Relationship of rockburst and energy dissipation characteristics of brittle rock at great depth

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Abstract. Rockburst is defined as a major geological disaster of hard rock mass. At present, rockburst analysis mostly focuses on its mechanism, prediction, and preventive measures, and great progress has been made. However, a few comprehensive analyses on the rockburst mechanism still need to be investigated from different energy perspectives. From the energy perspective, this study analyzes the relationship between a rockburst and the destructive properties of T2b marble in the deep buried tunnel of the Jinping Secondary Hydropower Station. Our analysis includes strain energy accumulation and dissipation, shear fracture, energy release, and acoustic emission (AE). The obtained results show that in the energy release and dissipation processes, three dilatancy mechanisms trigger a rockburst, namely the tensile fracture extension control mechanism, closed fracture friction control mechanism, and their mutual transformation compound control mechanisms. Different mechanisms lead to different energy mutation patterns that determine the rockburst extent and scale. We also found that the strain energy of brittle rocks linearly increases with the increase of the confining pressure during the failure of the brittle rocks. The energy storage rate of the front peak at the lower confining pressure was significantly greater than that of the back peak. However, the difference gradually decreases as the confining pressure increases. The total shear fracture energy with the increase of the confining pressure first increases and then decreases. The peak before the shear fracture energy nonlinearly increases gradually, and the two fractures can be similar until the brittle–ductile transition. Lastly, the AE experiment shows that during the addition and unloading of brittle rocks at a great depth, three types of energy active periods and three types of energy decay periods are observed. The precursor to an instantaneous rockburst is the second type of energy fading period, while that to a delayed rockburst is the third type of energy fading period. The second type of energetically active period refers to the birth of a rockburst. The third type refers to the occurrence of a standard rockburst or a recurrence, such as a discontinuous rockburst.

Keywords: rockburst, strain energy accumulation and dissipation, dilatancy mechanism, shear fracture energy.

1 Introduction
In southwestern China, deep-cut river valleys are developed, and geological tectonic movements are intense. With the construction of many underground projects in this area, the rock mass is put at a very high stress level under the combined action of tectonic and self-weight stresses when the buried depth
of the project is large. This makes the area prone to engineering problems, such as rockbursts, landslides, splitting, and spalling, which seriously threaten the safety of on-site personnel and mechanical equipment and affect the project’s progress. The rockburst mechanism is complicated because it has many influencing factors and is also difficult to accurately predict. Hence, it has become one of the hottest and most difficult problems to solve in the field of underground engineering with a large buried depth.

In this regard, many scholars have conducted long-term in-depth studies. For one, Feng et al. analyzed various technical means to study the developmental process of rockbursts. These included laboratory-scale and physical model tests, numerical simulations, comprehensive on-site inspections, and on-site monitoring, which revealed the developmental mechanisms of different rockburst types and the microseismic evolution of the rockburst development caused by these excavation methods[1]. The acoustic emission test of the granite rockburst process under true triaxial loading conditions was also performed using a true triaxial rockburst test system, and the spatio-temporal evolution of the acoustic emission during the rockburst process was revealed as a result (Su et al., 2019)[2]. Chen et al. (2020) investigated the destruction mode, mechanism, and precursor characteristics of deep-buried granite in southwest China through acoustic emission, elastic wave velocity, and scanning electron microscopy tests for uniaxial compression. Their results showed that the granite in tunnels has “time-delay” and “medium” failure characteristics. This “time-delay” failure also has “time-delay” failure characteristics and “intermittent” features[3]. Existing bodies of research show that the initiation of rockbursts is closely related to the generation and development of micro-cracks inside the rock. The generation of new fractures and the initiation of original fractures need to absorb energy under high stress. The friction slip between the fracture surfaces when the fracture penetrates also dissipates and releases energy; hence, the process of rockburst pregnancy is essentially the comprehensive result of energy dissipation and release[4–6].

The Jinping II Hydropower Station is located in the landform slope zone between the Qinghai–Tibet Plateau and the Sichuan Basin. The rock mass is composed of Triassic strata. The lithology is mainly carbonate rock with a small amount of sandstone, slate, and chlorite schist. The overlying rock mass along the tunnel has a buried depth of 1500–2000 m. The maximum buried depth is 2525 m. The maximum principal stress along the line exceeds 60 MPa. It is characterized by a large buried depth, a long tunnel line, and a large diameter and is a typical deep-buried long tunnel super-large underground project. High burial depth and high stress have caused frequent rockburst occurrences, which have jeopardized the construction safety for many times. Rockbursts have become a major engineering geological problem endangering the construction of diversion tunnels. Based on the uniaxial, triaxial, and true triaxial test research on Jinping II deep marble (burial depth: approximately 2500 m) and the acoustic emission monitoring results obtained from the failure strain energy, shear fracture energy, and rock release energy of the rock, this study focuses on analyzing the characteristics and laws of the energy evolution of deep marble during deformation and fracture. At the same time, the energy dissipation and release mechanism in the process of destruction and rupture and its relationship with rockburst are revealed from three different energy perspectives.

2 Characteristics and regularity of energy evolution

2.1 Test equipment and process

The marble used in this test was taken from the deep buried section of the Jinping II diversion tunnel (buried at a depth of approximately 2500 m), which is the second group of Triassic marble (T2b) in the Baishan Formation. This marble is characterized by a carbonate mineral composition, a metamorphic structure, a dense massive structure, and a good macroscopic uniformity. The mineral composition is mainly calcite.

The rock sample used in the uniaxial and triaxial compression tests had a standard cylindrical shape. The test equipment used was a multi-functional electro-hydraulic servo-controlled MTS815-type pressure tester. The true triaxial test sample measured 50 × 50 × 100 mm. The test equipment used was a rock high-pressure true three-axis compression tester. The equipment can realistically simulate the complex stress state and stress path of the engineering rock body by independently changing the three
main stresses. These test systems can realize a real-time collection of parameters, such as load and displacement during the test. The acoustic emission monitoring in the abovementioned test process uses the Disp multi-channel acoustic emission system of the American Physical Acoustics Company, which can achieve a real-time acquisition of acoustic emission waveforms and characteristic parameters during the loading process. The acoustic emission threshold was set to 45 dB. The sampling rate was 1 MSPS. The waveform sampling length was 1 K. In the uniaxial test, the acoustic emission sensor was directly placed on the side of the rock sample. Meanwhile, in the triaxial and true triaxial tests, the acoustic emission sensor was placed on the outermost steel body. Four to six acoustic emission sensors were used during the test. These sensors were arranged in different positions to be able to perform a three-dimensional location analysis of the rock damage. The displacement control method was adopted in the conventional uniaxial and triaxial tests. The speed used was 1.0×10⁻³ mm/s. The control method adopted in the true triaxial test was stress control with a rate of 0.5 MPa/s.

2.2 Failure strain energy

Under a multiaxial stress state, the energy actually absorbed by a rock sample per unit volume is expressed as follows:

\[ E_n = \int \sigma_1 d\varepsilon_1 + \int \sigma_2 d\varepsilon_2 + \int \sigma_3 d\varepsilon_3 \]  

The unit of energy of Eq. (1) is MJ.m⁻³, which represents the energy stored, released, and dissipated by the rock sample during the damage process. The energy calculated by this formula cannot express energies, such as the light and thermal energies, released during rock sample damage and destruction. However, in general, it can express the law of energy evolution in the whole process of rock sample damage and destruction. Equation (1) is expressed as follows in the conventional triaxial compressive stress state:

\[ E_n = \int \sigma_1 d\varepsilon_1 + 2 \int \sigma_3 d\varepsilon_3 \]  

In the uniaxial compressive stress state, it can be expressed as follows:

\[ E_n = \int \sigma_1 d\varepsilon_1 \]  

The energy characteristics of deep brittle rocks are obtained from the above formulae. The typical stress–strain–energy relationship of the deep marbles in Figure 1 shows that before the crack instability propagation inside the rock, the energy \( E_n \) absorbed by the rock increases in a concave curve as the strain increases. Furthermore, the growth rate gradually increases. The energy absorbed in this part is mainly used for elastic storage, new fracture generation, initiation of original fractures, and steady expansion. The rock begins to expand, and it is precisely with the gradual increase of the energy consumed by the expansion that the rock is concave, the curve grows, and the increase rate accelerates. The rock significantly expands when the stress continues to increase, and the fracture instability expands. In addition, the stress–volume strain curve bends to the left (Figure 1). At this time, the ratio of the absorbed energy of the rock reaches the maximum. After which, the cracks penetrate each other, and shear cracks form at the weakest structure. The friction slip between the crack surfaces gradually replaces the brittle fracture of the tensile cracks, thereby becoming one of the main energy dissipation mechanisms. The ratio of the energy absorbed by the rock at this stage begins to gradually decrease and reaches a minimum after the macroscopic fracture formation after the peak. Although the ratio of the absorbed energy of the rock has decreased, the energy absorbed by the rock continues to increase until the residual stress section. The stress remains unchanged, and the deformation increases. The absorbed energy is mainly used for plastic dissipation and release. The deformation linearly increases, and the absorbed energy ratio is constant. This conclusion is confirmed by the acoustic emission test[7]. The abovementioned energy evolution analysis is a typical process of deep brittle rock absorption and its dissipation and release. However, it also has a confining pressure effect, that is, some differences in the energy dissipation and release mechanisms remain at different stages under different confining pressures, regardless of whether the main problem is the brittle fracture of the tensile fracture or the friction slip. Figure 2 illustrates the relationship between the typical axial strain and the energy under different confining pressures in deep marbles. Under low confining pressures, especially when the confining
pressure is less than 10 MPa, the failure control mechanism of rocks is mainly based on the tensile fracture brittle fracture, which can meet the needs of the fracture by absorbing less energy, while the energy used for the friction slip is very small. It is mainly manifested by the low ratio of the absorbed energy after the macro-fracture after the peak, and the actual energy required is very small. As a result, the energy absorbed before the peak is not much different from that absorbed by the entire rock (see Figure 3, where $E_{n_g}$ is the energy absorbed throughout the process, and $E_{n_p}$ is the energy absorbed in the peak). With the confining pressure increase, the rock failure control mechanism mainly comes from the tensile and brittle fracture and friction slip control under a high confining pressure and gradually switches to the damage control mechanism mainly based on the friction slip under a high confining pressure. The main manifestation is as follows: the ratio of the absorbed energy after the macro-fracture after the peak continuously increases, and the actual absorbed energy continues to increase. This clearly shows that the difference between the energy absorbed before the peak and that absorbed by the entire rock is increasing (Figures 2 and 3). Three types of expansion mechanisms induce rockbursts during the energy dissipation and release of brittle rocks: 1) control mechanism of the tensile fracture expansion; 2) control mechanism of the closed fracture friction; and 3) their mutual transformation. Different manifestations of the sudden energy changes determine the rockburst level and scale.

Figure 3 depicts the linear relationship between the confining pressure and the mean value of energy in deep marble. The relationship between the overall energy absorbed by the rock and the confining pressure is presented in Eq. (4). Its correlation coefficient is $R^2 = 0.98$. The relationship between the energy absorbed at the peak and the confining pressure is presented in Eq. (5), and its correlation coefficient is $R^2 = 0.90$.

\[
E_{n_g} = 0.09\sigma_3 + 0.15 \quad \text{(4)}
\]
\[
E_{n_p} = 0.03\sigma_3 + 0.12 \quad \text{(5)}
\]

![Fig. 1. Typical stress–strain–energy relationship of deep marble (confining pressure: 10 MPa)](image1)

![Fig. 2. Typical axial strain–energy relationship under different confining pressures in deep marble](image2)
Fig. 3. Relationship of the confining pressure and the energy mean of deep marble (En: energy absorbed throughout the process; Enp: energy absorbed to the peak)

2.3 Shear fracture energy

A large number of experimental studies have shown that a deformation concentration zone is formed along the shear fracture surface when the rock approaches the peak stress. Before and after the shear fracture of the rock sample, most of the deformation appears as slipping along the macro fracture surface. The shear fracture energy refers to the energy that the shear band needs to absorb per unit area. Xu (2002) obtained the shear fracture energy expression according to the J-integration method proposed by Rice\cite{9}. Yang (2007) further gave the expression formulas of the peak value and the total shear fracture energy based on the triaxial stress–strain entire process curve\cite{10} (Eqs. (6) and (7)):

\[
SFE_{cp} = L \int_{0}^{\varepsilon_c} (\sigma_1 - \sigma_3) d\varepsilon_1 - \frac{\sigma_3^2}{2E},
\]

\[
SFE_{g} = L \int_{0}^{\varepsilon_c} (\sigma_1 - \sigma_3) d\varepsilon_1 - \frac{\sigma_3^2}{2E} + L \int_{u_c}^{u_d} \left(\frac{\sigma_1 - \sigma_3}{2} du - (u_d - u_c)(\sigma_d - \sigma_3) \sin 2\theta\right),
\]

where, \(L\) is the rock sample length; \(\sigma_c\) and \(\varepsilon_c\) are the deviating stress and the peak axial strain at the peak of the rock sample, respectively; \(E\) is the elastic modulus of the rock; \(\sigma_1\) and \(\sigma_3\) are the axial stress and the confining pressure of the rock sample, respectively; \(\varepsilon_1\) is the axial strain of the rock sample; \(u\) is the sliding strain after the peak strength (\(u = (\varepsilon_1 - \frac{\sigma_1 - \sigma_3}{E})/\cos \theta\)); \(u_c\) and \(u_d\) are the peak and residual sliding strains of the rock sample, respectively; \(\sigma_d\) is the axial stress of the rock sample; and \(\theta\) is the angle between the shear band and the axial stress.

The pre-peak and overall shear fracture energies of the rock were calculated according to the abovementioned formula. Figure 4 shows the relationship between the pre-peak (\(SFE_{cp}\)) and total shear (\(SFE_{g}\)) fracture energies of the rock and the confining pressure. The total shear fracture energy can rapidly increase as the confining pressure increases. The shear fracture energy begins to decrease after reaching a certain confining pressure (e.g., 30 MPa). The peak shear fracture energy non-linearly and gradually increases when the confining pressure is equal to the brittle–ductile diversion confining pressure. Moreover, the peak shear fracture energy is equal to the total shear fracture energy, indicating the absence of a post-peak shear fracture energy under the approximate ideal elastoplastic state. The peak shear fracture energy of a rock sample is the total shear fracture energy. This law shows that for rocks under a triaxial stress, shear cracks develop when the partial stress reaches the peak strength, making the rock material show weakening characteristics; however, this weakening disappears after a certain confining pressure (i.e., usually the brittle–ductile diversion confining pressure).
This section mainly discusses the law and the characteristics of energy release in the deep brittle rock loading and unloading tests based on the simultaneous acoustic emission (AE) test of the deep brittle rock.

A large number of rock AE monitoring experimental studies have shown that the energy released by rocks is closely related to the AE activity, and the cumulative energy activity number of AE can both indicate the strength of the AE activity and display the energy release. Figures 5 and 6 show the typical stress–acoustic emission–time relationship curves in the uniaxial and true triaxial tests. The AE activity is expressed by the cumulative energy activity number. The energy activity occurs, and this energy is mainly released by the damage occurring during the closure of the original fracture; however, the number of energy activities is small and mainly concentrated when the fracture begins to close. Before the stress reaches the crack initiation stress (approximately 45% of the peak intensity), the number of energy activities lessens or no energy activity is observed when the stress increases. This segment can be considered as the first calm energy activity before the crack initiation in this period with a time interval of approximately 35 s. No new fractures occur in the rock, and no primary fractures have occurred. The energy activity starts to suddenly become active when the stress reaches the crack initiation stress. At this time, the original crack in the rock begins to crack; new cracks are generated; and the expansion phenomenon occurs. In the uniaxial stress state, if the stress continues to increase at this time after reaching the fracture instability expansion stress (approximately 85% of the peak strength), a period of relatively quiet energy activity occurs, and the energy activity with time as the independent variable is significantly reduced. This quiet period continues until the first stress reduction after the peak. Subsequently, a new energy activity then begins to appear. This phenomenon is different from that in the results found by other researchers and is not a rapid increase in the acoustic emission activity before the peak. However, a calm period of the significant energy activity will exist before the rock is damaged (or the bearing capacity is reduced). At this time, the calm period before the reduction of the rock's bearing capacity is called the second type of calm period of the rock energy activity with a time interval of approximately 55 s (i.e., approximately 1.6 times the time interval of the first type of rock energy activity). This phenomenon can explain the phenomenon of “no sign” before the brittle failure of the on-site rock and is basically consistent with the on-site monitoring results. As for the loading and the unloading after the rock peak, a second type of quiet period of the rock energy activity will also be observed (Figure 5). After the peak stress decreases for the first time, it will again be loaded. No new number of the same energy activity appears during the entire loading process. However, in the second type of calm period, the stress decreases again, and a significant number of energy activities appear. The loading and unloading again prove the existence of this phenomenon. The abovementioned second type of calming phenomenon of the rock energy activity can also be observed in the true triaxial tests (Figure 6). A sudden increase in the acoustic emission activity before or after unloading is observed when unloading before the true triaxial peak. A second type of quiet period of the rock energy activity occurs before the unloading, confirming the existence of a second type of quiet period phenomenon of the rock.
energy activity before rock damage or bearing capacity reduction or unloading before and after peak. This is an important and objective phenomenon that can be used to explain the reason for the absence of a sign related to brittle failure (e.g., rockbursts and gangs).

The evolution law of the energy activity number of these acoustic emission tests and the energy absorption law of the rock in the previous section indicated that in the tensile fracture stage of the rock, the absorbed energy was mainly used for energy release during crack initiation and propagation and new crack formation. Moreover, the energy activity was active and intensive, but the energy required in this process was very small. During the rock instability and failure stage, the energy used for the rock failure was small; the energy release was small; and the number of AEs was lower than the number of energy activities in the tensile rupture stage. The absorbed energy was also mainly dissipated in the internal friction slip, that is, in the second type of the quiet period of energy activities. This phenomenon became more prominent as the confining pressure increased\(^8\). As a dissipative structure, the brittle rock showed deformation and failure that exhibited a process of energy release and dissipation. In this process, the relationship between acoustic emission and stress changed from a Mogi to a compact type and gradually transitioned to a compact and unstable type. This confirmed that the tensile crack control mechanism at the low hydrostatic pressure, the friction slip control mechanism at the high hydrostatic pressure, and the interaction between the two control mechanisms changed with the hydrostatic pressure (Figure 7).

**Fig. 5.** Typical stress–acoustic emission–time curve in the uniaxial compression test for deep marble

**Fig. 6.** Typical stress–acoustic emission–time relationship curve in the deep triaxial true triaxial tests
Fig. 7. Relationship between the two control mechanisms of strength and failure of the brittle rock and the hydrostatic pressure

3 Conclusions
The following conclusions are obtained from this study:
(1) Three types of expansion mechanisms induce rockburst during the energy dissipation and release of brittle rocks: 1) control mechanism of the tension fracture propagation; 2) control mechanism of the friction control of closed fractures; and 3) their compound control mechanism formed by mutual transformation. The different manifestations of the sudden energy changes under these control mechanisms determine the rockburst level and scale.
(2) The energy absorbed by a rock during the damage and rupture process is basically linear with the confining pressure. Moreover, the ratio of the absorbed energy before the peak is significantly greater than that after the peak at a low confining pressure; however, this difference gradually decreases as the confining pressure increases.
(3) The total shear fracture energy first increases and then decreases with the confining pressure increase, while the shear fracture energy at the peak value non-linearly and gradually increases. The two remain equal until the brittle–ductile transition.
(4) During the loading and unloading process of brittle rocks, three types of sudden-increase period of the number of energy activities are observed: two types of calm period of the number of energy activities and one type of decline period of the number of energy activities. The quiet period of the second type of the number of energy activities (loading rockburst) or the decline period of the first type of the number of energy activities (unloading rockburst) constitute the rockburst precursor. Meanwhile, the bursting active period of the third type of the number of energy activities means a rockburst occurrence or reoccurrence (loading and unloading coupling rockburst). The abovementioned laws provide an important basis for the reasonable explanation of the causes and phenomena of brittle failure, such as rock bursts.

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