigma_1=\sigma_2=0$, combined with the Equation (2) and (3), the critical value of the maximum energy release rate G_{t} is shown in Equation 4.

$$G_{\mathrm{t}} = K_3 \frac{\sigma_{\mathrm{t}}^3}{2E_0} \tag{4}$$

When the rock unit is in tension, the elastic strain energy is easily released along the direction of the maximum tensile stress σ_3, and the overall failure of the rock unit will occur when it satisfies:

$$G_3 = K_3 \sigma_3 U^{\mathrm{e}} = G_{\mathrm{t}} \tag{5}$$

The ultimate energy storage value of the rock unit in the state of tension can be obtained as:

$$U_0 = \frac{\sigma_{\mathrm{t}}^3}{2E_0\sigma_3} \tag{6}$$

② State of compression

In practical engineering, most of the rock is in triaxial compression before tunnel excavation, that is (The compressive stress is positive). To fully express the stress state of each rock unit throughout the whole excavation of the tunnel, and to further reflect the energy evolution of the rock unit under different stress paths, the compressive stress state of the rock unit is taken into account. The energy release is distributed along the three principal stress directions according to the difference with the minimum compressive stress, assuming that the rock energy release rate is G_i, which is expressed as:

$$G_i = K_i(\sigma_1 - \sigma_i)U^{\mathrm{e}} \tag{7}$$

Where K_i is the material constant (i=1,2,3).

The maximum energy release rate tends to occur in the direction of the minimum principal stress σ_3, which is expressed as:

$$G_3 = K_3(\sigma_1 - \sigma_3)U^{\mathrm{e}} \tag{8}$$

Assuming that the critical strain energy release rate for the overall failure of the rock unit in compression is G_{c}, which is a material constant determined by the uniaxial compression test, suppose that $\sigma_1=\sigma_{\mathrm{c}}$, $\sigma_2=\sigma_3=0$, combined with Equation (2), the critical value of the maximum energy release rate Gc can be obtained as follows:

$$G_{\mathrm{c}} = K_3 \frac{\sigma_{\mathrm{c}}^3}{2E_0} \tag{9}$$

When the rock unit is in the critical failure state, suppose that $G_3=G_{\mathrm{c}}$, the ultimate energy storage value of the rock unit in compression is:

$$U_0 = \frac{\sigma_{\mathrm{c}}^3}{2E_0(\sigma_1 - \sigma_3)} \tag{10}$$

Further combined with Figure 1, it can be seen that the rock unit is partly converted into dissipative energy U^{d} and partly into releasable elastic strain energy U^{e} under the action of external force. When $U^{\mathrm{e}}=U_0$, that is, U_{e} reaches the critical value of energy U_0 required for rock unit failure, the static failure of the rock unit occurs; When $U^{\mathrm{e}}>U_0$, the dynamic failure of the rock unit occurs, and the overflowing elastic strain energy $\Delta U=U^{\mathrm{e}}-U_0$ will be converted into the kinetic energy required by rock ejection or splashing. Therefore, if the energy ratio U^{e} / U_0 under different stress paths is chosen as the energy storage factor, it can better reflect the stress state of each rock unit. The expressions of the energy ratio U^{e} / U_0 under the state of compression and tension are shown in Equation (11).

$$\begin{cases} \dfrac{U^{\mathrm{e}}}{U_0} = \dfrac{(\sigma_1\text{-}\sigma_3)2E_0U^{\mathrm{e}}}{\sigma_{\mathrm{c}}^3}(\sigma_3 \geq 0) \\ \dfrac{U^{\mathrm{e}}}{U_0} = \dfrac{\sigma_3 2E_0U^{\mathrm{e}}}{\sigma_{\mathrm{t}}^3}(\sigma_3 < 0) \end{cases} \tag{11}$$

2.3.2 *The proposition of rockburst criterion*

The intensity level of rockburst occurrence is limited by the mechanical environment, the lithology, and integrity of the rock, energy storage, and other factors. Based on the energy principle, combined with the influence of mechanical, brittle, integrity, and energy storage factors on the inducing rockburst hazard in the process of rockburst development failure, and considering the logical relationship of the "and" between the above factors and the evaluation indexes, the expression form of the product is adopted on the mathematical expression. A multi-parameter rockburst tendency evaluation index suitable for deep underground engineering is proposed. The expression is shown in Equation (12):

$$REC = K_{\mathrm{v}}\left(\frac{\sigma_\theta}{\sigma_{\mathrm{c}}}\frac{\sigma_{\mathrm{c}}}{\sigma_{\mathrm{t}}}\right)\frac{U^{\mathrm{e}}}{U_0} = K_{\mathrm{v}}\frac{\sigma_\theta}{\sigma_{\mathrm{t}}}\frac{U^{\mathrm{e}}}{U_0} \tag{12}$$

Where: K_{v}, $\sigma_\theta / \sigma_{\mathrm{c}}$, $\sigma_{\mathrm{c}} / \sigma_{\mathrm{t}}$, and U^{e} / U_0 are the integrity factor, mechanical factor, brittleness factor, and energy storage factor of the rock mass, respectively.

To determine the threshold of the rockburst intensity level, combined with the five-factor criterion, the rockburst potential criterion P_{rb} and the multi-parameter rockburst tendency criterion *MRC* (ZHU et al, 2021), the limit values of the integrity factor K_{v}, mechanical factor $\sigma_\theta / \sigma_{\mathrm{c}}$, brittleness factor $\sigma_{\mathrm{c}} / \sigma_{\mathrm{t}}$, and energy storage factor U^{e} / U_0 are shown in Table 2. On this basis, considering that the multi-factor threshold value has a certain range of variation, the probability of each index reaching the limit value at the same time is small, and it needs to be suitable for engineering practice. Combining with Equation (12), the rockburst intensity classification of the criterion *REC* is shown in Equation (13).

$$REC = \begin{cases} < 0.40 & \text{No} \\ 0.40 \sim 1.00 & \text{Weak} \\ 1.00 \sim 5.00 & \text{Morderate} \\ > 5.00 & \text{Intense} \end{cases} \tag{13}$$

Table 2. Relationship between rockburst intensity and main control factors

Rockburst grade	No	Weak	Moderate	Intense
$\sigma_\theta / \sigma_{\mathrm{c}}$	<0.20	0.20~0.30	0.30~0.55	>0.55
$\sigma_{\mathrm{c}} / \sigma_{\mathrm{t}}$	<15.00	15.00~18.00	18.00~22.00	>22.00
U^{e} / U_0	<0.22	0.22~0.30	0.30~0.52	>0.52
K_{v}	<0.55	0.55~0.60	0.60~0.80	>0.80
P_{rb}	<1.70	1.70~3.30	3.30~9.70	>9.70
MRC	<1.82	1.82~3.24	3.24~9.15	>9.15

2.4 *Calculation application of typical rockburst engineering cases*

To further verify the validity, accuracy, and applicability to engineering cases of the multi-parameter rockburst tendency index *REC*, this criterion is applied to some typical rockburst engineering cases, a preliminary comparative analysis is made with the actual rockburst occurrence situation, the results are shown in Table 3. The values of σ_2 and σ_3 are taken with reference to the in-situ stress distribution law in China and supplemented with the results of the in-situ stress test. σ_θ is approximately calculated by the *Kirsch. G* equation ($\sigma_\theta=3\sigma_1\text{-}\sigma_3$).

The criterion *REC* is used to calculate and verify some typical rockburst engineering cases. It can be seen from Table 3 that the prediction results are essentially consistent with the actual condition of rockburst occurrence, and the evaluation accuracy reaches about 72.7%. It can be more accurate and reasonable to quantitatively determine the intensity level of rockburst during the tunnel construction, and the stress state of the rock unit before and after unloading in one direction is comprehensively considered, which reflects the integrity factor K_v, energy storage U^e / U_0, mechanical factor σ_θ / σ_c and brittleness factor σ_c / σ_t in the rockburst development failure process. The physical meaning of these factors is straightforward and explicit, which has great engineering applicability for rockburst prediction. However, the occurrence of rockburst is also affected by the depth, excavation method, and unloading rate of the tunnel. In some engineering cases, the prediction of rockburst is inaccurate enough. For example, the actual occurrence of a rockburst in Linglong Gold Mine is moderate rockburst, but the prediction result of the *REC* is weak, indicating no or weak rockburst. In addition, the specific location of the rockburst can not only be predicted by the equation calculation of engineering cases. Therefore, the use of numerical simulation software can better predict the rockburst occurrence of different location ranges and intensity levels in deep underground engineering, and also provide more research methods and means for rockburst intensity level prediction and rockburst occurrence location.

3 ENGINEERING VERIFICATION

This section takes the Sangzhuling Tunnel of the Sichuan-Tibet Railway as an example, First, the numerical calculation program is written in the FISH language, and the multi-parameter rockburst criterion *REC* proposed in this study is extended to the second development of 3D discrete element numerical simulation software. Then the distribution law of the rockburst criterion and the actual rockburst occurrence are compared and analyzed. Finally, the rationality and engineering applicability of the rockburst tendency criterion *REC* are verified.

3.1 *Construction of the discrete element model*

(1) Numerical model and boundary constraints

Sangzhuling Tunnel is one of the major control tunnels of the Sichuan-Tibet Railway, which is a typical deep buried long tunnel. In the D1K173+650-DK190+105 section, the tunnel burial depth is about 300~1500m, and the maximum and minimum deep burial of the tunnel are located in this section, and its engineering geological environment is complex and variable. The longitudinal section of the tunnel is shown in Figure 2. Large-scale, multi-point weak and moderate grade rockburst occurred during excavation, and strong rockburst occurred in local areas. In this section, this part of the rockburst section is taken as an example, and the section D1K182+987~ D1K183+037 is selected as the numerical model in the tunnel excavation simulation. Based on the inversion results of the in-situ stress field, it can be seen that the initial stress field of the surrounding rock in this section is dominated by the vertical burial depth. The surrounding rock level is grade II, and the rock lithology exposed on the tunnel face is diorite. The rock mass integrity is good, the joints are not developed, the tunnel face is dry and there is no obvious structural surface nearby. The analysis of the numerical simulation inversion results shows the specific in-situ stress state in Table 4 (LUO, 2018), where: σ_x, σ_y, and σ_z represent the normal stresses acting on the x, y, and z planes and along the x, y, and z directions, respectively.

Table 3. Verification of the *REC* calculation results in typical rockburst engineering

Rockburst cases	Principal stress / MPa			σ_c /MPa	σ_t /MPa	K_v	Rockburst grade	*REC*
	σ_1	σ_2	σ_3					
Jinping I hydropower station (ZHANG et al, 2011)	9.00 35.00	8.44 17.50	4.50 10.80	60	5.0	0.53	Weak~ Moderate	0.005(No) 1.316(Moderate)
Jinping II hydropower station (Chinese Society for Rock Mechanics and Engineering, 2009; ZHANG et al, 2011)	38.00 71.00	32.40 67.50	19.00 35.50	110	5.5	0.76	Moderate ~Intense	0.500(Weak) 5.832(Intense)
Linglong Gold Mine, Shandong province (CAI et al, 2001)	50.00 60.00	27.00 30.00	25.00 27.00	130	7.0	0.75	Moderate	0.488(Weak) 1.079(Moderate)
Erlang Mountain Road (XU and WANG, 1999)	53.70	26.85	20.79	64	8.0	0.75	Intense	5.225(Intense)
Underground workshop of Ertan Hydropower Station (JI et al, 2000; WILLIAM and YANG, 1999)	32.00 57.20	16.00 28.60	5.40 10.80		7.4	0.80	Moderate ~Intense	0.589(Weak) 5.802(Intense)
Cangling Tunnel of Tai-Jin Highway (WU and YANG, 2005)	59.50 59.50	29.75 29.75	20.41 8.10	150	8.0	0.75	Weak~ Moderate	0.728(Weak)

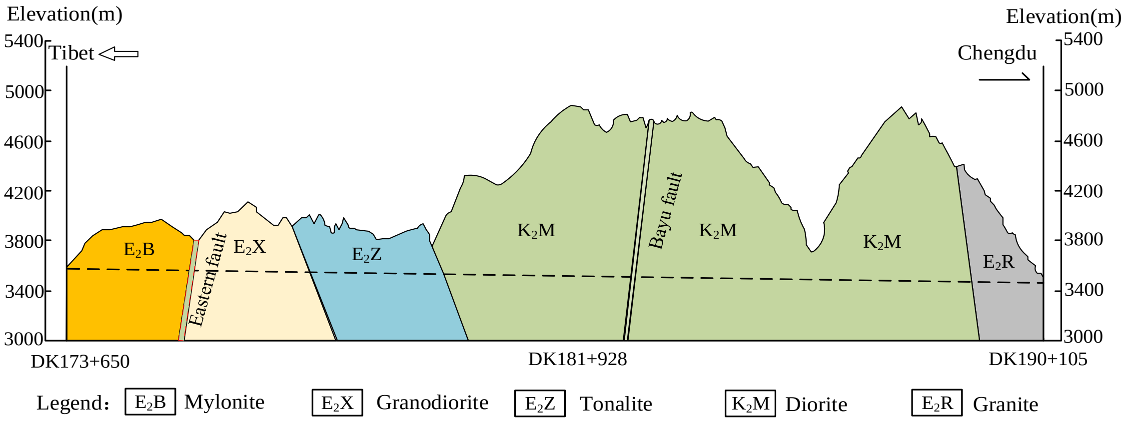
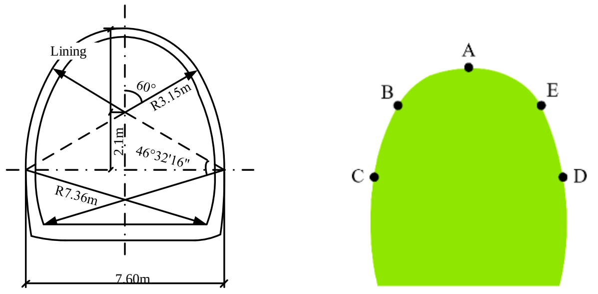


Figure 2. Longitudinal section of the Sangzhuling Tunnel

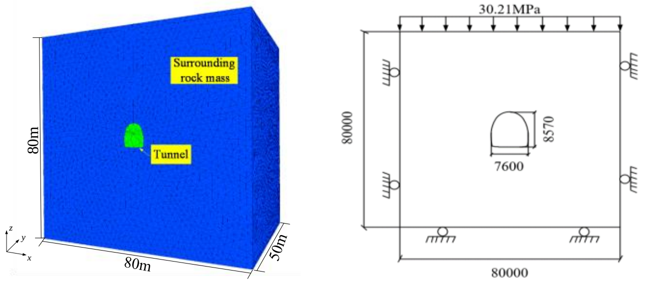
Table. 4 In-situ stress state of rockburst section D1K182+987-D1K183+037

Buried depth / m	σ_x / MPa	σ_y / MPa	σ_z / MPa
1218	-4.27	-17.03	-30.21



(a) (b)

Figure 3. Cross-sectional dimensions and monitoring point arrangement of the Sangzhuling tunnel. a Actual sectional dimension of the tunnel; b Monitoring position of the surrounding rock



(a) (b)

Figure 4. Modeling and boundary conditions of the Sangzhuling tunnel. a Numerical model; b Model boundary conditions and dimensions (unit: mm)

To ensure that the simulation results are realistic and reliable, and can truly reflect the stress state of the rock unit, based on the Saint-Venant Principle and the excavation effects of the tunnel, while fully considering the geological environment of the surrounding rock in the Sangzhuling tunnel and the boundary effects generated by the simulation calculations, numerical models and boundary conditions are determined by the following methods: Centered on the axis of the tunnel, 80m (x)×80m (z) was selected as the calculation range on the vertical axis plane, and 50m (y) was extended along the direction of tunnel excavation. The left and right sides of the model boundary constrain the displacement of the horizontal x direction, the front, and back of the model boundary constraint the displacement of y direction, the bottom of the model boundary constrains the displacement of the vertical and horizontal direction, and the vertical and horizontal stresses equivalent to the weight of the overlaying rock are applied to the upper boundary. In the process of 3DEC modeling, the actual section size of the tunnel, the monitoring point layout of the simulation tunnel rockburst section, the numerical model, and the model boundary conditions and dimensions are shown in Figures 3-4.

(2) Constitutive model and mechanical parameters

During the numerical calculation process, the selection of the constitutive model should be consistent with the actual engineering characteristics. To truly reflect the stress state of the surrounding rock, the model constitutive relation adopts the Mohr-Coulomb yield criterion (SHI et al, 2016), which is a flow law related to tensile failure. The physical and mechanical parameters of the rock are obtained by referring to the calculation results of the physical and mechanical parameters in the Sangzhuling tunnel by Wang et al (2017), as shown in Table 5. And the rock lithology is assumed to be a homogeneous isotropic continuum and the material parameters conform to the Mohr-Coulomb constitutive relation during the process of numerical calculation.

Table 5. Value of physical and mechanical parameters of rock mass

Formation lithology	Elastic Modulus (GPa)	Poisson's ratio	Density (kg / m^3)	Cohesion (MPa)	Internal friction angle (°)	Compressive strength (MPa)	Tensile strength (MPa)
Diorite	36	0.20	2600	2.3	45	143.78	7.04

3.2 *Analysis of rockburst tendency distribution characteristics*

In the process of numerical simulation, FISH language programming is used to write the calculation program for releasable elastic strain energy U^e, energy storage factor U^e / U_0 under different stress states and rockburst tendency criterion *REC*, and the energy evolution process of the tunnel at different locations was monitored. According to the numerical simulation results, the energy field, stress field, and threshold value distribution of the *REC* are compared and analyzed with the actual rockburst occurrence on the site, as shown in Figures 5-8.

(1) On-site rockburst characteristics

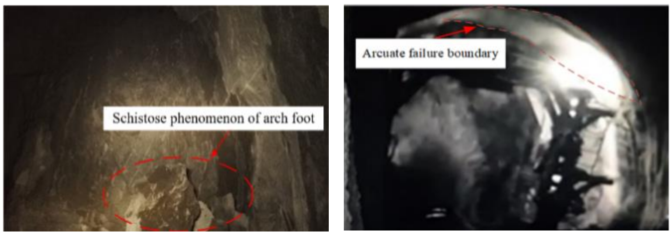
According to the survey of the four parties on the site, it was observed that an arc-shaped concave cavity on the right side of the vault behind the tunnel face, the fracture is shell-shaped, the spalled rock is flaky, and there are occasional schistose phenomena at the arch foot of the tunnel. The video data provided by the construction site revealed that there was a crisp cracking or "crackling" sound when the rockburst occurred. And it is comprehensively evaluated that there is a moderately strong rockburst within the scope of this section according to the on-site stratum lithology, rock mass structure, hydrogeological conditions, and image data provided on the site, as shown in Figure 5.

(2) Analysis of energy release evolution process

The distribution characteristics of the principal stress difference and elastic strain energy of the surrounding rock after tunnel excavation are shown in Figure 6. It can be seen from Figures 6(a) and (b) that the maximum value of the principal stress difference after excavation is mainly distributed in the vault, both sides of the spandrel and arch foot of the tunnel. The maximum stress difference is about 101.13MPa. With the increase of the distance from the tunnel axis, the value of the principal stress difference gradually decreases. From the analysis of the cloud diagram of elastic strain energy density distribution, it can be obtained that the elastic strain energy at various locations within the surrounding rock has been released to different degrees after excavation. The stress concentration of the surrounding rock makes the energy accumulation increase, the value of the releasable elastic strain energy at the location of the tunnel vault and spandrel on both sides is larger, and the value of the maximum elastic strain energy density can reach about 0.44MJ / m^3, and the elastic strain energy density also gradually decreases with the tunnel axis radius. The distribution law is consistent with the rockburst characteristics on the site. Figure 7 shows the spatiotemporal distribution of elastic strain energy about five different monitoring points of the tunnel vault, spandrel, and arch haunch. It can be seen from Figure 7 that the change value of the elastic strain energy density at point A is the largest at the vault location, and its elastic strain energy density is significantly higher than that at other locations; It can be concluded that the rockburst tendency at the tunnel vault is stronger and rockburst is prone to occur; In contrast, the elastic strain energy densities of points C and D on both sides of the arch haunch are relatively weak, and the energy distribution characteristics are consistent with the on-site rockburst situation, which further verifies that the elastic strain energy density can better reflect the failure state of tunnel surrounding rock.

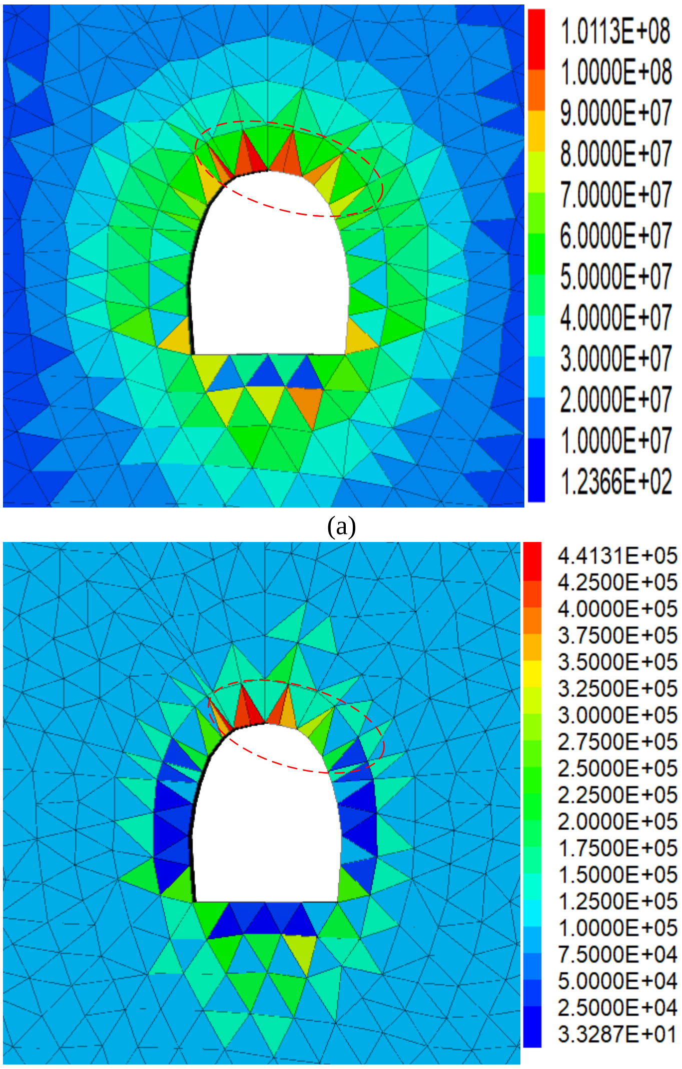
(3) Distribution characteristics of rockburst tendency index

The variation law of the criterion *REC* threshold value at different positions in the tunnel section is shown in Figure 8. It can be seen from Figure 8 that the maximum threshold value of the *REC* in the surrounding rock can reach 7.567, which indicates that the tunnel surrounding rock has strong rockburst tendency and is prone to intense rockburst. The range of the *REC* threshold value near the tunnel vault is 2.250~6.540, which is prone to moderate or intense rockburst. At the side wall on both sides of the tunnel, the threshold value of the *REC* is mainly concentrated in the range of 0~0.900, and there is almost no rockburst or the possibility of a weak rockburst. At the location of the arch foot on both sides of the tunnel, the *REC* threshold value is mainly concentrated in 1.350~1.800, and there is a propensity for the moderate rockburst to occur. Compared with the distribution characteristics of rockburst occurrence, principal stress difference, and elastic strain energy density of tunnel surrounding rock, it can be found that the distribution characteristics are consistent with the distribution of the rockburst tendency index *REC*, that is, both the rockburst occurrence location is roughly the same, but the accuracy of rockburst tendency evaluation is still inadequate. Moreover, the threshold distribution characteristic of the *REC* is similar to the distribution law of the stress field and energy field, which approximately presents axisymmetric distribution.



(a) (b)

Figure 5. Actual situation of rockburst failure. a Schistose phenomenon of the arch foot; b The moment when the vault rockburst occurs



(a)

(b)

Figure 6. Contour of stress field and energy field. a Contour maps of principal stress difference (unit: Pa); b Contour maps of elastic strain energy density (unit: J / m^3)

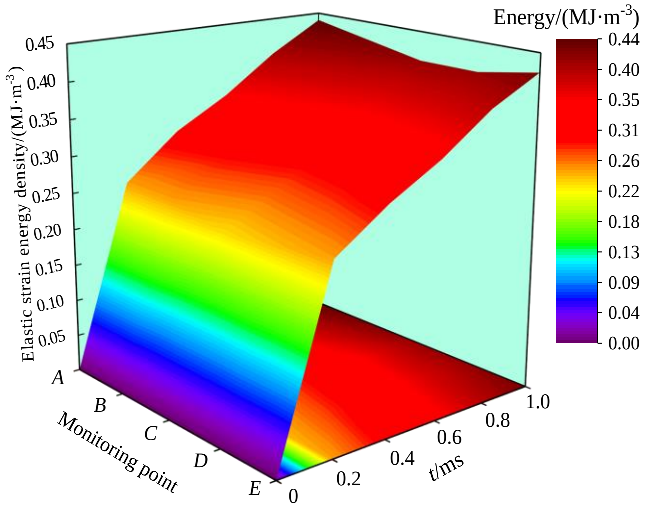


Figure 7. Spatiotemporal distribution of elastic strain energy density

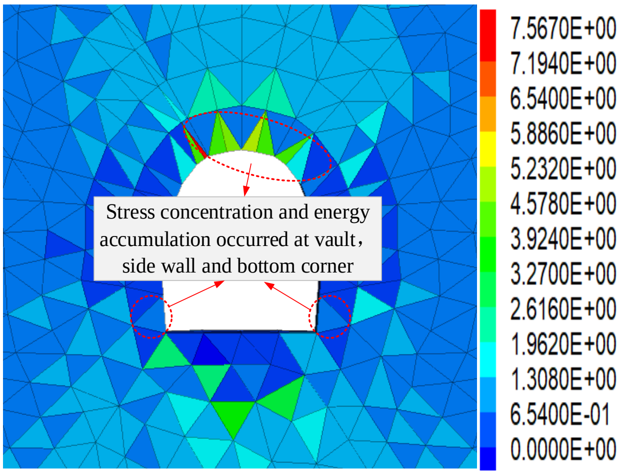
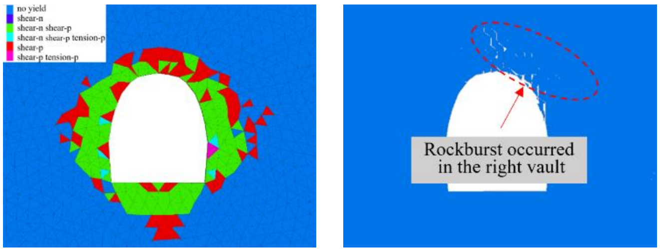


Figure 8. Contour maps of rockburst criterion threshold

Figures 9 (a) and (b) respectively show the distribution of plastic zone and the occurrence of rockburst in the section of surrounding rock after tunnel excavation. It can be seen through the analysis that the position of the plastic zone and rock occurrence is consistent with the on-site rockburst situation, mainly occurring near the right of the tunnel vault. The *REC* reflects the area where rockburst may occur. The phenomena of surrounding rock fracture and rock ejection appear at the *REC* maximum position. The distribution of the plastic zone of surrounding rock and the simulated rock ejection of rockburst after tunnel excavation are consistent with the actual situation (Fig. 5), and the accuracy of the *REC* is further verified.



(a) (b)

Figure 9. Numerical simulation results. a Distribution of tunnel plastic zone; b Schematic of rockburst block ejection

In conclusion, numerical simulations were carried out based on the rockburst engineering case that occurred in the Sangzhuling Tunnel, it can be obtained from the simulations that the simulation results are consistent with the rockburst situation on the site, the rockburst tendency of surrounding rock can be roughly evaluated to a certain extent, which verifies the rationality of the *REC* and simulation method of the rockburst based on the 3D discrete element numerical simulation platform, it further reflects the good engineering applicability of the *REC*. Because the criterion and grading standards proposed in this paper are only preliminary conclusions based on theoretical analysis, there are certain limitations and errors. Therefore, to further study whether the criterion proposed in this paper is universal, the other engineering rockburst cases need to be carried out to verify.

4 CONCLUSION

In this paper, the significant factors that affect the rockburst development process in tunnels are comprehensively considered as the control factors for the prediction of the rockburst tendency. According to the energy conversion and overall failure mechanism in the rock failure process, a new multi-parameter rockburst tendency criterion is proposed by adequately considering the stress state of the rock unit under the path of tension and compression respectively. The calculation and numerical simulation of typical rockburst cases are carried out to obtain the following conclusions.

(1) Summarize and analyze typical rockburst tendency criteria and intensity classification by comprehensively considering the rock mechanical properties, the surrounding rock properties, and the advantages of comprehensive indexes. The mechanical factor (σ_c / σ_t), brittleness factor (σ_θ / σ_c), integrity factor (K_v), and the rock energy storage factor (U^e / U_0) are selected as the main control factors of tunnel rockburst evaluation index.

(2) According to the energy conversion and overall failure mechanism in the process of the rock failure, fully considering the above control factors, a new rockburst criterion and its intensity classification under different stress states are established. The criterion is simple and practical, and the physical meaning of the relevant factors is clear. Its mathematical expression is the product of multiple rockburst main control factors, which is conducive to the understanding of the on-site construction personnel.

(3) The calculation and verification of typical rockburst engineering cases show that the results of rockburst prediction in actual engineering based on the rockburst criterion proposed in this paper are approximately consistent with the actual rockburst intensity on the site, which can reasonably and quantitatively determine the rockburst occurrence during the construction of deep underground engineering, and has good engineering applicability.

(4) During the process of numerical simulation in the Sangzhuling tunnel, the distribution characteristics of the criterion threshold value are consistent with the distribution characteristics of principal stress difference and elastic strain energy density of the tunnel surrounding rock. There is a strong rockburst tendency in the right position of the tunnel vault, which is more consistent with the rockburst situation on the site. To a certain extent, the *REC* can be used to roughly evaluate the rockburst tendency of the surrounding rock.

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6 CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper.

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