Determination of an intrinsic proneness index for strainburst and its verification by true triaxial compression tests

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Abstract. A part of the elastic strain energy stored in Class II rock will be converted into kinetic energy, which results in rock ejection after the peak stress. This part of the strain energy is the intrinsic potential energy for strainburst. Therefore, the strainburst proneness of the rock can be quantitatively estimated by the intrinsic burst energy density or the corresponding intrinsic ejection velocity. This study aims to validate the idea of using the intrinsic ejection velocity as a strainburst proneness index by laboratory true triaxial compression tests. In the study, servo-controlled uniaxial compression tests were conducted on six types of rock. The intrinsic burst energy density of these rocks was determined based on the stress–strain curves of the rocks obtained under uniaxial compression. The strainburst proneness of the rocks was then assessed. The same types of rock were then carried out single-free-face true triaxial compression testing to examine the rationality of the evaluation result.

1. Introduction

Rockburst in underground rock excavation has become increasingly prominent with the increasing number and depth of tunnels and underground chambers in hydropower construction, civil and mining engineering [1–4]. It is one of the main forms of disaster occurring in deep underground excavation [5]. Severe strainbursts usually occur when the excavation is carried out in an undisturbed rock mass in a depth of more than 1 km. The occurrence of rockburst affects the safety of personnel and equipment. In view of the hazard posed and the complexity of the phenomenon, the assessment of rockburst risk is important.

The rockburst proneness can be used to estimate the intensity of a rockburst in the preliminary design stage of an underground engineering work. At present, evaluation of the rockburst proneness is mainly performed based on energy release and brittleness estimated on the stress–strain curve of rock specimens under uniaxial compression. The typical indices of the rockburst proneness are discriminant index of impact property [6], strain energy storage index [7], decreased modulus index [8], potential energy of elastic strain [9], rock brittleness index [10], and peak-strength strain energy storage index [11]. These discriminant indices are helpful for rock support design in the preliminary design stage of deep underground engineering works. However, some of the indices are difficult to determine, some are not consistent each other, and some are lack of verifications. Therefore, the existing rockburst proneness indices are still unsatisfactory in providing an objective estimation of rockburst risk for a given rock mass.

In this study, the intrinsic burst energy density (IBED) of six types of rocks was determined based on the stress–strain curves of the rocks obtained under uniaxial compression. The burst proneness of the
rocks was then assessed. The same types of rock were then tested by single-free-face true triaxial compression (TTC) tests to examine the burst intensity of the rocks.

2. An index for strainburst proneness

Figure 1 shows a schematic stress–strain curve of Class II rock under uniaxial compression. For Class II rock, under servo-controlled loading conditions, the axial stress begins to decrease after reaching the peak stress point P, and the axial strain reverts to point A with the decrease in the axial stress, as shown in Figure 1. Point A is the turning point of the post-peak strain. Below point A, the axial strain begins to increase with the decrease in axial stress, and it returns to the strain of the peak stress P at point B. Thereafter, external energy needs to be input for further rock fracture. After passing through the peak stress P, a portion of the elastic strain energy accumulated in the pre-peak stage is dissipated for rock fracturing, which is represented by the area bounded by OPABCO in Figure 1 ($W_{bk}$). The rest portion of the elastic strain energy, represented by the shaded area $W_{bk}$ in the Figure 1, is released when the axial stress drops from the peak stress P to point B. Under servo-controlled loading conditions, the actuator of the testing machine retracts, and the released strain energy is returned to the testing machine. If the test is not servo-controlled, no matter under stress-control or strain-control, this portion of strain energy will be transformed to kinetic energy to eject the rock, that is, a rockburst occurs. The elastic energy released in Class II rock mainly depends on the lithology of the rock and is a constant per unit volume of the rock. Therefore, it is called the intrinsic burst energy density (IBED) of the rock in this paper [12]. The intrinsic burst energy density $W_{bk}$ is a parameter that expresses the strainburst proneness of Class II rock [13].

When a strainburst occurs, a portion of the rock is ejected and displaced from the original place. The larger the intensity of the strainburst, the higher the rock ejection velocity. The average ejection velocity ($v$) of the rock can be derived from the intrinsic burst energy density $W_{bk}$ as follows:

$$v = \sqrt{\frac{2W_{bk}}{\rho}}$$

where $\rho$ is the density of the rock in kg/m$^3$, the ejection velocity $v$ is in m/s and the intrinsic burst energy density $W_{bk}$ is in kJ/m$^3$. Both $W_{bk}$ and $v$ express the intensity of the possible strainburst, but the ejection velocity is more direct and easier to understand.

![Figure 1. Schematic stress–strain curve of Class II rock under uniaxial compression. $W_{bk}$ is the intrinsic burst energy density, representing the strain energy in the rock transformed to kinetic energy during rockburst, and $W_{bf}$ is the strain energy dissipated for rock fracturing.](image)

3. Evaluation of the strainburst proneness of some rocks

3.1. Specimens and experiment procedure

Six types of rocks were tested under uniaxial compression for the determination of their strainburst proneness. The types and parameters of the rocks are presented in Table 1. Cylindrical specimens in dimensions of Ø50 mm × 100 mm were prepared according to the method suggested by the International Society for Rock Mechanics and Rock Engineering [14]. The specimens of the same rock type were drilled in the same block to reduce bias caused by possible mineral inhomogeneity.

The uniaxial compression tests were conducted on the ZTR-276 hard rock triaxial apparatus, which has an axial load capacity of 2000 kN and a frame stiffness of 7 GN/m. The complete stress–strain curve of each rock specimen was registered under radial displacement control through built-in linear
variable differential transformer (LVDT) sensors with a measurement range of 5 mm and a precision of 0.1%.
The testing procedure was divided into two steps. First, the rock specimens were axially loaded at a rate of 0.5 MPa/s under axial stress control until the axial stress reached approximately 60% of the expected peak stress. Then the loading mode was switched to radial displacement control, and the radial displacement rate at the moment of switching was used to continue the loading process. To ensure the repeatability of the test results, two specimens were tested for each rock type.

**Table 1.** Rock types and physical and mechanical properties.

| Rock source          | Rock type | ρ (kg/m³) | P-wave vel. (m/s) |
|----------------------|-----------|-----------|-------------------|
| Jinzhou, China       | Granite   | 2642      | 4624              |
| Shandong, China      | Granite   | 2605      | 3710              |
| Beishan, China       | Granite   | 2590      | 3736              |
| Yunnan, China        | Sandstone | 2240      | 2637              |
| Shenyang, China      | Sandstone | 2588      | 4386              |
| Chifeng, China       | Basalt    | 2902      | 5900              |

3.2. Test results and analysis

Figure 2 shows the stress–strain curves of six types of rock specimens obtained under uniaxial compression. It is seen in the figure that the two curves of each rock type exhibit good repeatability. Taking the Shandong granite specimens as an example to analyze its stress–strain behavior. Figure 2b shows that the rock specimens exhibit initial compaction, elastic deformation, stable rock fracturing, and unstable rock fracturing in pre-peak stage. In post-peak stage, the axial strain of the Shandong granite specimens first reverses with the decrease in the axial stress, implying that the stored strain energy is partially released out of the specimens and the rock is of Class II. The intrinsic burst energy density \( W_{bk} \) of the Shandong granite is 14.4 kJ/m³. The corresponding intrinsic ejection velocity \( v \), calculated using Eq. (1), is 3.3 m/s. Two types of sandstone specimens, Shenyang sandstone and Yunnan sandstone, were tested in the study. Figure 2(d) and (e) shows the stress–strain curves of the sandstone specimens under uniaxial compression. The Shenyang sandstone is stronger than the Yunnan sandstone. The difference between the two sandstones may be related to their microstructure or stress history. Even if it is sandstone in the same area, the strength of sandstone with a buried depth of 4800 m is 5.5 times that of sandstone with a buried depth of 1000 m [15].

![Figure 2](image_url)
The intrinsic ejection velocities of the six rocks are calculated using Eq. (1) and are presented in Table 2, ranging from 1.0 to 4.0 m/s. Back-calculations have shown that the average ejection velocity of rockburst bodies is usually lower than 6 m/s, even though Ortlepp and Stacey claimed that the ejection velocity of rock could be 10 m/s [16]. In reality, ejection velocities higher than 10 m/s have been observed only for small rock pieces in rockburst events. Since the intrinsic ejection velocity is close to the average ejection velocities observed at sites, it is possible that the kinetic energy of a strainburst comes mainly from the intrinsic burst energy of the rock, that is, the excess elastic energy released by the burst rock. Based on the magnitude of the intrinsic ejection velocity, the strainburst proneness of the six rocks is in such order from high to low: Jinzhou granite, Shandong granite, Chifeng basalt, Shenyang sandstone, Yunnan sandstone, and Beishan granite.

**Table 2.** Intrinsic strainburst ejection velocity \( v \), calculated using Eq. (1)

| Rock type         | Average \( v \) (m/s) | Rock type         | Average \( v \) (m/s) |
|-------------------|-----------------------|-------------------|-----------------------|
| Jinzhou granite   | 4.0                   | Shenyang sandstone| 2.8                   |
| Shandong granite  | 3.3                   | Yunnan sandstone  | 2.1                   |
| Chifeng basalt    | 3.0                   | Beishan granite   | 1.0                   |

### 4. Laboratory simulation tests of strainburst

#### 4.1. Test background

Take a small rock prism at the contour of an underground opening as an example. Before excavation, the prism is pressed under the state of triaxial stresses with \( \sigma_1 > \sigma_2 > \sigma_3 \), where \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are the in-situ major, intermediate, and minor principal stresses, respectively. After excavation, the loading condition of the prism is changed to such a state that it is stressed on five of its six faces with one face of free stress, as shown in figure 3. The radial stress (\( \sigma_r \)) on the tunnel surface is zero, but it is slightly greater than zero on the backside of the rock prism. The tangential stress (\( \sigma_\theta \)) is gradually increased during excavation and it becomes significantly greater than the major principal stress, that is, \( \sigma_\theta > \sigma_1 \) in figure 3b. When \( \sigma_\theta \) exceeds the rock strength, the rock will fail and a portion of the elastic strain energy stored in the rock will suddenly release resulting in a strainburst. Most strainbursts induced by tangential stress concentration usually occur within 2~5 hours or 1~3 days after excavation [17]. The burst delay implies that the rock failure is a progressive process. The loading condition and the failure process of the tunnel surface rock can be simulated in a single-free-face TTC test [18,19]. The six rock types were selected to conduct single-free-face TTC tests, the burst intensity of the specimens was ascertained by two parameters – the volume of burst pits in the specimen and the mass of the ejected fragments.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Sketches illustrating the stress state of (a) the rock element in the tunnel sidewall on the site and (b) the specimen for the single-free-face TTC test in the laboratory.
4.2. Specimens and test procedure

In the single-free-face TTC tests, the rock specimens were prismatic with dimensions of 100 mm × 100 mm × 200 mm. All the prismatic specimens of a given rock type in the TTC tests were prepared from the same rock as the cylindrical specimens for determination of the intrinsic burst energy density of the rock. At least two single-free-face TTC tests were performed for each type of rock.

The single-free-face TTC tests in this study were conducted on the Guangxi University’s true triaxial rockburst testing machine [17,18], which has a stiffness of 9 GN/m in the vertical direction and 5 GN/m in the horizontal direction. The axial load capacity of the machine is 5000 kN, and the lateral load capacity is 3500 kN. Loads can be independently applied to the specimen in three orthogonal directions.

The stress state of the rock specimen in the single-free-face TTC tests is shown in figure 4a. The stress paths in the test are illustrated in figure 4b. First, \( \sigma_1 \), \( \sigma_2 \), and \( \sigma_3 \) are synchronously applied to 5 MPa. Then, \( \sigma_1 \) and \( \sigma_2 \) are simultaneously increased to 30 MPa while \( \sigma_3 \) remains unchanged. Finally, \( \sigma_1 \) is increased until failure of the specimen while both \( \sigma_2 \) and \( \sigma_3 \) remain unchanged. The stresses are applied at a rate of 0.5 MPa/s in all three stages.

![Figure 4](image.jpg)

**Figure 4.** The stress state of the rock specimen and (b) the loading paths in single-free-face TTC tests.

4.3. Test results and analysis

4.3.1. Failure mode

The failure modes of the rock specimens are shown in figure 5. The failure of the rock specimens was mainly limited on the free face and in the \( \sigma_1-\sigma_2 \) loading plane. Burst pits appear on the free face and fine white powders are on the surface of the burst pits, such as, the Jinzhou granite specimens. In addition, many extension fractures appear in locations close to the free face. Macro shear fractures are distant from the free face.

The volume of the burst pit in the rock specimen is a measure to evaluate the intensity of a strainburst. It seems that it is related to the extent of fracturing of rock specimens. Taking Jinzhou granite, Shandong granite, and Beishan granite as examples, large burst pits are generated on the free faces of the Jinzhou granite and Shandong granite specimens (figures 5a, b), but there are not many fractures in these rock specimens. The burst pits on the free face of the Beishan granite specimens are relatively small, but there are more fractures in the specimens. This phenomenon is consistent with the distribution of the potential strain energy after the peak stress as described in figure 1. If the number of newly generated fractures in the rock specimen is small, a small portion of the strain energy, that is, \( W_{bf} \), will be dissipated for rock fracturing, whilst the portion for rock ejection (\( W_{ke} \)) will be greater, thus generating a larger pit volume. This is the case with the failure of the Jinzhou granite and Shandong granite (figures 5a, b). On the contrary, if the energy used to generate fractures is large, the energy for rock ejection will be small so that a smaller burst pit is created. The Beishan granite
exhibits this mode of failure (figure 5f). Based on the magnitude of the average volumes of the burst pits, the burst intensity of the six rocks is in such order from high to low: Jinzhou granite, Shandong granite, Chifeng basalt, Shenyang sandstone, Yunnan sandstone, and Beishan granite. The order of the six rock types by the average volumes of the burst pits is consistent with the order by the intrinsic ejection velocity.

**Figure 5.** Failure modes of all rock specimens in the single-free-face TTC tests.

### 4.3.2. The mass of ejected rock fragments

In the single-free-face TTC tests, the formation of burst pits on the free face of the rock specimens is mainly induced by two types of failures: strainburst which causes the ejection of rock fragments and extension spalling leading to the peeling of rock fragments under gravity. After the test, the fracture type can be judged from the distance between the ejected rock fragments and the free face of the specimen. Specifically, it is thought that the fragments are produced by strainburst if they spread all over around the specimen and the distance from the specimen is greater than 50 mm, whilst they are produced owing to spalling if the fragments are piled at the toe of the rock specimen. The mass of the ejected rock fragments of the specimens are presented in the diagram in figure 6a. It is seen that the
mass of the ejected rock fragments is similar for the two specimens in each rock type, indicating that the results are reliable. For the six rock types, the average masses of ejected rock fragments are 709.6 g for Jinzhou granite, 439.4 g for Shandong granite, 331.35 g for Chifeng basalt, 243.2 g for Shenyang sandstone, 164.1 g for Yunnan sandstone, and 114.8 g for Beishan granite, respectively. For comparison, the intrinsic ejection velocities of the six rock types are presented in figure 6b. It is seen that the order of the six rock types according to the mass of the ejected fragments in figure 6a is the same as the order according to the intrinsic ejection velocity in figure 6b.

![Figure 6](image_url)

**Figure 6.** (a) The masses of the ejected rock fragments of the six rock types and (b) the intrinsic strainburst ejection velocity v of six types of rocks.

5. Conclusions
The intrinsic burst energy density and the corresponding intrinsic ejection velocity of six rock types was measured on the stress–strain curves of cylindrical rock specimens under uniaxial compression. The intrinsic burst energy density is larger than zero in the six rock types, indicating that the above six rocks are prone to strainburst. The intrinsic ejection velocity of the rock ranges from 1 to 4.0 m/s among the six rock types.

The six rock types were selected to conduct single-free-face true triaxial compression tests. All specimens of the six rock types failed in the form of strainburst in the tests. The tests results show that the orders of the six rock types by the burst volume and mass are consistent with the order of the rocks by the intrinsic ejection velocity. Therefore, the intrinsic ejection velocity can be used as the strainburst proneness index.

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