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Research Article

Damage Evaluation for Rock Burst Proneness of Deep Hard Rock under Triaxial Cyclic Loading

Shuang You ,[1,2] Hongguang Ji,[1] Zijian Zhang,[1] and Chenghan Zhang[1]

[1] *School of Civil and Resources Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[2] *NBK Institute of Mining, The University of British Columbia, Vancouver, BC, Canada*

Correspondence should be addressed to Shuang You; shuang_you@163.com

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High stress and strong excavation disturbance are the main causes of dynamic disasters, rock burst in deep hard rocks, and are more frequent and violent than those in shallow, which seriously restricts the deep mining. Given rock burst encountered in deep mining of Lingnan metal mines, the optimized triaxial cyclic loading and unloading tests are designed to characterize the performance of rock failure and to evaluate the rock burst proneness. The correlation between elastic energy index and damage evolution is built, and rock burst proneness in each status is analyzed; furthermore, the dissipation energy in the failure process of deep rocks is explicated. In this paper, the law that the elastic energy index via damage increases is drawn. In terms of the dynamic disaster conditions in the deep rock, the identification approach for the damage zone of the rock burst is established.

1. Introduction

The energy in the rocks of underground mining includes the stored elastic energy and the dissipated energy produced by the loading/unloading process [1]. Stress redistribution during the galleries excavation induces changes in elastic energy and dissipated energy of the rocks; elastic energy is mainly accumulated by the elastic strain of the rock, and rock burst occurs when the stored elastic energy exceeds the storage limit [2], so it needs to determine the stress and elastic energy storage characteristics of surrounding rocks in a gallery to evaluate the proneness of rock burst [3]. Dissipated energy is mainly consumed by crack expansion at the prepeak stage, which is closely related to the accumulation of elastic energy, and the energy released by the elastic stress decreases at the postpeak stage, which determines the strength of the rock burst [4].

The analytical method of elastic-plastic mechanics always uses stress-strain to describe mechanical characteristics in the failure process of rocks, establishing the constitutive equation and strength theory of rocks [5–7]. Due to variable external loading conditions and inhomogeneous organizational structures of rocks which have led to nonlinear characteristics of the stress-strain relationship, it is difficult to establish the strength criterion of rocks solely relied on stress-strain [8]. Furthermore, the energy dissipation is an irreversible process in the deformation and failure of rocks. External loading on rocks changes the stress-strain state of rocks (stored elastic energy) and also affects the rock damage state (dissipated energy) [9]. Mutual effects of the external and internal stress make the deformation and failure process of rocks complicated, so it is not appropriate to simply use the degree of stress or strain as the failure criterion. Moreover, rock strength usually exhibits the discreteness, and the failure of rocks is an instability phenomenon driven by energy. Therefore, if the strength theory of rocks is established based on the energy transfer and conversion as the failure criterion, it is more suitable to analyze the rock failure mechanism in field.

Cook et al. [10] proposed the energy theory of rock burst in the 1960s arguing that if the energy released by the surrounding rock system when its mechanical equilibrium is destroyed and is greater than the energy consumed, rock burst will occur. In the 1970s, Brauner [11] put forward the theory of the energy rate. This theory was based on the law of conservation of energy, got rid of the constraints of traditional theories, and solved the energy problem of rock burst.

In China, Li et al. [12] studied the criterion of fault instability in the form of energy. Zhang [13] further proposed a similar theory of rock burst instability. Tang [14] presented an energy index of rock burst from the perspective of the stress-strain curve of rocks. However, the existing energy theory lacks the quantitative index and makes it difficult to determine the scope of the surrounding rock related to the rock burst destroyed in field and hard to calculate the energy involved in rock burst.

2. Experimental Progress

Surrounding rocks are the equilibrium states that are formed after destruction through tectonic movements. The mechanical properties exhibited by the surrounding rock are actually the postpeak strength characteristics, it is a loading/unloading process on the surrounding rock during the excavation, and the surrounding rock exhibits different postpeak characteristics under different loading and unloading paths. In this paper, the damage parameters of rock are studied under different postpeak stress paths.

Samples are selected from the Lingnan gold mine at the depth of about 1,000 m, and the diameter of the specimen is 50 mm with the height of 100 mm. The triaxial cyclic loading and unloading tests use the TAW-2000 servorock triaxial testing machine. The axial and hoop extensometers are used to measure the deformation of rocks. In the process of the tests, the load-unload cycles are controlled by the strain. First, the initial axial deformation reaches to 100 μm; the axial load decreases to 0.1 MPa; and then the axial loading increased by 100 μm again, and the axial also unloaded to 0.1 MPa, the cyclic loading test stopped till a rock failure. Confining pressures 1, 5, 10, 20, and 30 MPa were separately conducted in the triaxial compression load-unload cycle tests. The servopressure machine is controlled by the deformation with a loading rate of 0.01 mm/min and an unloading rate of 0.04 mm/min.

3. Damage Analysis Theories of Rock Burst Proneness

3.1. Damage Parameters Selection. Vermeer and De Borst [15] proposed the strength of the rock affected by the dilatancy angle, and the dilatancy angle is a plastic deformation parameter, so the relationship between rock strength and plastic deformation can be inferred. Martin [16] used plastic volumetric strain to describe the occurrence of damage. The plastic shear strain can also express the damage of the rock and facilitate the acquisition of data in the laboratory, which is calculated as follows:

$$\gamma_p = \varepsilon_1^p + \varepsilon_3^p, \quad (1)$$

where γ_p is the plastic shear strain, ε_1^p is the maximum plastic strain, and ε_3^p is the minimum plastic strain.

The damage point corresponds to the reloading of the point after unloading to the peak stress at this point [17], which is more applicable in stress analysis; especially after determining the zero damage stress point, a complete circuit can be formed with the unloading point as the starting point, but this is not applicable in the determination of energy dissipation; and if the preunloading point is taken as a reloading point, it can reach the peak stress, which is a completely different way in energy analysis, and the damage points can be determined as follows: (i) it is essential to discuss the ratio of the loading energy and the unloading energy to judge the rock burst tendency of rock, and a complete loading and unloading curve is particularly important; (ii) the unloading point is used as the damage parameter, which can determine the damage of the rock during the whole loading process; and (iii) due to the damage accumulation, the data points after unloading are used as the damage parameters, and the cumulative damage will be reflected in the damage parameters after unloading (Figure 1).

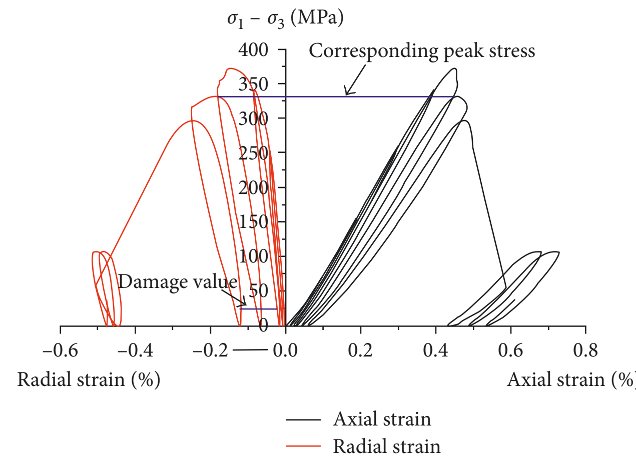

Figure 1: Diagram of damage value determination.

Through more load-unload cycles are performed in the laboratory experiments, the curves can be fitted through denser points, and then the rock burst proneness can be achieved through the interpolation points.

3.2. Energy Computation in the Process of Rock Failure. Accurately computing the energy accumulation and dissipation will increase the accuracy of predicting rock burst. In the triaxial equal confining pressure tests, the damage energy is mainly input by the mechanical loading system, which converted into the internal energy of rocks, and can be evaluated as follows [18]:

$$U = \int \sigma_1 \, d\varepsilon_1 + 2 \int \sigma_3 \, d\varepsilon_3. \quad (2)$$

Due to continuous loading, some are stored as elastic energy U_e inside the rocks (3), which induced rocks to change into an instability state with higher internal energy, and others are released as dissipated energy U_d (4) with the defects and cracks extension [19, 20]:

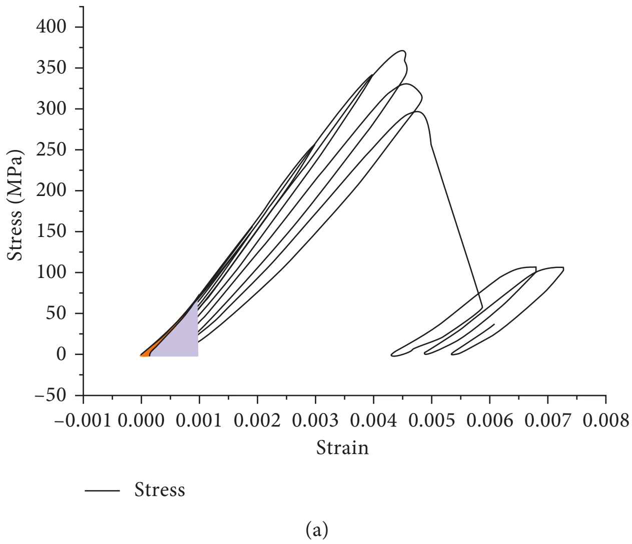

Figure 2: A diagram of the elastic energy index.

$$U_e = \frac{1}{2E_i}\left[\sigma_1^2 + 2\sigma_3^2 - 2\nu_i\left(2\sigma_1\sigma_3 + \sigma_3^2\right)\right], \tag{3}$$

$$U_d = U - U_e, \tag{4}$$

where ε_1 is the axial strain of rocks; ε_3 is the radial strain of rocks, and $\varepsilon_3 = -\nu\varepsilon_1$, in which ν is the Poisson ratio; σ_1 is the maximum principal stress; σ_3 is the minimum principal stress; E_i is the unloading elastic module of the i point; and ν_i is the Poisson ratio.

3.3. Analysis of Rock Burst Proneness Based on the Elastic Energy Indicator. Elastic energy index is used as an indicator describing the state of rock burst [21, 22], which is the ratio of the elastic energy to the dissipated energy. In the cyclic load-unload cycles, the elastic energy index of rocks under different damages is analyzed, which can be applied as a process quantifier to predict rock burst in the process of loading, as shown in the following equation:

$$W_{et} = \frac{U_e}{U_d}. \tag{5}$$

At the ascending stage of the elastic energy index, microcracks are compacted in rocks, internally dissipated energy is relatively small, and the rock burst will not occur at this stage. At the descending stage of the elastic energy index, the dissipated energy increases, and the elastic energy accumulates constantly due to the higher elastic energy index (Figure 2).

4. Damage Evaluation of Rock Burst Proneness under Triaxial Load-Unload Cycling Tests

4.1. The Influence of Confining Pressure on Damage Energy of Rocks. The residual properties of failure rock cannot be ignored on the analysis of the state of rock burst. In this paper, the relationship among the damage parameters, elastic energy, and dissipated energy are explicated to analyze damage evolution of hard rocks. In the laboratory tests, the process of the load-unload cycles after rock failure are designed, the occurrence of rock burst could be judged by the computation of energy accumulation and dissipation, and the elastic energy indicator can be compared in different rock burst prone conditions. Figure 3 shows the stress-strain curve under different confining pressures under the triaxial load-unload cycles of hard rock. The peak stress is 229.81 MPa, 321.99 MPa, 382.24 MPa, 500.14 MPa, and 583.73 MPa with confining pressures of 1 MPa, 5 MPa, 10 MPa, 20 MPa, and 30 MPa separately. The corresponding damage energy U is 488.9 kJ/m^3, 783.7 kJ/m^3, 1202.4 kJ/m^3, 1710.1 kJ/m^3, and 2130.0 kJ/m^3.

According to the linear fitting of the confining pressure and the peak stress (Figure 4), the fitting correlation coefficient is 0.968, the internal friction angle is 57°, and the cohesive force is 38.07 MPa.

The axial pressure does positive work, the confining pressure does negative work, the combined effect of them is the total work performed by the testing machine on the rock samples, which means that damage energy per unit volume of rocks increases obviously and keeps a certain linear relationship with the confining pressure, and the fitting curve of confining pressure and damage energy of rocks is shown in Figure 5, the correlation coefficient is 0.976, and the fitting equation is calculated as follows:

$$U = 56\sigma_3 + 521. \tag{6}$$

Figure 6 shows the approximately linear relationship between dissipated energy and shear strain in a cycle of the rock. It indicates that the change of the plastic shear strain is positively related to the dissipated energy. The damage increases continuously with the loading of the stress. The energy dissipated inside the rock also increases accordingly. It also exhibits the uniqueness and irreversibility of the damage.

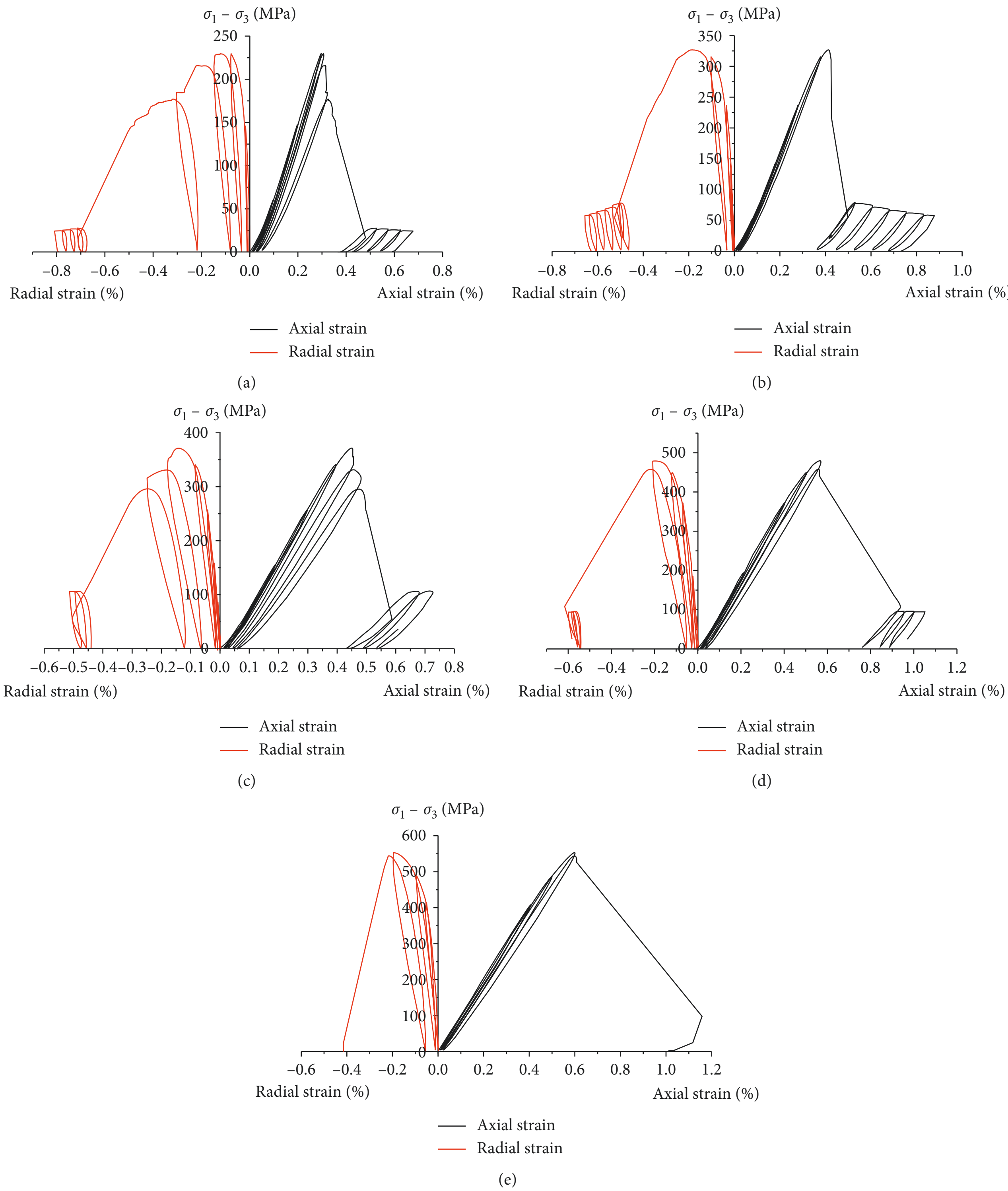

FIGURE 3: Stress-strain curve of deep rock under different confining pressures in triaxial cyclic loading-unloading tests: (a) 1 MPa; (b) 5 MPa; (c) 10 MPa; (d) 20 MPa; (e) 30 MPa.

From the above analysis, it indicates the confining pressure limits the sliding friction inside the rocks, and it needs to consume more energy to produce the conjugate shear surface under high confining pressure.

4.2. The Rock Burst Proneness under Triaxial Cyclic Loading-Unloading Process. In order to obtain the damage energy from the testing machine, the elastic energy and dissipated energy of rocks corresponding to different damage levels of

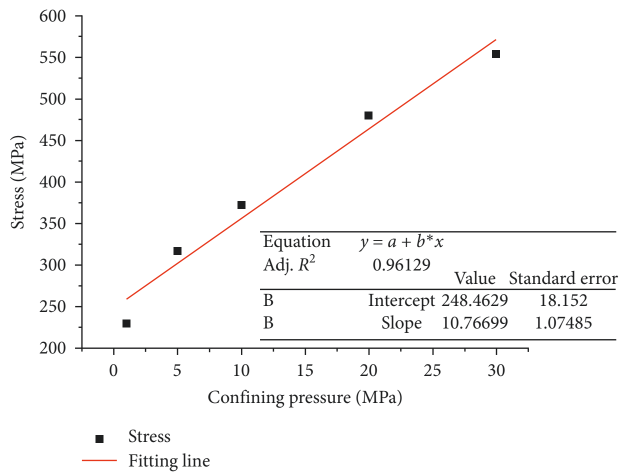

Figure 4: Confining pressure and peak stress of rocks fitting curve.

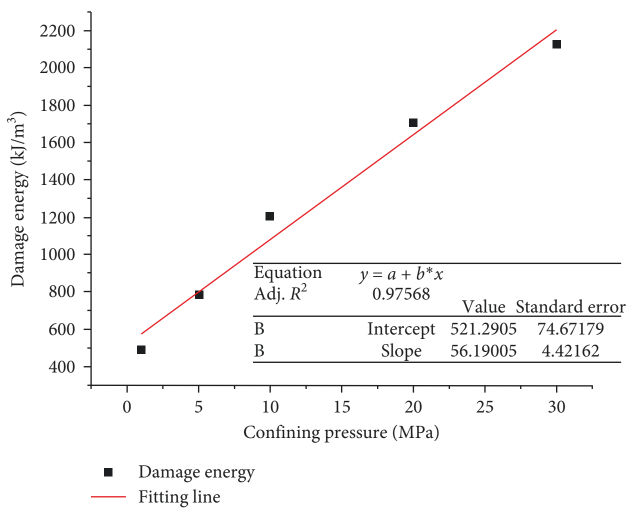

Figure 5: Confining pressure and damage energy of rocks fitting curve.

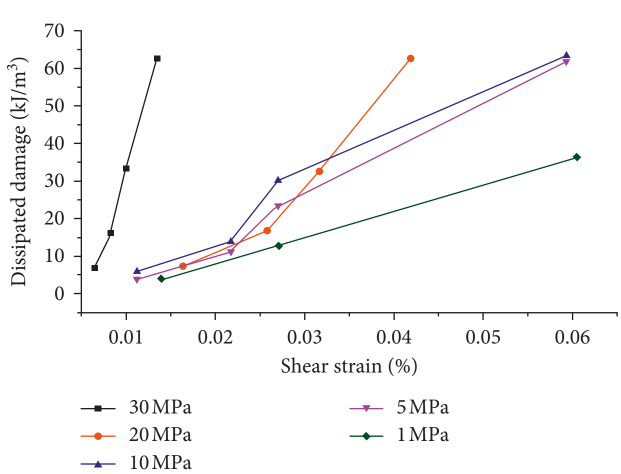

Figure 6: Relationship between shear strain and dissipated energy under different confining pressures.

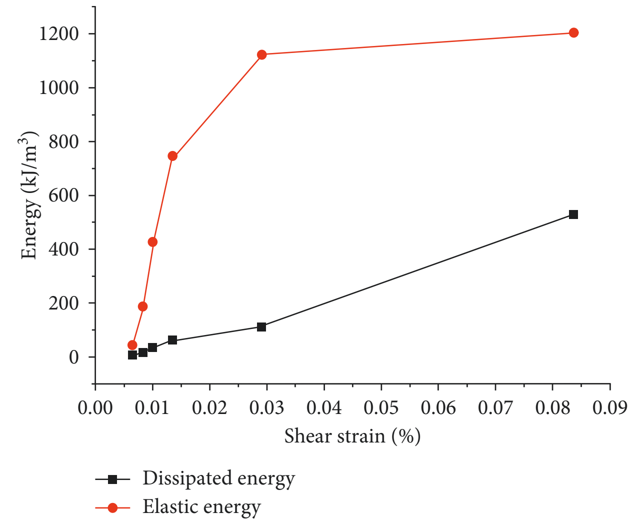

Figure 7: The elastic energy and damage energy corresponding to different damage points at each shear strain under the confining pressure of 30 MPa.

rocks and the cyclic loading and unloading triaxial tests are carried out. The elastic energy and damage energy corresponding to different damage points at each unloading point are drawn in Figure 7. Figure 8 is drawn to analyze the changes of the elastic energy indicator caused by the damage under different confining pressures accompanied by the loading process.

During the cyclic loading-unloading tests, the elastic and dissipated energy of rocks can be calculated after the each cycle. Therefore, the elastic energy indicator of rocks can be calculated by the previous cycle when the failure occurs. Figure 8 is the fitting curve of the plastic shear strain (expressed as the rock damage) and elastic energy index under different confining pressures, it shows that there is an increase and then decrease of the elastic energy indicator in the compression damage process of rock, and the peak elastic energy indicator reaches above 10. When the elastic energy indicator is rising, the elastic energy of rocks increases rapidly with less dissipated energy, which is mainly due to rocks being in the elastic stage, and the internal energy dissipation mainly focuses on crack compactness. When keeping on loading, the elastic energy indicator decreases, dissipated energy plays a key function, microcracks in rocks begin to be integrated gradually, and the damage in rocks continues to increase. When the dissipated energy reaches a certain value under the loading, cracks inside rocks are integrated, and rocks are failed as rocks exceed its bearing capacity. In addition, sufficient elastic energy is stored before failure as the strong energy storage ability of rocks and stored elastic energy will be released intensely when rocks are cracked by the dissipated energy.

The point when the rock burst occurs is not the peak of stress. Rocks cannot bear the pressure from the testing machine at the peak value due to internal damage; so, this dissipation energy is not enough for rock failure. If the

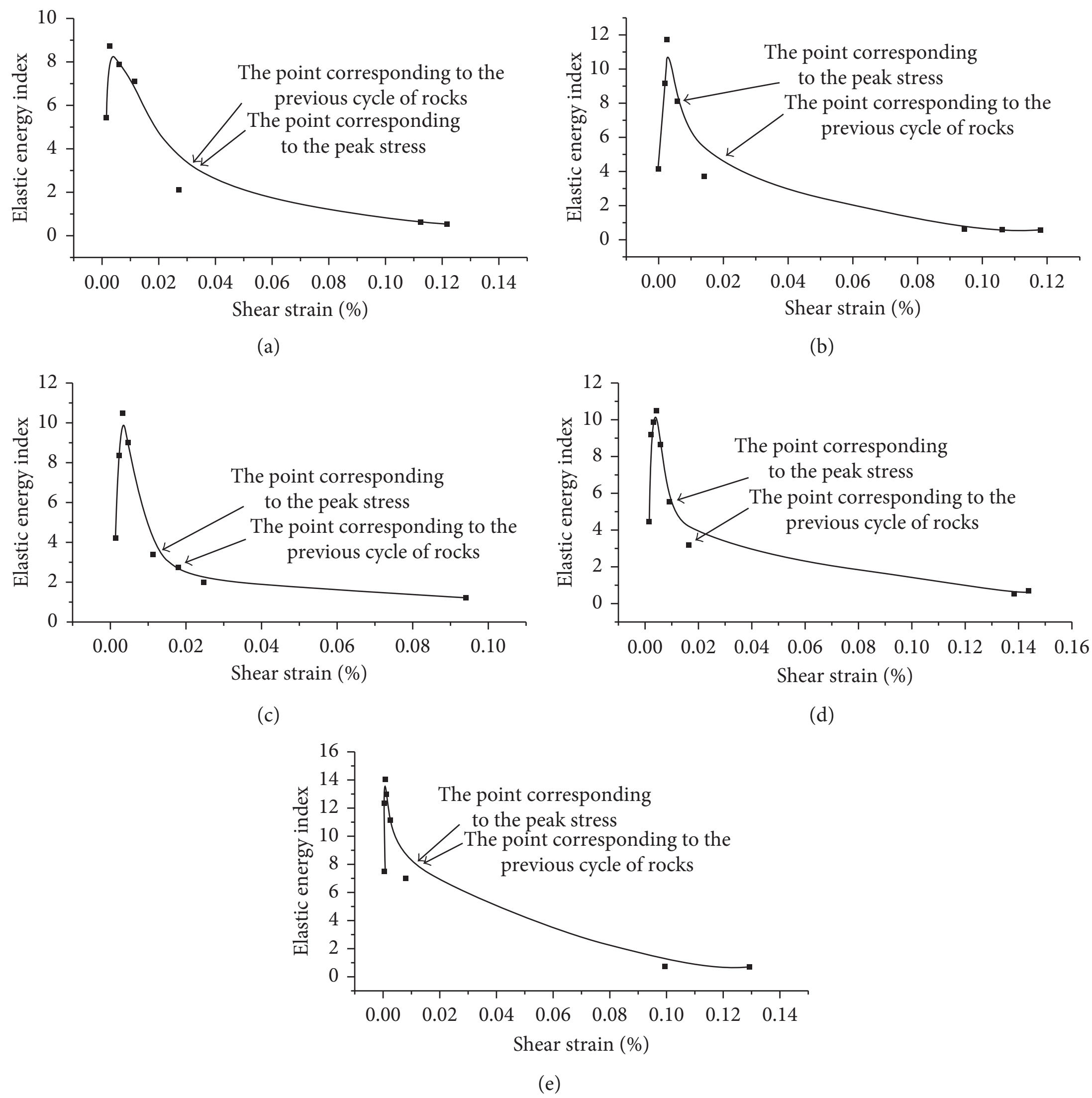

Figure 8: Fitting curve of plastic shear strain and elastic energy index under different confining pressures: (a) 1 MPa; (b) 5 MPa; (c) 10 MPa; (d) 20 MPa; (e) 30 MPa.

dissipated energy is enough for rock burst, the stored elastic energy is released abundantly and rock burst will occur.

4.3. The Range of Rock Burst Based on the Elastic Energy Index. Figure 8 shows the elastic energy index before the rock burst is within the range of 3–6 at the descending stage of the cyclic loading and unloading experiments, so this range is defined as the dangerous area of rock burst in the Lingnan gold mine. The following indicators can be obtained as follows:

$$W_{et} = \begin{cases} \text{Ascending stage,} & \text{slightly,} \\ \text{Descending stage} \begin{cases} 3 \le W_{et} \le 6, & \text{moderatly,} \\ W_{et\,max} \ge 10, & \text{strongly.} \end{cases} \end{cases} \tag{7}$$

Equation (7) connects the elastic energy index of rock burst with the loading and unloading process of rocks. It can be used to analyze rock damage and the relative changes in the energy of rocks at all stages of mechanical loading. It can be summarized as (i) rocks have strong rock burst proneness if $W_{et\,max} \ge 10$; (ii) rocks keep a constant energy input due to the damage during loading; (iii) rocks have enough dissipated energy to make crack extension at the descending stage, and the dissipated energy of rocks gradually increases; and (iv) rocks have sufficient elastic energy to support rock burst, and the elastic energy index ranges in $3 \le W_{et} \le 6$; although dissipated energy increases at this stage, the relatively high elastic energy index can still provide enough elastic energy for the release of energy-induced rock burst.

5. Conclusions

The rock burst proneness in the deep rock is relatively high, which can store more elastic energy before damage, resulting in a higher intensity of destruction. Through the optimization of the triaxial cyclic loading-unloading compression tests, with the correlation analysis of the elastic energy index and the damage parameter characterizing rock burst proneness, the results show that the elastic energy index increases as damage increases. In terms of the occurrence conditions of rock burst in the deep rock of the Lingnan gold mine, the rock burst prone conditions are discussed, and the elastic energy index ranges from 3 to 6 at the descending stage, its high proneness for rock burst. It would be an effective method to judge the rock burst for the surrounding rock in the mine.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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