Evaluation of the rockburst proneness of red sandstone with prefabricated boreholes: an experimental study from the energy storage perspective

Zhichao He\textsuperscript{a}*, Fengqiang Gong\textsuperscript{a,b} and Song Luo\textsuperscript{a}

\textsuperscript{a}School of Resources and Safety Engineering, Central South University, Changsha, China; \textsuperscript{b}School of Civil Engineering, Southeast University, Nanjing, China

**ABSTRACT**

To reveal the function of drilling pressure relief (DPR) in preventing rockbursts from the energy storage perspective, we investigated the rockburst proneness of red sandstone with different number and arrangement of prefabricated borehole via uniaxial compression tests. The experimental result revealed the failure intensity characteristics of specimen can be quantitatively described using the peak-strength strain energy storage index (PESI). The PESI of red sandstone specimens with boreholes decreased by 23.2%--70.2% compared with that of intact specimens, i.e. DPR can effectively reduce the rockburst proneness of rocks. Furthermore, the effects of the number and arrangement of boreholes on rockburst proneness were evaluated. The PESI decreased as the number of boreholes increased. When the arrangement angle with the loading direction changed from 90° to 27° and then to 0°, the PESI first decreased and then increased; when the arrangement angle with the loading direction was 27°, the efficiency of eliminating rockburst proneness and weakening peak compression strength was the best. The borehole arrangement angle affects rockburst proneness more than the number of boreholes does. This paper offers a novel approach of quantitatively evaluating the rockburst proneness of rocks after DPR and clarifies the effectiveness DPR in reducing the probability of rockbursts.

**ARTICLE HISTORY**

Received 16 February 2021
Accepted 10 July 2021

**KEYWORDS**

Rockburst; rockburst proneness; drilling pressure relief; peak-strength strain energy storage index; linear energy storage law

1. Introduction

With the increasing depth in underground engineering, high stress concentration, energy accumulation, and other adverse factors become increasingly prominent in some complex geological conditions during excavation and resource exploitation (Durrheim et al. 1998; Feng et al. 2017; Ranjith et al. 2017; Wong et al. 2017; Wang et al. 2020; Zhang et al. 2020). The frequency of geological hazards such as rockburst
is increasing under the effects of these potential adverse factors, which significantly endangers the safety of personnel and equipment (Ortlepp and Stacey 1994; Jiang et al. 2010; Kaiser and Ming 2012; Panthi 2012; Zhou et al. 2015; Gong et al. 2018, 2020; Feng et al. 2019). Recently, to effectively control and prevent rockbursts in high-stress zones, drilling pressure relief (DPR) has been widely used by many researchers in rock engineering (Zhu et al. 2009; Konicek et al. 2013; Huang et al. 2014; Li et al. 2016; Keneti and Sainsbury 2018; Zhang et al. 2019). Extensive relevant outcomes have been achieved during practical applications and experimental investigation. In a practical application, Li et al. (2016) investigated the effectiveness of large diameter drilling in reducing rockbursts in the Yuejin Coal Mine; they created approximately 3210 pressure relief boreholes following the direction of the headgate in the coal rock mass and later confirmed that the occurrence of rockbursts significantly decreased. Li et al. (2016) conducted DPR in the stress concentration area of a working face in a coal mass, and they observed that the electromagnetic radiation intensity in this area significantly decreased after DPR. Huang et al. (2014) conducted in situ geo-stress measurements using the borehole stress-relief method, and the negative effects of geostress distribution on safe mining close to the fault areas were minimized. Furthermore, experts and scholars have employed different experimental methods to study the mechanism of DPR in reducing and preventing rockbursts (Liu et al. 2007, 2014; Zhang et al. 2017; Huang et al. 2018; Qi et al. 2018; Zhang et al. 2019; Si et al. 2020). Liu et al. (2014) studied the prevention mechanism of rockbursts using a rock drilling mechanical test and introduced the concept of zone management in high rockburst stress zones. Qi et al. (2018) suggested that the diameter of a pressure relief borehole has a size effect on the DPR, i.e. a reasonable diameter of the pressure relief borehole should be selected for DPR. Zhang et al. (2019) and Huang et al. (2018) investigated the effects of borehole layout parameters (number and arrangement of boreholes) on the mechanical behaviours of coal-rock masses after DPR to select reasonable borehole parameters to guide a DPR plan. Using numerical calculation methods, Zhang et al. (2017) obtained the change law of a stress concentration zone formed in deep high-stress granite after DPR with increasing depth. Liu et al. (2007) analyzed the failure of a roadway surrounding rock structure and the transfer of high stress caused by a reasonable drilling layout.

The crack evolution and energy dissipation of borehole rock masses have been investigated by scholars to reveal the mechanism of DPR in preventing rockbursts. Jia et al. (2017) investigated the crack propagation and number of cracks induced by various DPR parameters using particle flow code (PFC) software, and they indicated that the pressure relief caused by crack propagation and penetration is the fundamental reason for DPR. Lin et al. (2015) and Wong and Lin (2015) studied the crack evolution mechanism of pre-holed granite specimens with various sizes, distributions, and spacings of the holes using an uniaxial compression test. Their experimental and numerical results revealed that the crack-coalescence mechanisms of specimens with holes primarily depend on the hole arrangement (rock-bridge angle and length). Huang et al. (2019) investigated the cracking process of a granite specimen containing multiple pre-holes under uniaxial compression, and they indicated that the failure modes of pre-holed specimens were dependent on the rock-bridge angle and number.
of holes. We can be infer that the rock-bridge angle, length, and number of holes of a specimen with multiple holes affects the evolution mechanism of cracks. In addition, Zeng et al. (2018) investigated the force field distribution before and during cracking of brittle sandstone specimens with a hole under uniaxial compression. The results indicated the force fields effects the crack initiation and propagation, and the formed cracks also affect the force field distribution. Wu et al. (2020) used the digital image correlation (DIC) method to monitor the crack development and stress distribution of pre-holed red sandstone specimens of five shapes via uniaxial test. The results revealed that the macro failure of specimen was dominated by the shear cracks coalescing with the slabling fracturing zones. Furthermore, Wang et al. (2016) analyzed the failure mechanism of the surrounding rock of borehole, and they studied an evaluation method of the effect of the borehole to reduce the rockburst from the perspective of the energy dissipation rate. Zhu et al. (2015) proposed a method to determine drilling parameters based on the energy dissipation index to optimize a DPR plan. The above researches significantly enriched the investigation of the DPR mechanism in preventing rockbursts and provided solutions to rockburst problems. However, most previous studies focussed on the specific mechanical behaviours of rocks or coal-rock masses after the drilling, i.e. compression strength, elastic modulus, failure pattern, crack evolution, energy dissipation, etc. However, the mechanism of DPR in weakening rockburst proneness has not been sufficiently investigated from the energy perspective. The occurrence of rockbursts is accompanied by the conversion of energy (Xie et al. 2005, 2009; Li et al. 2014; Wasantha et al. 2014; Peng et al. 2015; Meng et al. 2016; Gong et al. 2018, 2019a, 2019b; Su et al. 2021) and a amount of stored elastic energy will be released suddenly at the critical point of the rockburst, thereby causing severe damage to rock engineering structures (Bernabé and Revil 1995; Sujatha and Kishen 2003; Ju et al. 2010; Zhang and Gao 2015; Cai 2016; Deng et al. 2016). Therefore, it is essential to investigate the rockburst proneness of rocks after DPR through energy interpretation.

In this study, we conducted a series of single-cyclic loading–uniaxial compression (SCLUC) tests on intact red sandstone specimens and those with seven prefabricated borehole arrangements. The characteristics of energy transfer in the rock specimens after drilling were identified, and the effects of the borehole arrangements on the rockburst proneness index $W_{ET}^P$ were quantitatively analyzed. In addition, the failure process of the specimens under uniaxial loading was recorded using a high-speed camera. Examining the failure characteristics and $W_{ET}^P$, the results confirmed that $W_{ET}^P$ was consistent with the specimen’s failure characteristics. This paper offers a method of selecting the most effective DPR to reduce the probability of rockburst from the perspective of rockburst proneness after the DPR of rocks, which can enrich the references relating to the DPR mechanism.

2. Peak-strength strain energy storage index (PESI $W_{ET}^P$)

Many discriminant indexes of rockburst proneness have been proposed by scholars to predict rockbursts, such as the strain energy storage index ($W_{ET}$) (Kidybiński 1981), peak-strength strain energy storage index ($W_{ET}^P$) (Gong et al. 2019a), residual elastic
energy index \(A_{EF}\) (Gong et al. 2018, 2021), elastic strain potential energy \(P_{ES}\) (Wang and Park 2001), brittleness index \(B\) (Cai 2016), and surplus energy index (Tang et al. 2002). Because indoor bursting only appears and develops while the applied load induces the peak stress of the rock specimens (Gong et al. 2019a), the use of the index \(W_{ET}\) to assess the rockburst proneness is more reasonable. In this study, the specimen was processed into a cuboid shape (Figure 2). Yang et al. (2020) analyzed the effects of specimen shape (cylindrical specimen 50 mm \(\times\) 100 mm and cuboid specimen 50 \(\times\) 50 \(\times\) 100 mm\(^3\)) on \(W_{ET}\) and observed that the specimen shape has a minimal effect on \(W_{ET}\) (\(W_{ET}\) values of the cuboid and cylindrical specimens were 3.16 and 3.13, respectively), i.e. the indexes \(W_{ET}\) and \(W_{ET}^P\) are suitable for cuboid specimens.

Figure 1 shows the ideal method for calculating \(W_{ET}^P\) (Gong et al. 2019a), and the formula is as follows

\[
W_{ET}^P = \frac{u_e^p}{u_d^p}
\]  

(1)

where \(u_e^p\) and \(u_d^p\) are the peak elastic and peak dissipated energy densities of the rock specimen, respectively. Meanwhile, to accurately obtain \(u_e^p\) and \(u_d^p\), Gong et al. (2019b) observed that an intact rock specimen (without holes) experiences linear energy storage and dissipation laws, i.e. the apparent linear interrelations between the elastic energy \(u_e\), dissipated energy \(u_d\) and total input energy \(u_o\). The specific linear relationships can be expressed as

\[
\begin{align*}
  u_e &= Au_o + B \\
  u_d &= (1-A)u_o - B
\end{align*}
\]  

(2)

Figure 1. Ideal approach of calculating the peak-strength strain energy storage index (Gong et al. 2019a).
where $A$ and $B$ are the fitting parameters. Therefore, the $u_P^e$ and $u_P^d$ of a rock specimen can be obtained using Eq. (2). The specific calculation expressions are expressed as

$$u_P^e = \int_0^{e_c} \sigma_c \, \text{d}e$$

(3)

$$\begin{align*}
u_P^e &= Au_P^o + B \\
u_P^d &= (1 - A)u_P^o - B
\end{align*}$$

(4)

where $u_P^o$ is the total input energy density of the rock specimen at the peak stress point. The $W_{ET}^P$ of the rock specimen is calculated using Eqs. (1) and (3).

3. Experimental preparation and procedures

3.1. Specimen preparation

As sedimentary rock, red sandstone is widely distributed in underground rock formations such as tunnels (roadways) surrounding rocks and coal roof slabs. With the exploitation of resources and construction of underground projects, mechanical behaviour problems associated with red sandstone have been increasing in recent years, such as rockbursts, spalling, fracture, and weakening of rock strength (Yang et al. 2012, 2013; Luo 2020; Zhang et al. 2020; Chen et al. 2021; He et al. 2021; Jiang 2021; Li et al. 2021; Tang et al. 2021; Wang et al. 2021; Xu et al. 2021). Therefore, to evaluate the rockburst proneness of rock with prefabricated borehole, fine-grained brittle red sandstone specimens with different prefabricated borehole arrangements collected from Junan County, Shandong Province, China were selected for tests (Figure 2). According to the processing accuracy of ISRM standards (Fairhurst and Hudson 1999), the red sandstone was processed into cuboid specimens and the specimen dimensions are shown in Figure 2. In addition, holes were drilled in the cuboid specimen.
specimens, which were arranged around the centre or at the centre by professionals using ZC50 (drilling and milling) equipment. The diameter of the holes in the specimens was 5 mm ($\Phi = 2r = 5$ mm). For the rock specimen with multiple holes, the distance between the holes was $d = 7.5$ mm ($d = 3r$) (Figure 2a). The basic parameters (density $\rho$, P-wave velocity $v$, peak compressive strength $\sigma_c$, etc.) of eight types of the specimen are listed in Table 1. The prepared specimens were named as follows:

### Table 1. Specimen types and basic parameters.

| Specimen types | Specimen no. | Number of holes | $L$ (mm) | $W$ (mm) | $H$ (mm) | $D(2r/mm)$ | $P\cdot v$ (m/s) | $\rho$ (g/cm$^3$) | $\sigma_c$ (MPa) |
|----------------|--------------|-----------------|---------|---------|---------|------------|----------------|----------------|----------------|
| I              | I-0          | 50.41 50.36 100.39 | 3541   | 2.45   | 107.39  |
|                | I-1          | 50.53 49.28 100.50 | 3674   | 2.47   | 105.65  |
|                | I-2          | 49.28 50.35 100.38 | 3921   | 2.49   | 116.75  |
|                | I-3          | 50.40 50.42 100.40 | 3968   | 2.45   | 115.32  |
|                | I-4          | 50.60 50.52 100.82 | 3440   | 2.44   | 110.60  |
|                | I-5          | 50.32 50.45 100.50 | 3925   | 2.47   | 110.46  |
| S              | S-0          | 50.42 50.15 100.42 | 3869   | 2.42   | 94.28   |
|                | S-1          | 49.38 50.48 100.56 | 4006   | 2.47   | 103.94  |
|                | S-2          | 50.34 50.18 100.58 | 3883   | 2.47   | 98.95   |
|                | S-3          | 50.43 50.13 100.43 | 3818   | 2.46   | 95.40   |
|                | S-4          | 50.41 50.15 100.42 | 3884   | 2.46   | 101.89  |
| D-H            | D-H-0        | 50.31 50.17 100.43 | 3775   | 2.45   | 89.50   |
|                | D-H-1        | 50.44 50.45 100.52 | 3843   | 2.45   | 92.65   |
|                | D-H-2        | 50.34 50.40 100.52 | 3778   | 2.43   | 89.10   |
|                | D-H-3        | 50.08 50.29 100.36 | 3801   | 2.46   | 87.32   |
|                | D-H-4        | 50.42 50.28 100.35 | 3802   | 2.45   | 91.16   |
|                | D-H-5        | 50.27 50.26 100.36 | 3837   | 2.46   | 89.61   |
| D-D            | D-D-0        | 50.24 50.40 100.36 | 3772   | 2.46   | 84.94   |
|                | D-D-1        | 50.20 50.30 100.35 | 3772   | 2.45   | 83.67   |
|                | D-D-2        | 50.51 49.84 100.35 | 3882   | 2.47   | 82.48   |
|                | D-D-3        | 50.32 50.28 100.60 | 3796   | 2.45   | 83.71   |
|                | D-D-4        | 50.48 50.30 100.60 | 3612   | 2.46   | 78.65   |
|                | D-D-5        | 50.18 50.22 100.36 | 3794   | 2.45   | 82.32   |
|                | D-D-6        | 50.28 50.18 100.42 | 3881   | 2.46   | 82.83   |
| D-V            | D-V-0        | 50.20 50.35 100.35 | 3801   | 2.46   | 93.47   |
|                | D-V-1        | 50.54 50.21 100.48 | 3857   | 2.46   | 94.24   |
|                | D-V-2        | 50.53 50.34 100.44 | 3790   | 2.45   | 95.76   |
|                | D-V-3        | 50.29 50.32 100.44 | 3833   | 2.45   | 94.14   |
|                | D-V-4        | 50.15 50.16 100.35 | 3904   | 2.47   | 93.95   |
|                | D-V-5        | 50.30 50.32 100.40 | 3839   | 2.46   | 93.19   |
| T-H            | T-H-0        | 50.36 50.36 100.48 | 3763   | 2.44   | 83.44   |
|                | T-H-1        | 50.40 50.37 100.48 | 3714   | 2.44   | 82.24   |
|                | T-H-2        | 50.42 50.38 100.48 | 3707   | 2.42   | 79.31   |
|                | T-H-3        | 50.44 50.45 100.60 | 3746   | 2.41   | 77.61   |
|                | T-H-4        | 50.33 50.06 100.46 | 3748   | 2.45   | 78.92   |
|                | T-H-5        | 50.30 50.34 100.48 | 3735   | 2.44   | 80.20   |
| T-D            | T-D-0        | 50.32 50.30 100.56 | 4022   | 2.46   | 68.97   |
|                | T-D-1        | 50.37 50.19 100.42 | 3761   | 2.46   | 68.92   |
|                | T-D-2        | 50.46 50.26 100.82 | 3811   | 2.43   | 70.29   |
|                | T-D-3        | 50.37 50.25 100.50 | 3821   | 2.45   | 69.86   |
|                | T-D-4        | 50.38 50.21 100.48 | 3798   | 2.44   | 65.89   |
|                | T-D-5        | 50.33 50.30 100.18 | 3263   | 2.43   | 76.34   |
|                | T-D-6        | 49.92 49.82 100.28 | 3287   | 2.44   | 76.60   |
| T-V            | T-V-0        | 50.38 50.18 100.44 | 3923   | 2.46   | 91.35   |
|                | T-V-1        | 50.36 50.22 100.55 | 3703   | 2.44   | 91.60   |
|                | T-V-2        | 50.46 50.18 100.42 | 3664   | 2.44   | 92.38   |
|                | T-V-3        | 50.43 50.20 100.46 | 3755   | 2.43   | 90.30   |
|                | T-V-4        | 50.36 50.33 100.38 | 3704   | 2.44   | 92.90   |
|                | T-V-5        | 50.34 50.30 100.44 | 3706   | 2.45   | 92.47   |
|                | T-V-6        | 50.46 50.31 100.54 | 3830   | 2.43   | 90.00   |
intact-specimen (I); single-hole specimen (S); double-horizontal-hole specimen (D-H); double-diagonal-hole specimen (D-D); double-vertical-hole specimen (D-V); triple-horizontal-hole specimen (T-H); triple-diagonal-hole specimen (T-D); triple-vertical-hole specimen (T-V) (Figure 2a).

3.2. Test instrument

The INSTON 1346 servo-hydraulic testing system was used in the tests (Figure 3a). The maximum loading system could reach 2000 kN under quasi-static loading. During testing, the axial load of the specimens was captured using the data acquisition system, and the axial displacement of the specimen was measured using a 2.5 mm displacement extensometer. (To obtain the actual displacement data of the specimen deformation, the deformation caused by the steel gasket was subtracted out during the calculation). As presented in Figure 3b, a high-speed camera was adopted to record the failure process of the specimens, and it could capture 125 images per second.

3.3. Test procedure for the single-cyclic loading-unloading uniaxial compression (SCLUC) test

Figure 4 shows the loading path in a SCLUC test. The experiments proceeded as follows: first, the peak compressive strength ($\sigma_c$) of the rock specimen was determined through the traditional uniaxial compression (UC) test with a loading rate of 60 MPa/min second, five unloading stress levels 'k' based on $\sigma_c$ values were set for the same type of the rock specimen ('k' was equal to the ratio of the compressive stress at the setting unloading stress level to $\sigma_c$ of the rock specimen, which was approximately 0.1, 0.3, 0.5, 0.7, and 0.9). Subsequently, five rock specimens with the same type were selected to conduct SCLUC tests at different unloading stress levels (Figure 4).

3.4. Calculation method of energy density parameters

Energy density parameters ($u_o$, $u_e$, and $u_d$) were determined using the area integral approach. Figure 4 shows the integration areas of different energy density parameters,
and the specific calculation method can be expressed as

\[
\begin{align*}
    u_o &= \int_0^{\varepsilon_k} f(\varepsilon) \, d\varepsilon \\
    u_e &= \int_{\varepsilon_0}^{\varepsilon_k} f_1(\varepsilon) \, d\varepsilon \\
    u_d &= u_o - u_e
\end{align*}
\] (5)

where \( f(\varepsilon) \) and \( f_1(\varepsilon) \) are fitting functions, \( \varepsilon_0 \) is the permanent plastic strain, and \( \varepsilon_k \) is the total strain.

4. Test results

4.1. Energy evolution characteristics of red sandstone specimens with different borehole arrangements

The energy density parameters of eight types of specimens experiencing various unloading stress levels \( (k) \) were calculated using the method described in Sec. 3.4. The calculations \( u_o, u_e, \) and \( u_d \) are listed in Table 2. Figure 5 shows the variation in the energy density parameters at different stress levels. We observed that the energy density parameters \( u_o, u_e \) and \( u_d \) all increased with \( k \), despite the presence of borehole inclusions of the rock specimens.

Figure 6 shows the relationships between \( u_e, u_d \) and \( u_o \), which are deduced from the data in Table 2. It can be observed that \( u_e \) and \( u_d \) increased linearly with \( u_o \), and strong linear relationships between \( u_o, u_d \) and \( u_e \) were observed (the linear correlation coefficient \( R^2 \) ranged from 0.9755 to 0.9996, and the specific linear fitting functions are shown in Figure 6). Similar to the intact red sandstone specimen (I) (Figure 6a), the results also indicated the linear relationships between \( u_e, u_d \) and \( u_o \) of the red sandstone with different prefabricated borehole arrangements (Figure 6b–h),
indicating that prefabricated boreholes do not hinder the presence of linear energy storage laws during loading.

4.2. Energy parameters at the peak stress

Using the calculation method mentioned in Sec. 2, the peak energy density parameters \( u_o, u_e, \) and \( u_d \) and index \( W_{ET}^P \) of each specimen type were obtained (Table 3). Figure 7 shows the peak energy density parameters \( u_o, u_e, \) and \( u_d \) and \( W_{ET}^P \) of eight types of red sandstone specimens. We observed that the total input

| Specimen no. | Actual unloading stress level \((k)\) | \( u_o \)(mJ/mm\(^3\)) | \( u_e \)(mJ/mm\(^3\)) | \( u_d \)(mJ/mm\(^3\)) |
|--------------|--------------------------------------|-------------------------|-------------------------|-------------------------|
| I-1          | 0.11                                 | 0.010                   | 0.007                   | 0.003                   |
| I-2          | 0.28                                 | 0.037                   | 0.028                   | 0.009                   |
| I-3          | 0.47                                 | 0.086                   | 0.070                   | 0.017                   |
| I-4          | 0.69                                 | 0.171                   | 0.134                   | 0.037                   |
| I-5          | 0.90                                 | 0.246                   | 0.196                   | 0.050                   |
| S-1          | 0.09                                 | 0.007                   | 0.004                   | 0.003                   |
| S-2          | 0.30                                 | 0.034                   | 0.026                   | 0.009                   |
| S-3          | 0.52                                 | 0.082                   | 0.062                   | 0.020                   |
| S-4          | 0.67                                 | 0.130                   | 0.106                   | 0.024                   |
| S-5          | 0.96                                 | 0.237                   | 0.176                   | 0.060                   |
| D-H-1        | 0.10                                 | 0.007                   | 0.004                   | 0.003                   |
| D-H-2        | 0.31                                 | 0.032                   | 0.024                   | 0.008                   |
| D-H-3        | 0.52                                 | 0.069                   | 0.052                   | 0.017                   |
| D-H-4        | 0.69                                 | 0.128                   | 0.099                   | 0.029                   |
| D-H-5        | 0.91                                 | 0.198                   | 0.134                   | 0.051                   |
| D-D-1        | 0.10                                 | 0.007                   | 0.004                   | 0.003                   |
| D-D-2        | 0.31                                 | 0.031                   | 0.027                   | 0.004                   |
| D-D-3        | 0.50                                 | 0.060                   | 0.045                   | 0.015                   |
| D-D-4        | 0.74                                 | 0.119                   | 0.091                   | 0.028                   |
| D-D-5        | 0.91                                 | 0.185                   | 0.132                   | 0.053                   |
| D-D-6        | 0.94                                 | 0.202                   | 0.142                   | 0.060                   |
| D-V-1        | 0.10                                 | 0.008                   | 0.005                   | 0.004                   |
| D-V-2        | 0.30                                 | 0.034                   | 0.025                   | 0.010                   |
| D-V-3        | 0.51                                 | 0.079                   | 0.061                   | 0.018                   |
| D-V-4        | 0.78                                 | 0.162                   | 0.125                   | 0.037                   |
| D-V-5        | 0.91                                 | 0.216                   | 0.155                   | 0.060                   |
| T-H-1        | 0.10                                 | 0.006                   | 0.004                   | 0.002                   |
| T-H-2        | 0.32                                 | 0.030                   | 0.020                   | 0.010                   |
| T-H-3        | 0.53                                 | 0.060                   | 0.046                   | 0.014                   |
| T-H-4        | 0.72                                 | 0.105                   | 0.079                   | 0.026                   |
| T-H-5        | 0.91                                 | 0.176                   | 0.132                   | 0.044                   |
| T-D-1        | 0.10                                 | 0.005                   | 0.003                   | 0.003                   |
| T-D-2        | 0.30                                 | 0.022                   | 0.015                   | 0.007                   |
| T-D-3        | 0.50                                 | 0.046                   | 0.034                   | 0.013                   |
| T-D-4        | 0.75                                 | 0.087                   | 0.064                   | 0.023                   |
| T-D-5        | 0.92                                 | 0.166                   | 0.116                   | 0.050                   |
| T-D-6        | 0.96                                 | 0.191                   | 0.131                   | 0.060                   |
| T-V-1        | 0.10                                 | 0.008                   | 0.005                   | 0.003                   |
| T-V-2        | 0.30                                 | 0.032                   | 0.023                   | 0.009                   |
| T-V-3        | 0.51                                 | 0.069                   | 0.054                   | 0.016                   |
| T-V-4        | 0.69                                 | 0.124                   | 0.096                   | 0.028                   |
| T-V-5        | 0.90                                 | 0.201                   | 0.152                   | 0.049                   |
| T-V-6        | 0.97                                 | 0.249                   | 0.176                   | 0.074                   |
Figure 5. Energy density parameters growth laws at different stress levels of eight types of specimens.
Figure 6. Relationship of the three energy parameters of red sandstone specimen with different borehole arrangements.
energy densities ($u_P^o$) were different during the loading process, among which the $u_P^o$ of specimen I was the highest, which is 0.357 mJ/mm$^3$. In contrast, the $u_P^o$ values of other specimen types were lower than that of specimen I. The $u_P^o$ of specimen T-D was the lowest (0.205 mJ/mm$^3$), which was 42.6% lower compared with that of specimen (I). We inferred that the change in the rock specimen’s internal structure would affect $u_P^o$ during the loading. Figure 7 also shows that the energy dissipation densities ($u_P^d$) were approximately constant for each specimen type (the standard deviation of $u_P^d$ of eight types of red sandstone specimen was 0.009, i.e. the dispersion was small). The reason was that the impact of the drilling relative to the intact rock mass structure is relatively small, and the energy dissipated was less during the loading of the rock (a large amount of $u_P^o$ converted into $u_P^e$, and $u_P^d$ accounts for only a small part of $u_P^o$). Therefore, we can conclude that $u_P^d$ of specimens from the same rock material is less affected by the slight change in the internal structure.

| Specimen type | $\sigma_c$ (MPa) | $u_P^o$ (mJ/mm$^3$) | $u_P^e$ (mJ/mm$^3$) | $u_P^d$ (mJ/mm$^3$) | $W_{ET}^p$ | $X_{\sigma_c}$ | $X_{u_P^o}$ | $X_{u_P^e}$ | $X_{u_P^d}$ | $X_{W_{ET}^p}$ |
|---------------|------------------|---------------------|---------------------|---------------------|-----------|---------------|-------------|-------------|-------------|-------------|
| I             | 111.03           | 0.357               | 0.284               | 0.073               | 3.880     | –             | –           | –           | –           | –           |
| S             | 97.83            | 0.304               | 0.231               | 0.073               | 3.148     | 11.89%        | 14.80%     | 5.30%       | 0%          | 23.20%      |
| D-H           | 89.90            | 0.264               | 0.198               | 0.066               | 3.010     | 19.04%        | 26.10%     | 8.60%       | 9.60%       | 28.90%      |
| D-D           | 82.66            | 0.254               | 0.182               | 0.073               | 2.949     | 25.55%        | 28.90%     | 10.20%      | 0%          | 55.60%      |
| D-V           | 94.13            | 0.314               | 0.238               | 0.076               | 3.148     | 15.22%        | 12.00%     | 4.60%       | -4.10%      | 23.30%      |
| T-H           | 80.29            | 0.209               | 0.157               | 0.052               | 3.025     | 27.69%        | 41.50%     | 12.70%      | 28.80%      | 28.30%      |
| T-D            | 70.98           | 0.205               | 0.143               | 0.063               | 2.280     | 36.07%        | 42.60%     | 14.10%      | 13.70%      | 70.20%      |
| T-V            | 91.57            | 0.299               | 0.218               | 0.081               | 2.707     | 17.52%        | 16.20%     | 6.60%       | -10.90%     | 43.40%      |

(For $X_{\sigma_c}$, $X_{u_P^o}$, $X_{u_P^e}$, and $X_{u_P^d}$, see Table 3.)

**Table 3.** Peak-strength parameters and their reduction proportion of the specimen with boreholes relative to the intact red sandstone specimen (I).

![Figure 7](image_url). Energy density parameters ($u_P^o$, $u_P^e$, and $u_P^d$) and strain energy storage index ($W_{ET}^p$) at the peak strength of eight types of specimens.
Figure 8a shows that $u_P^e$ was approximately positively correlated with $r_c$, i.e. $u_P^e$ increased with the increase in $r_c$ (the fitting formula is shown in Figure 8a, with $R^2$ equal to 0.9601). The $r_c$ reflects a rock’s ability to resist deformation and failure to a certain extent, and it can also represent the ability of the specimen to accumulate elastic energy. A higher $r_c$ means, more energy is stored at the peak point (Meng et al. 2016). However, $u_P^d$ was unaffected by the $r_c$ of the specimen (Figure 8b). Figures 7 and 8 imply that the arrangement of the boreholes and $r_c$ remarkably affect the $u_P^e$ at rock failure. In contrast, $u_P^d$ is insensitive to the internal drilling structures and compressive strengths for the same type of rock. In conclusion, the arrangement of the borehole structures can effectively change $u_P^e$ during the loading.
4.3. Failure characteristics of the specimens with different borehole arrangements

Figure 9 shows the failure process at a certain time of each type of representative specimens with different drilling arrangements during loading. The existence of drilling structure seemed to affect the failure intensity of the specimens. Figure 9a shows the failure characteristics of the intact specimen (I). We observed that the macroscopic failure pattern of specimen I was conjugate shearing. The entire failure process lasted a long time (6.192 s), and many rock fragments and debris were ejected during failure, accompanied by a continuous crisp cracking sound. The failure of specimen I was more violent than that of the holed one (note that the entire failure process of a specimen refers to the process from the critical failure point to the complete failure). In contrast, the failure intensity of the specimens with borehole structures was more weaker than that of specimen I, and the entire failure process lasted a shorter time (when a crack initiated, it rapidly expanded and caused specimen failure instantly). In addition, fewer rock fragments and debris were ejected, and the specimens remained relatively intact after the final failure (Figure 9b–h). For instance, the whole failure process of specimen (T-D) (Figure 9g) lasted 0.192 s, and a small amount of rock powder and debris was ejected from the upper and lower parts of the specimen close to the indenter. The specimen after final failure was relatively intact. Thus, this indicated that borehole structures can effectively reduce the failure intensity of a specimen.

Meanwhile, we observed that the arrangement angle of the boreholes affected the failure characteristics of the specimens: (1) When the arrangement angle of specimens D-H and T-H with the loading direction was 90°, their macroscopic failure modes were mixed shearing and splitting (Figure 9c,f). (2) When the arrangement angle of specimens D-D and T-D with the loading direction was 27° (diagonal arrangement), they exhibited the splitting failure mode (Figure 9d,g). (3) When the arrangement angle of specimens D-V and T-V with the loading direction was 0°, the single-sided V-shape macroscopic shearing failure mode was observed, and the rock block was exfoliated into a convex V-shape (Figure 9e,h). Among the three drilling arrangements angle, specimens D-D and T-D were arranged diagonally, whose failure intensities were weaker than those of the specimens with other drilling arrangements. In addition, we can infer that when the specimens are arranged with double and triple boreholes, they will exhibit similar macroscopic failure modes. However, the failure intensity of the specimens with triple boreholes was weaker than that of the specimens with double boreholes (fewer rock fragments and debris were ejected from the specimens with triple boreholes).

5. Results analysis and discussion

The occurrence of rockburst is accompanied by the conversion of energy and a large amount of stored elastic energy will be released suddenly at the critical point of rockburst. Therefore, it is more reasonable to investigate the rockburst proneness of rocks after DPR to explain the probability of reducing rockbursts from an energy perspective. To select a reasonable DPR method by the energy evaluation, Zhu et al. (2015)
Figure 9. Representative failure process of each type red sandstone specimen with different drilling arrangement: (a) I; (b) S; (c) D-H; (d) D-D; (e) D-V; (f) T-H; (g) T-D; (h) T-V. (Note: ‘T’ and ‘S’ are the tensile crack mode and shear crack mode, respectively).
Figure 9. Continued.
Figure 9. Continued.
Figure 9. Continued.
Figure 9. Continued.
Figure 9. Continued.
Figure 9. Continued.
Figure 9. Continued.
Figure 9. Continued.
Figure 9. Continued.
Figure 9. Continued.
Figure 9. Continued.
and Zhang et al. (2019) analyzed the effects of prefabricated boreholes of specimens on the energy dissipation behaviours via an energy dissipation index ($X_{u}$) (the calculation method of $X_{u}$ ($X_{u}$) is shown in Figure 10). In this study, we analyzed the effects of prefabricated boreholes on the specimens on energy dissipation through the index $W_{PE}$ method (as described in Sec. 2). To further investigate the accuracy of the evaluation methods in reducing the risk of rockburst after DPR, the $X_{u}$ and $W_{PE}$ method were compared (Figure 10).

Figure 11 shows the reduction proportion of the average peak-strength parameters of the specimen with different borehole arrangements relative to specimen I. $X_{\sigma_{c}}$ (Figure 11a), $X_{u_{e}}$ (Figure 11c) and $X_{W_{PE}}$ (Figure 11e) exhibited similar variation trends of reduction proportion. The existence of a linear relationship between the $\sigma_{c}$ and $u_{e}$ (see Sec. 4.2) was observed, i.e. $\sigma_{c}$ can characterize the capacity of a specimen to store the elastic energy, and a higher $\sigma_{c}$ means more $u_{e}$ can be stored (Meng et al. 2016). We infer that for the rock mass after DPR, the $\sigma_{c}$ and $u_{e}$ of the rock mass reduced, thus reducing the risk of rockbursts in high-stress concentration areas. $W_{PE}$ is a rockburst tendency index and is the ratio of $u_{e}$ to $u_{d}$ at the peak stress of the specimen. In this study, we observed that $u_{d}$ of the same type of material is less affected by the internal drilling structure and compressive strength (see Sec. 4.2 and Figure 12d), thus, $W_{PE}$ was consistent with $u_{e}$. Moreover, according to the relationship between the failure characteristics and $W_{PE}$ (as described in Sec. 5.1), we observed that the failure intensity was in agreement with $W_{PE}$ of the specimens. Therefore, $W_{PE}$ can accurately describe the rockburst proneness of rock after DPR.

Figure 11b shows the variations in the reduction proportion of the energy dissipation index ($X_{u}$) of the specimens with different borehole arrangements relative to specimen I, which were inconsistent with the variation trend of the reduction proportion of $X_{\sigma_{c}}$ ($X_{u}$) of specimens T-H and T-D were approximately the same, while $X_{\sigma_{c}}$ of specimen D-D was higher than that of the specimen T-H). In addition, $X_{u}$ was determined by the total input energy ($u_{o}$), and $u_{o}$ was equal to the sum of $u_{e}$ and $u_{d}$.

![Figure 10. Calculation method of the energy dissipation index (Zhu et al. 2015; Zhang et al. 2019).](image-url)
Figure 11. The reduction proportion of the peak strength parameters of the specimen with boreholes relative to the intact specimen (I): (a) $X_{\sigma_c}$; (b) $X_{\varepsilon_p}$; (c) $X_{u_p}$; (d) $X_{u_q}$; (e) $X_{W_{ET}}$. 
(Xie et al. 2005). However, the rockburst was primarily induced by the sudden release of the $\mu_P$ of the rocks. Hence, studying the $\mu_P$ of the specimen after DPR is feasible and reliable in explaining the mechanism of DRR in reducing the probability of rockbursts from an energy perspective.

In summary, as the intensity of rockburst is closely related to the peak elastic energy, it is rational to use $W_{ET}$ to quantitatively analyze the rockburst proneness of rock after DPR and to measure the sensibility of DPR for weakening rockbursts. In addition, to further evaluate $W_{ET}$ to reduce the risk of rockbursts after DPR and to select a reasonable DPR method, the relationship between the failure characteristics and $W_{ET}$ of the specimen, and the effects of the number and arrangement angle of boreholes on $W_{ET}$ are discussed hereinafter.

### 5.1. Relationship between the failure characteristics and $W_{ET}$

Brittle red sandstone was tested in this study, whose $W_{ET}$ was 3.88 (with a low rockburst tendency of $2 < W_{ET} < 5$) (Gong et al. 2019a). Figure 8 shows the
Figure 12. Effects of the number of boreholes (N) on peak-strength strain energy storage index $W_{ET}^p$. 
$W_{ET}^P$ of the red sandstone specimens with different arrangements of prefabricated boreholes. The intact specimen I had the largest $W_{ET}^P$ (3.88). The $W_{ET}^P$ of the specimens with prefabricated boreholes were lower than that of specimen I, and the range of reduction was 23.2%–70.2% (Figure 12e). Specimen T-D had the largest reduction of $W_{ET}^P$ relative to the intact specimen (I), resulting in a decrease of 70.2%. We can conclude that drilling can change the $W_{ET}^P$ of the rock specimens. That is, DPR is an effective method of reducing the $u_e^P$ stored in rocks. In addition, Figure 9 shows the failure characteristics of the red sandstone specimens with different borehole arrangements. The exfoliation and ejection of rock fragments were observed during the failure process of the specimens when the critical failure point at which the specimens would fail was instantaneously attained (from the initial rock failure phase to the final rock failure). Examining the relationship between the failure characteristics and $W_{ET}^P$, we observed that the failure characteristics agreed with the energy index $W_{ET}^P$. For example, the intact red sandstone specimen (I), whose $W_{ET}^P$ was 3.88, failed more violently. The entire failure process lasted 6.192 s. Meanwhile, since a large amount of elastic strain energy was stored in the specimen during loading, many rock fragments and debris were ejected when the specimen attained the critical failure point, accompanied by a continuous crisp cracking sound (Figure 9a). The $W_{ET}^P$ of the specimens with boreholes was lower, and their failure intensities were than that of specimen I. For example, the entire failure process of specimen T-D (Figure 9g), whose $W_{ET}^P$ was 2.280, lasted 0.192 s, and a small amount of powder and debris was ejected from the upper and lower parts of the specimen near the indenter, whereas the specimen remained still relatively intact after final failure. This indicated that the failure intensity characteristics of red sandstone specimens can be quantitatively described by $W_{ET}^P$, and the failure intensity agreed with the $W_{ET}^P$ values.

5.2. Effect of the number of boreholes on $W_{ET}^P$

Figure 12 shows the effect of borehole number on $W_{ET}^P$. $W_{ET}^P$ decreased with an increasing number of boreholes, e.g. when the arrangement angle of boreholes with the loading direction was 90°, $W_{ET}^P$ decreased as the number of boreholes increased, which was 28.9% lower than that of specimen I (Figure 12a). When the arrangement angle of boreholes with the loading direction was 27° (diagonal arrangement), the $W_{ET}^P$ decreased with the increasing number of boreholes. The $W_{ET}^P$ of specimen T-D decreased by 70.2% relative to specimen I (Figure 12b); when the arrangement angle of boreholes with the loading direction was 0°, $W_{ET}^P$ tended to decrease with the increasing number of boreholes, which was 43.4% lower than that of specimen I (Figure 12c). We can conclude that as the number of boreholes increases, $W_{ET}^P$ exhibits a downward trend, i.e. the more pressure relief borehole are drilled into a rock, the lower the rockburst proneness is (note: in actual in situ problems, based on the principle that fewer drillings is adopted as much as possible, this study only considered a maximum of three boreholes).
5.3. Effect of the arrangement angle of boreholes on $W_{ET}^P$

Figure 13 shows the effect of the arrangement angle of multiple boreholes on $W_{ET}^P$. When the number of boreholes was 2, the $W_{ET}^P$ of the specimens were 3.010 (D-H), 2.494 (D-D), and 3.148 (D-V). When the number of boreholes is 3, the $W_{ET}^P$ of the specimens were 3.025 (T-H), 2.280 (T-D), and 3.148 (T-V). As the arrangement angle with the loading direction changed from 90° to 0°, $W_{ET}^P$ first decreased and then increased (Figure 13a). Specifically, $W_{ET}^P$ attained its the minimum value when the boreholes were diagonally arranged (D-D). When the number of boreholes was 3, $W_{ET}^P$ exhibited the same changing trend with the specimens with two boreholes (Figure 13b).
Thus, $W_{ET}^P$ attains the minimum value when the boreholes are arranged diagonally. This is because diagonally arranged boreholes can accelerate the shear failure of red sandstone specimens. In our results, during the axial loading process of the intact red sandstone specimen (I), the crack initiated at the end corner near the pressure plate and extended diagonal. Finally, it formed a macro shear failure mode. Compared with the intact red sandstone specimen, the specimen with two or three boreholes arranged diagonally effectively reduced the impact tendency of rock. This was because the cracks between the boreholes developed, fused, coalesced and penetrated along the direction of the rock bridge, which accelerated the shear failure of the red sandstone and caused it to store less elastic energy. Therefore, the boreholes should be arranged diagonally to increase the efficiency of eliminating rock rockburst proneness. Additionally, we can infer that when DPR is conducted in high-stress areas, the drilling holes should be arranged along the diagonal of the direction in which the rock bears the maximum principal stress (i.e. the occurrence of shear failure’s direction) because it can effectively reduce the elastic energy stored in the rock.

5.4. Relationship between the peak compressive strength and $W_{ET}^P$

Based on the above analysis, we further explored the relationship between $\sigma_c$ and $W_{ET}^P$ of rock specimens, as well as comparatively analyzed the effects of the number and arrangement angle of boreholes on $\sigma_c$ and $W_{ET}^P$. A good correspondence was observed between $\sigma_c$ and $W_{ET}^P$ of rock specimens (Figure 14). The larger $\sigma_c$ is, the greater $W_{ET}^P$ of rock specimens is. We also observed that when the number of boreholes ($N$) increased from 1 to 3, the $\sigma_c$ and $W_{ET}^P$ of rock specimens exhibited a downward trend (the triangle symbols distributed in the black triangle frame and small squares in the red triangle area represents the data of rock specimens with two and three holes, respectively.). The decrease $W_{ET}^P$ and $\sigma_c$ of rock specimen with three holes was more noticeable. In addition, it can also be seen that, when the number of holes was 2 or 3 and the hole arrangement angle was $27^\circ$, $\sigma_c$ and $W_{ET}^P$ of the rock specimens were the smallest, compared with the arrangement angle of boreholes with the loading direction set to $0^\circ$ or $90^\circ$. Specimen T-D with three holes and an angle of $27^\circ$ between the borehole arrangement and loading direction had the lowest $\sigma_c$ and $W_{ET}^P$. The above analysis indicates that the borehole arrangement angle affects $\sigma_c$ and $W_{ET}^P$ more than the number of boreholes.

In summary, the results confirmed that the bursting failure intensity of red sandstone can be quantitatively characterized by the PESI ($W_{ET}^P$). The result indicated that the rockburst proneness of the specimens with prefabricated boreholes was weaker than that of the intact specimen, the PESI of the red sandstone specimens with boreholes decreased by 23.2%–70.2% compared with that of the intact specimen, i.e. DPR can effectively reduce the rockburst proneness of rocks. Furthermore, $W_{ET}^P$ was affected by the number and arrangement angle of boreholes. It decreased with the number of boreholes increased, and first decreased and then increased when the arrangement angle with the loading direction
changed from 90° to 27° and then to 0°. When the boreholes were arranged diagonally, the efficiency of eliminating rock rockburst proneness was the best. Additionally, the borehole arrangement angle affected peak compressive strength and rockburst proneness more than the number of boreholes did. These findings provide an effective method of eliminating rockbursts in potential rockburst areas. In addition, this paper presents our preliminary study (the specimens with prefabricated boreholes were used to investigate the effects of drilling on the rockburst proneness of rocks). In the future, in order to simulate the in-situ DPR conditions, we will conduct real-time drilling on the rock specimens whilst loading to investigate the effect of DPR on reducing rockbursts.

6. Conclusions

In this study, the rockburst proneness of red sandstone specimens with and without prefabricated boreholes was investigated using a series of SCLUC tests. The main conclusions are as follows:

1. The failure intensity of red sandstone specimens can be quantitatively described by the peak-strength strain energy storage index (PESI) $W_{PE}^P$, i.e. the failure intensity agrees well with $W_{PE}^P$ of the specimens. The $W_{PE}^P$ of the red sandstone specimens with boreholes decreased by 23.2%–70.2% compared with that of the intact specimens, i.e. drilling pressure relief (DPR) can effectively reduce the rockburst proneness of a rock.

2. $W_{PE}^P$ decreases as the number of boreholes increases, i.e. the more pressure relief borehole are drilled into a rock, the lower the rockburst proneness is. As the arrangement angle with the loading direction changes from 90° to 27° and then to 0°, $W_{PE}^P$ first decreases and then increases; when the pressure relief boreholes

Figure 14. Relationship between peak compressive strength ($\sigma_c$) and peak-strength strain energy storage index ($W_{PE}^P$).
are arranged diagonally, the efficiency of eliminating rockburst proneness is the best.

3. There was a good correspondence between \( \sigma_c \) and \( W_{ET}^p \) of the rock specimens. A larger \( \sigma_c \) resulted in a larger \( W_{ET}^p \). The borehole arrangement angle affects rockburst proneness more than the number of boreholes does.

**ORCID**

Zhichao He [http://orcid.org/0000-0001-6095-2554](http://orcid.org/0000-0001-6095-2554)

**Data availability statement**

The data that support the findings of this study are available from the corresponding author, Professor Fengqiang Gong, upon reasonable request.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

**Funding**

This work was supported by the National Natural Science Foundation of China (Grant No. 41877272), the Fundamental Research Funds for the Central Universities of Central South University (Grant No. 2021zzts0868) and the Fundamental Research Funds for the Central Universities of Southeast University (Grant No. 2242021R10080).

**References**

Bernabé Y, Revil A. 1995. Pore-scale heterogeneity, energy dissipation and the transport properties of rocks. Geophys Res Lett. 22(12):1529–1532.

Cai MF. 2016. Prediction and prevention of rockburst in metal mines – a case study of Sanshandao gold mine. J Rock Mech Geotech. 8(2):204–211.

Chen B, Xia ZG, Xu YD, Liu S, Liu XZ. 2021. Failure characteristics and mechanical mechanism of study on red sandstone with combined defects. Geomech Eng. 24(2):179.

Deng Y, Chen M, Jin Y, Zou D. 2016. Theoretical analysis and experimental research on the energy dissipation of rock crushing based on fractal theory. J Nat Gas Sci Eng. 33:231–239.

Durrheim RJ, Haile A, Roberts MKC, Schweitzer JK, Spottiswoode SM, Klokow JW. 1998. Violent failure of a remnant in a deep South African gold mine. Tectonophysics. 289(1–3):105–116.

Fairhurst CE, Hudson JA. 1999. Draft ISRM suggested method for the complete stress-strain curve for intact rock in uniaxial compression. Int J Rock Mech Min Sci. 36:281–289.

Feng XT, Pei SF, Jiang Q, Zhou YY, Li SJ, Yao ZB. 2017. Deep fracturing of the hard rock surrounding a large underground cavern subjected to high geostress: in situ observation and mechanism analysis. Rock Mech Rock Eng. 50(8):2155–2175.

Feng XT, Zhou YY, Jiang Q. 2019. Rock mechanics contributions to recent hydroelectric developments in China. J Rock Mech Geotech Eng. 11(3):511–526.

Gong FQ, Wang YL, Luo S. 2020. Rockburst proneness criteria for rock materials: review and new insights. J Cent South Univ. 27(10):2793–2821.
Gong FQ, Wang YL, Wang ZG. 2021. A new criterion of coal burst proneness based on the residual elastic energy index. Int J Min Sci Technol. 2095–2686. https://doi.org/10.1016/j.ijmst.2021.04.001.

Gong FQ, Yan JY, Li XB. 2018. A new criterion of rock burst proneness based on the linear energy storage law and the residual elastic energy index. Chin J Rock Mech Eng. 37(09):1993–2014.

Gong FQ, Yan JY, Li XB, Luo S. 2019a. A peak-strength strain energy storage index for rock burst proneness of rock materials. Int J Rock Mech Min Sci. 117:76–89.

Gong FQ, Yan JY, Luo S, Li XB. 2019b. Investigation on the linear energy storage and dissipation laws of rock materials under uniaxial compression. Rock Mech Rock Eng. 52(11):4237–4255.

He ZC, Gong FQ, Wu WX, Wang WH. 2021. Experimental investigation of the mechanical behaviors and energy evolution characteristics of red sandstone specimens with holes under uniaxial compression. Bull Eng Geol Environ. 80(7):5845–5865.

Huang B, Guo WY, Fu ZY, Zhao TB, Zhang LS. 2018. Experimental investigation of the influence of drilling arrangements on the mechanical behavior of rock models. Geotech Geol Eng. 36(4):2425–2436.

Huang MQ, Wu AX, Wang YM, Han B. 2014. Geostress measurements near fault areas using borehole stress-relief method. T Nonferr Metal Soc. 24(11):3660–3665.

Huang YH, Yang SQ, Tian WL. 2019. Cracking process of a granite specimen that contains multiple pre-existing holes under uniaxial compression. Fatigue Fract Eng Mater Struct. 42(6):1341–1356.

Jia CY, Jiang YJ, Zhang XP, Wang D, Wang CS. 2017. Laboratory and numerical experiments on pressure relief mechanism of large-diameter boreholes. Chin J Geotech Eng. 39:1115–1122.

Jiang JQ. 2021. Experimental investigation on uniaxial compressive mechanical characteristics of red-sandstone containing single fissure after rainfall infiltration. Arab J Geosci. 14(5):1–11.

Jiang Q, Feng XT, Xiang TB, Su GS. 2010. Rockburst characteristics and numerical simulation based on a new energy index: a case study of a tunnel at 2,500m depth. Bull Eng Geol Environ. 69(3):381–388.

Ju Y, Wang HJie, Yang Y, Hu QAng, Peng R. 2010. Numerical simulation of mechanisms of deformation, failure and energy dissipation in porous rock media subjected to wave stresses. Sci China Technol Sci. 53(4):1098–1113.

Kaiser PK, Ming C. 2012. Design of rock support system under rockburst condition. J Rock Mech Geotech. 4(3):215–227.

Keneti A, Sainsbury BA. 2018. Review of published rockburst events and their contributing factors. Eng Geol. 246:361–373.

Kidybiński A. 1981. Bursting liability indices of coal. Int J Rock Mech Min Sci. 18(4):295–304.

Konicek P, Soucek K, Stas L, Singh R. 2013. Long-hole destress blasting for rockburst control during deep underground coal mining. Int J Rock Mech Min Sci. 61:141–153.

Li TC, Du YT, Zhu QW, Ran JL, Zhang H, Xing XY. 2021. Experimental study on strength properties, fracture patterns, and permeability behaviors of sandstone containing two filled fissures under triaxial compression. Bull Eng Geol Environ. 80:5921–5938.

Li Y, Huang D, Li XA. 2014. Strain rate dependency of coarse crystal marble under uniaxial compression: strength, deformation and strain energy. Rock Mech Rock Eng. 47(4):1153–1164.

Li YY, Zhang SC, Gao LQ, Kong Dz, Kong H. 2016. Mechanism and prevention of pressure burst in step region based on overburden strata movement of unequal length working face. Rock Soil Mech. 37(11):3283–3290.

Li ZL, Dou LM, Cai W, Wang GF, Ding YL, Kong Y. 2016. Roadway stagger layout for effective control of gob-side rock bursts in the longwall mining of a thick coal seam. Rock Mech Rock Eng. 49(2):621–629.
Lin P, Wong RH, Tang CA. 2015. Experimental study of coalescence mechanisms and failure under uniaxial compression of granite containing multiple holes. Int J Rock Mech Min Sci. 77:313–327.

Liu HG, He YN, Xu JH, Han LJ. 2007. Numerical simulation and industrial test of boreholes destressing technology in deep coal tunnel. J China Coal Soc. 32:33–37.

Liu J, Jiang F, Sun G, Zhang Z, Tan W. 2014. Mechanism of intensive venting pulverized coal to prevent coal burst and its application. Chin J Rock Mech Eng. 33:747–754.

Luo Y. 2020. Influence of water on mechanical behavior of surrounding rock in hard-rock tunnels: an experimental simulation. Eng Geol. 277:105816.

Meng QB, Zhang MW, Han L, Pu H, Nie TY. 2016. Effects of acoustic emission and energy evolution of rock specimens under the uniaxial cyclic loading and unloading compression. Rock Mech Rock Eng. 49(10):3873–3814.

Ortlepp WD, Stacey TR. 1994. Rockburst mechanisms in tunnels and shafts. Tunnell Underground Space Technol. 9(1):59–65.

Panthi KK. 2012. Evaluation of rock bursting phenomena in a tunnel in the Himalayas. Bull Eng Geol Environ. 71(4):761–769.

Peng RD, Ju Y, Wang JG, Xie HP, Gao F, Mao LT. 2015. Energy dissipation and release during coal failure under conventional triaxial compression. Rock Mech Rock Eng. 48(2):509–526.

Qi YJ, Jing HW, Meng B, Dong ZX, Liu DJ. 2018. Experimental modelling on size effect of pressure relief hole. J Min Safe Eng. 35:539–544.

Ranjith PG, Zhao J, Ju M, De Silva RVS, Rathnaweera TD, Bandara AKMS. 2017. Opportunities and challenges in deep mining: a brief review. Engineering. 3(4):546–551.

Si XF, Huang LQ, Gong FQ, Liu XL, Li XB. 2020. Experimental investigation on influence of loading rate on rockburst in deep circular tunnel under true-triaxial stress condition. J Cent South Univ. 27(10):2914–2929.

Su YQ, Gong FQ, Luo S, Liu ZX. 2021. Experimental study on energy storage and dissipation characteristics of granite under two-dimensional compression with constant confining pressure. J Cent South Univ. 28(3):848–865.

Sujatha V, Kishen JMC. 2003. Energy release rate due to friction at bimaterial interface in dams. J Eng Mech. 129(7):793–800.

Tang JZ, Yang SQ, Elsworth D, Tao Y. 2021. Three-dimensional numerical modeling of grain-scale mechanical behavior of sandstone containing an inclined rough joint. Rock Mech Rock Eng. 54(2):905–919.

Tang LZ, Pan CL, Wang WX. 2002. Surplus energy index for analysing rock burst proneness. J Cent South Univ T. 33(2):129–132.

Wang JA, Park HD. 2001. Comprehensive prediction of rockburst based on analysis of strain energy in rocks. Tunnell Underground Space Technol. 16(1):49–57.

Wang P, Jia HJ, Zheng PQ. 2020. Sensitivity analysis of bursting liability for different coal-rock combinations based on their inhomogeneous characteristics. Geomat Nat Haz Risk. 11(1):149–159.

Wang Q, Hu XL, Zheng WB, Li LX, Zhou C, Ying CY, Xu C. 2021. Mechanical properties and permeability evolution of red sandstone subjected to hydro-mechanical coupling: experiment and discrete element modelling. Rock Mech Rock Eng. 54(5):2405–2423.

Wang SW, Pan JF, Liu SH, Xia YX, Gao XJ. 2016. Evaluation method for rockburst-preventing effects by drilling based on energy-dissipating rate. J China Coal Soc. 41(S2):297–304.

Wasantha PLP, Ranjith PG, Shao SS. 2014. Energy monitoring and analysis during deformation of bedded-sandstone: use of acoustic emission. Ultrasonics. 54(1):217–226.

Wong RHC, Lin P. 2015. Numerical study of stress distribution and crack coalescence mechanisms of a solid containing multiple holes. Int J Rock Mech Min Sci. 79:41–54.

Wong LNY, Li Z, Kang HM, Teh CI. 2017. Dynamic loading of Carrara marble in a heated state. Rock Mech Rock Eng. 50(6):1487–1505.
Wu H, Zhao GY, Liang WZ. 2020. Mechanical properties and fracture characteristics of pre-holed rocks subjected to uniaxial loading: a comparative analysis of five hole shapes. Theor Appl Fract Mec. 105:102433.

Xie HP, Li LY, Peng RD, Ju Y. 2009. Energy analysis and criteria for structural failure of rocks. J Rock Mech Geotech. 1(1):11–20.

Xie HP, Peng RD, Ju Y, Zhou HW. 2005. Energy analysis of rock failure. Chin J Rock Mech Eng. 24:2603–2608.

Xu L, Gong FQ, Luo S. 2021. Effects of pre-existing single crack angle on mechanical behaviors and energy storage characteristics of red sandstone under uniaxial compression. Theor Appl Fract Mech. 113:102933.

Yang JJ, Gong FQ. Liu Dq, Liu Zx 2020. Experimental study on the influence of specimen shape on rockburst proneness of red sandstone. Shock Vib. 2020(9):1–17.

Yang SQ, Jing HW, Wang SY. 2012. Experimental investigation on the strength, deformability, failure behavior and acoustic emission locations of red sandstone under triaxial compression. Rock Mech Rock Eng. 45(4):583–606.

Yang SQ, Liu XR, Jing HW. 2013. Experimental investigation on fracture coalescence behavior of red sandstone containing two unparallel fissures under uniaxial compression. Int J Rock Mech Min Sci. 2013 (63):82–92.

Zeng W, Yang SQ, Tian WL. 2018. Experimental and numerical investigation of brittle sandstone specimens containing different shapes of holes under uniaxial compression. Eng Fract Mech. 200:430–450.

Zhang D-X, Guo W-Y, Zang C-W, Gong X-F, Li Z-H, Qiu Y, Chen W-g. 2020. A new burst evaluation index of coal–rock combination specimen considering rebound and damage effects of rock. Geomat Nat Haz Risk. 11(1):984–999.

Zhang Q, Sun GQ, Suo JW, Wang HJ. 2017. The 3D numerical simulation of deep granite borehole unloading. Chin J App Mech. 34:988–994.

Zhang Q, Wang E, Feng X, Niu Y, Ali M, Lin S, Wang H. 2020. Rockburst risk analysis during high-hard roof breaking in deep mines. Nat Resour Res. 29(6):4085–4101.

Zhang SC, Li YY, Shen B, Sun XZ, Gao LQ. 2019. Effective evaluation of pressure relief drilling for reducing rock bursts and its application in underground coal mines. Int J Rock Mech Min Sci. 114:7–16.

Zhang ZZ, Gao F. 2015. Experimental investigation on the energy evolution of dry and water-saturated red sandstones. Int J Min Sci Technol. 25(3):383–388.

Zhou H, Meng F, Zhang C, Hu D, Yang F, Lu J. 2015. Analysis of rockburst mechanisms induced by structural planes in deep tunnels. Bull Eng Geol Environ. 74(4):1435–1451.

Zhu QH, Lu WB, Sun JS, Luo Y, Chen M. 2009. Prevention of rockburst by guide holes based on numerical simulation. Int J Min Sci Technol. 19(3):346–351.

Zhu ST, Jiang FX, Shi XF, Sun GJ, Zhang H. 2015. Energy dissipation index method for determining rockburst prevention drilling parameters. Rock Soil Mech. 36:2270–2276.