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Rockburst proneness criteria for rock materials: Review and new insights

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Abstract: To review the rockburst proneness (or tendency) criteria of rock materials and compare the judgment accuracy of them, twenty criteria were summarized, and their judgment accuracy was evaluated and compared based on the laboratory tests on fourteen types of rocks. This study begins firstly by introducing the twenty rockburst proneness criteria, and their origins, definitions, calculation methods and grading standards were summarized in detail. Subsequently, to evaluate and compare the judgment accuracy of the twenty criteria, a series of laboratory tests were carried out on fourteen types of rocks, and the rockburst proneness judgment results of the twenty criteria for the fourteen types of rocks were obtained accordingly. Moreover, to provide a unified basis for the judgment accuracy evaluation of above criteria, a classification standard (obtained according to the actual failure results and phenomena of rock specimen) of rockburst proneness in laboratory tests was introduced. The judgment results of the twenty criteria were compared with the judgment results of this classification standard. The results show that the judgment results of the criterion based on residual elastic energy (REE) index are completely consistent with the actual rockburst proneness, and the other criteria have some inconsistent situations more or less. Moreover, the REE index is based on the linear energy storage law and defined in form of a difference value and considered the whole failure process, and these superior characteristics ensure its accuracy. It is believed that the criterion based on REE index is comparatively more accurate and scientific than other criteria, and it can be recommended to be applied to judge the rockburst proneness of rock materials.

Key words: deep rock; rockburst; rockburst proneness; rockburst proneness criterion; rock mechanics

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1 Introduction

With the continuous development and utilization of underground space and mineral resources, more and more underground rock projects are being constructed at increasing depths [1−4]. During the excavation of deep buried caverns or tunnels, many unconventional surrounding rock failure phenomena are often encountered, such as spalling (or slabbing) [5−7], rockburst [8−10]. Different from spalling failure, rockburst is a dynamic geological disaster of deep rock mass, which is usually caused by the sudden and violent release of elastic strain energy stored in rock [9−12]. Due to the massive damage caused by rockburst, more and more attentions have been drawn to the research on rockburst in the past

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Table 1 Summary of twenty criteria calculation principles and their grading standards of rockburst proneness

No.	Criterion for rockburst proneness	Calculation formula	Parameter of formula	Grade of rockburst proneness					
				No	Existence				
					Very low	Low (Slight)	Medium (Moderate)	High (Heavy)	Very high
1	Strain energy storage index W_{ET} [35, 36]	$W_{ET}=\frac{U_{ET}^{e}}{U_{ET}^{d}}$	U_{ET}^{e} and U_{ET}^{d} are the elastic strain energy density and dissipated energy density at the unloading level, respectively.	<2.0	—	2.0–4.99	—	>5.0	—
2	Energy impact index A_{CF} [37]	$A_{CF}=\frac{U^{o}}{U^{a}}$	U^{o} and U^{a} are the pre-peak total input energy density and the post-peak failure energy density, respectively.	<1.0		1.0–2.0		>2.0	—
3	Potential energy of elastic strain PES/(kJ·m^{-3}) [38, 39]	$\mathrm{PES}=\frac{\sigma_c^2}{2E_s}$	σ_c and E_s are the uniaxial compression strength and the unloading tangential modulus, respectively.	—	≤ 50	50–100	100–150	150–200	>200
4	Strain energy storage index modified W_{ET} [40]	$W_{ET}=\frac{U_{ET}^{e}}{U_{ET}^{d}}$	U_{ET}^{e} and U_{ET}^{d} are the elastic strain energy density and dissipated energy density at the unloading level, respectively.	<2.0	—	2.0–3.5	3.5–5.0	>5.0	—
5	Peak-strength energy impact index A'_{CF} [41]	$A'_{CF}=U^e/U^a$	U^e and U^a are the peak elastic strain energy density and post-peak failure energy density, respectively.	<2.0		2.0–5.0		>5.0	—
6	Peak-strength strain energy storage index W^{P}_{ET} [42]	$W_{ET}^{P}=\frac{U^{e}}{U^{d}}$	U^e and U^d are the peak elastic strain energy density and the peak dissipated energy density, respectively.	<2.0	—	2.0–5.0	—	>5.0	—
7	Effective energy impact index W [43]	$W=A_{CF}\times\frac{W_{ET}}{1+W}$	W_{ET} and A_{CF} are the strain energy storage index and energy impact index, respectively.	<1.8	—	—	1.8–2.8	>2.8	—
8	Energy formula of rockburst E(J) [44]	$E=W_E=2\times w_e\times V$	W_E is the work done by the pressure, w_e is the pre-peak elastic energy density, and V is the volume of the specimen.	<15.7	—	—	15.7–39.25	39. 25–78. 5	>78. 5
9	Rockburst energy index B_q [45]	$B_q=\frac{U_q^e}{U_q^e+U^a}$	U_q^e represents the elastic strain energy density, and U^a denotes the failure energy density.	0–0.20	—	0.20–0. 50	0.50–0. 80	0.80–1. 00	—
10	Surplus energy index W_R [46]	$U_R^e=U^o\times\omega_R$, $W_R=\frac{U_R^e-\lvert U^a\rvert}{\lvert U^a\rvert}=\frac{\Delta W}{\lvert U^a\rvert}$	ω_R is the proportion of the elastic strain energy density to the input energy density at the level of 80% of peak strength; U^o represents the pre-peak total input energy density; U_q^e represents the peak elastic strain energy density; U^a represents the post-peak failure energy density; and ΔW represents the surplus energy density.	<0	≥ 0				
11	Residual elastic energy index A_{EF}/(kJ·m^{-3}) [41]	$A_{EF}=U^e-U^a$	U^e and U^a are the peak elastic strain energy density and the post-peak failure energy density, respectively.	<50	—	50–150	150–200	>200	—
12	Peak-strength potential energy of elastic strain PES^{P}/(kJ·m^{-3})	—	—	<100	—	100–200	200–300	>300	—
13	Brittleness index modified BIM [47, 48]	$\mathrm{BIM}=\frac{U^{o}}{U_{BIM}^{o}}$	U_{BIM}^{e} and U^o are the peak elastic strain energy density and the pre-peak total input energy density.	—	—	>1.5	1.2–1.5	1.0–1.2	—
14	Deformation brittleness index K_u [49]	$K_u=\frac{u}{u_1}=\frac{\varepsilon_p+\varepsilon_e}{\varepsilon_p}$	u and u_1 are the total deformation and permanent deformation; ε_p and ε_e are the plastic strain and the elastic strain, respectively.	<2.0	—	2.0–6.0	6.0–9.0	>9.0	—

to be continued

Continued

No.	Criterion for rockburst proneness	Calculation formula	Parameters of formula	Grades of rockburst proneness					
				No	Existence				
					Very low	Low (Slight)	Medium (Moderate)	High (Heavy)	Very high
15	Brittleness index of rockburst proneness B [50]	$B=\alpha\times\frac{\sigma_c}{\sigma_t}\times\frac{\varepsilon_f}{\varepsilon_b}$	α is an adjustable parameter that is usually taken as 0.1; σ_c and σ_t are the uniaxial compressive strength and uniaxial tensile strength, respectively; ε_f and ε_b are the pre-peak total strain and post-peak total strain, respectively.	<3.0	—	3.0–5.0	—	>5.0	—
16	Strength brittleness index B_1 [38, 51]	$B_1=\frac{\sigma_c}{\sigma_t}$	σ_c and σ_t are the uniaxial compressive strength and tensile strength, respectively.	<14.5	—	14.5–26.7	26.7–40	>40	—
17	Strength brittleness index B_2 [49]	$B_2=\frac{\sigma_c}{\sigma_t}$	σ_c and σ_t are the uniaxial compressive strength and tensile strength, respectively.	<10	—	—	10–18	>18	—
18	Strength brittleness index B_3 [40]	$B_3=\frac{\sigma_c}{\sigma_t}$	σ_c and σ_t are the uniaxial compressive strength and tensile strength, respectively.	<15	—	15–18	18–22	>22	—
19	Decrease modulus index DMI [52, 53]	DMI=$E_G/\lvert E_M\rvert$	E_G is the pre-peak deformation modulus, and E_M is the post-peak deformation modulus.	>1.0	≤1.0				
20	Lag time ratio index T_R [54]	$T_R=T_1/T_b$	T_1 is the interval time between the peak strength point and S-R point and is marked as the lag time, and T_b is the time of the whole loading period.	>0.25	—	0.20–0.25	0.15–0.20	<0.15	—

2.1 Strain energy storage index (W_{ET})

W_{ET} [35, 36] is a typical bursting proneness discriminant criterion for rocks, and is widely involved in many literatures [57−59]. The value of W_{ET} can be obtained according to the single loading−unloading uniaxial compression test, where the unloading level (the ratio of unloading point stress to the uniaxial compressive strength) ranges from 0.8 to 0.9, as shown in Figure 1.

It is defined as the proportion of the elastic strain energy density to the dissipated energy density at the corresponding unloading level. The formula for calculating the criterion is as follows:

$$U_{ET}^{e}=\int_{\varepsilon_0}^{\varepsilon_1^k}\sigma\mathrm{d}\varepsilon \tag{1}$$

$$U_{ET}^{o}=\int_{0}^{\varepsilon_1^k}\sigma\mathrm{d}\varepsilon \tag{2}$$

$$U_{ET}^{d}=U_{ET}^{o}-U_{ET}^{e} \tag{3}$$

$$W_{ET}=\frac{U_{ET}^{e}}{U_{ET}^{d}} \tag{4}$$

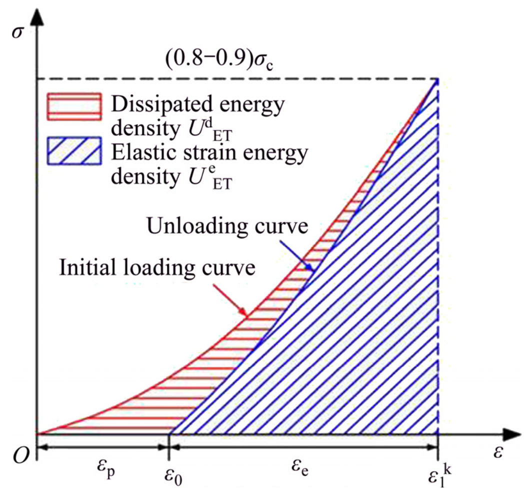

Figure 1 Calculation diagram of W_{ET} and K_u

where U_{ET}^{o}, U_{ET}^{e} and U_{ET}^{d} are the input energy densities, the elastic strain energy density and dissipated energy density at the corresponding unloading level, respectively; ε_1^k and ε_0 are the strain at the corresponding unloading level, and the residual strain when the stress is unloaded to 0, respectively.

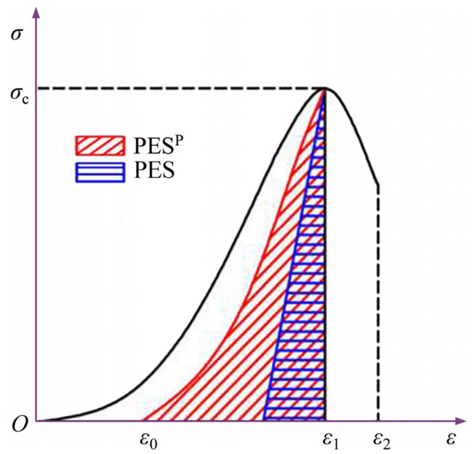

Figure 24 Comparison of PES and PES^P

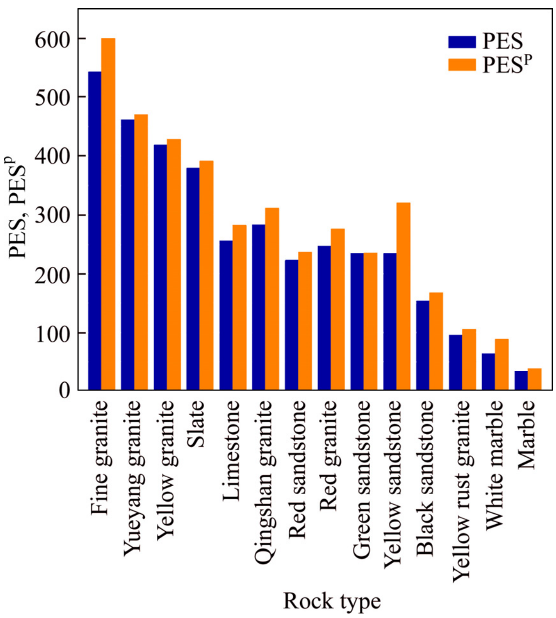

Figure 25 Comparison of PES and PES^P according to tests for fourteen rock materials

to calculate the peak elastic strain energy are more scientific and accurate. Among the summarized twenty criteria, A_{EF} meets all of the above characteristics, which indicates A_{EF} is a scientific and reliable rockburst proneness criterion.

7 Conclusions

1) Twenty criteria for rockburst proneness were summarized in detail, including their origins, definitions, calculation methods and grading standards. The detailed summaries provide convenience for evaluating the rockburst proneness of rock materials.

2) The judgement results of the twenty criteria were obtained by a series of laboratory tests on fourteen types of rocks. The results show that different criteria have diverse judgment results even for the same rock type, which implies the accuracy of them is worth evaluating and comparing.

3) The judgement accuracy of the twenty criteria was evaluated based on a classification standard for the rockburst proneness in laboratory tests (S_r) obtained from qualitative and quantitative aspects according to the practical test phenomena. The result shows that the judgment results of A_{EF} are completely consistent with the actual rockburst proneness. In contrast, all the other criteria have some inconsistencies.

4) The characteristics of the criteria were analyzed. The results show that the criteria that are energy-based, defined in the form of a difference value, involving the whole rock failure process, and based on precise methods to calculate parameters are more scientific and can evaluate the rockburst proneness accurately. A_{EF} meets all these characteristics, which further demonstrates the superiority of A_{EF}. Thus, we conclude that A_{EF} is relatively more accurate and scientific than other criteria and it is recommend to evaluate the rockburst proneness of rock materials.

Contributors

GONG Feng-qiang provided the idea of the study, developed the overarching research goal, and led the research activity planning and execution. GONG Feng-qiang also made great contribution to the improvement of manuscript after the initial draft finished. WANG Yun-liang conducted the experiments, analyzed the test data, and wrote the initial draft of the manuscript. LUO Song offered some valuable suggestions for the contents of the manuscript and polished the language of the manuscript. All authors replied to reviewers' comments and revised the final version.

Conflict of interest

GONG Feng-qiang, WANG Yun-liang and LUO Song declare that they have no conflict of interest.

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中文导读

岩石材料的岩爆倾向性判据研究：综述与新观点

摘要：为了对岩石材料的岩爆倾向性判据的判别准确性进行综合比较，本文归纳了现有的 20 种岩爆倾向性判据，并利用 14 种岩石进行了一系列实验室测试，根据试验结果综合评估这 20 种岩爆倾向性判据的判别准确性。文中首先详细介绍了 20 种岩爆倾向性判据，包括其文献出处、定义、计算方法和具体的判据分级标准。随后，对 14 种岩石进行了一系列的实验室测试，包括单轴压缩试验、一次加卸载单轴压缩试验和巴西劈裂试验等，利用所得试验数据计算了 20 种判据针对每种岩石的岩爆倾向性判别结果。此外，为了统一评估上述判别结果的准确性，引入了一种基于室内实验室测试岩石试样破坏结果和现象的岩爆倾向性分级标准。将依据该分级标准得出的各岩石的实际岩爆倾向性与 20 种判据的判别结果进行对比，结果表明，基于剩余弹性能指数这一判据的判别结果与 14 种岩石的实际岩爆倾向性完全一致，其他判据的结果均存在误判的情况。剩余弹性能指数以线性储能规律为基础，而且以差值的形式进行定义，并考虑了岩石破坏全过程的能量转化。上述特点确保了其判别准则的科学性和准确性。根据以上分析可以得出，基于剩余弹性能指数的岩爆倾向性判据相对于其他判据更加科学、准确，在对岩石材料的岩爆倾向性进行评价时推荐优先使用该判据。

关键词：深部岩石；岩爆；岩爆倾向性；岩爆倾向性判据；岩石力学