Experimental study on revealing the mechanism of rockburst prevention by drilling pressure relief: status-of-the-art and prospects

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\textbf{ABSTRACT}

High stress caused by excavation is an inevitable part of deep underground rock mass engineering or mining process, which is the key to induce disasters such as rockbursts. Drilling pressure relief (DPR) is a measure to eliminate deep excavation stress and prevent rockburst disasters, which is simple but effective. The experimental research results based on macroscopic (mechanical behavior characteristics, energy evolution) and microscopic (crack evolution) perspectives to study the mechanism of rockburst prevention by DPR were reviewed. According to the stress state of deep surrounding rock and current testing equipment conditions, six development directions for studying the mechanism of rockburst prevention by DPR were proposed: (1) developing drilling rig test equipment for real-time DPR simulation test under high stress; (2) considering real-time DPR simulation test with cyclic load disturbance factors; (3) exploring the relationship between drilling’s spatial size and surrounding rock stress field and strain energy evolution under two-dimensional high stress; (4) combining with true triaxial testing system to simulate the real-time DPR after rock excavation; (5) focusing energy perspective to study the mechanism of rockburst prevention by DPR; and (6) calculating and visualizing the energy evolution inside the rock mass based on ‘real-time DPR test + numerical simulation calculation’.

\textbf{1. Introduction}

Rockburst is a typical deep engineering geological hazard induced by rock engineering excavation and mining disturbance. At present, with the continuous development of rock engineering to the deep, the frequency of rockburst is increasing. High incidence of rockburst disaster not only seriously restricts the development of underground space construction, but also endangers the security of underground...
construction staff and equipment (Jiang et al. 2010; Li et al. 2011; Panthi 2012; Feng et al. 2017; Leveille et al. 2017; Yang et al. 2017; Keneti and Sainsbury 2018; Cai et al. 2019; Naji et al. 2019; Vazaios et al. 2019; Li and Gong 2021; Wang et al. 2021; Gong, Pan, et al. 2021). For instance, more than 750 rockbursts occurred in the construction of the diversion tunnel of Jinping II hydropower station with the largest buried depth of 2525 m in China, causing serious injuries to personnel and equipment (Li et al. 2012; Zhang et al. 2012; Feng et al. 2013; Su, Chen, et al. 2017). The rockburst cases in Jingping II hydropower station were illustrated in Figure 1. In the construction Sangzhuling tunnel from Lhasa to Nyingchi, Sichuan, China, the maximum frequency of rockburst can reach 20 times a day, and the distance of rockburst can reach 40 m (CCTV News Client 2016; Gong, Pan, et al. 2021).

Stress caused by excavation is an inevitable part of underground rock mass engineering or mining process (Xu et al. 2015; Arshad et al. 2020). The above-mentioned rockbursts and other disasters are also due to the damaging effect caused by excavation stress. Therefore, to prevent and avoid the occurrence of deep rockburst disasters, eliminating the stress state caused by excavation has become a hot issue concerned by researchers (Ortlepp and Stacey 1994; Kaiser and Cai 2012; Sainoki et al. 2017; Su, Chen, et al. 2017; Cai 2019; Moganedi and Stacey 2019; Gong et al. 2020; Gong, Pan, et al. 2021; Si et al. 2020; Zhao et al. 2020). Over a century, various methods have been developed to contain damaging effects of strain rockbursts, the relevant classification details were shown in Figure 2 (Mitri 2000). There are three types of recognized methods: (1) alternative mining methods, (2) preconditioning methods and (3) surrounding rock support. Furtherly, the preconditioning methods can be divided into hydraulic pressure relief, drilling pressure relief (destress drilling), destressing roadway and destress blasting (Liu et al. 2019; Zhou et al. 2020). Currently, drilling pressure relief (DPR) technology has become a recognized measure for preventing rockbursts in deep engineering construction sites due to its simple conformation and strong applicability to geological conditions (Ma et al. 2020). The effect of on-site implementation is also more effective (Konicek et al. 2013; Zhu et al. 2015; Li, Zhang, et al. 2016; Li, Dou, et al. 2016). For instance, Li, Zhang, et al. (2016) carried out DPR in the stress concentration area of an excavation face, and found the electromagnetic radiation intensity of the surrounding rock mass evidently reduced after DPR. Li, Dou, et al. (2016) conducted about 3210 drillings in the roof.
rock formations of roadway Yuejin Coal Mine, and subsequently confirmed that the occurrence times of rockbursts were significantly reduced. Nevertheless, due to the complexity of the site’s geological conditions, relying on empirical DPR construction scheme cannot effectively prevent deep rockburst disasters. Thus, the mechanism of DPR in preventing rockburst to optimize DPR scheme for engineering site has been paid more and more attentions.

Laboratory test is an effective means to study the disaster-causing mechanism of rock engineering. In the study of the mechanism of rockburst prevention by DPR, many scholars also adopted laboratory test to investigate the mechanism of rockburst prevention by DPR. For example, the mechanical response (Lin et al. 2015; Jia et al. 2017; Zhang et al. 2017; Huang et al. 2018; Qi et al. 2018; Zeng et al. 2018; Huang et al. 2019; Wu et al. 2019; Zhang et al. 2019) and energy evolution mechanism (Wang et al. 2021; He, Gong, and Luo 2021; He, Gong, Wu, et al. 2021) of prefabricated drilled rock were explored through uniaxial compression test, and the action mechanism of DPR in the process of rockburst prevention was revealed according to results of the weakening effect of non-drilled rock specimen. The test results clarified the mechanism of rockburst prevention by DPR to a certain extent, which also provided a basis for optimizing DPR scheme. However, due to the lack of test equipment of the ‘loading first and then drilling’, most of existing works used the method of ‘drilling first and then loading’ to explore the mechanism of rockburst prevention by DPR. In fact, the pattern of ‘drilling first and then loading’ ignores the stress state of rock during DPR. We know that the high stress condition of rock mass is the key to induce deep rockburst. Besides, the aim of DPR is to reduce the high stress condition of rock mass and eliminate the elastic energy stored in rock mass. Hence, the development of ‘loading first and then drilling’ test equipment is significant to deeply reveal the mechanism of deep rockburst prevention by DPR. On this basis, DPR

Figure 2. Methods to contain damaging efforts of strain rockburst (reproduced from Mitri 2000; Zhou et al. 2020).
simulation test of the ‘two-dimensional loading + real-time DPR’ and ‘three-dimensional loading + unloading + real-time DPR’ can also be realized. By this means, the effect of excavation stress disturbance, drilling spatial size and other factors on DPR to prevent rockburst can also be considered, and the mechanism of DPR to prevent rockburst can be better revealed.

The organization of this paper is as follows. The theoretical action the mechanism of rockburst prevention by DPR is introduced in Section 2. Section 3 comprehensively summarizes and analyzes the experimental research status the mechanism of rockburst prevention by DPR from the aspect of rock mechanical behavior, crack evolution and strain energy storage. Section 4 outlines serval typical evaluation methods for evaluating DPR schemes. The development trend for revealing the mechanism of rockburst prevention by DPR in the laboratory is put forward in Section 5, based on the developing drilling rig test equipment and the real-time DPR simulation test under high stress, followed by a summary in Section 6.

2. Theoretical action mechanism of rockburst prevention by DPR

According to the effect of on-site DPR to prevent rockburst, relevant scholars have constructed a theoretical hypothesis action mechanism model of DPR to prevent rockburst, as shown in Figure 3. From the theoretical model, it can be observed that after DPR is carried out in the high-stress surrounding rock area, cracks will occur around the pressure relief drilling under the action of stress, and a plastic fracture zone will be generated. At the same time, the plastic crushing areas between the multiple pressure relief drillings will coalesce and run through each other, forming an integral pressure relief area. The formation of the pressure relief area makes the original rock stress transfer to the deep, and then adjusts the surrounding rock structure to prevent rockburst. In addition, related scholars have also given further explanations for the specific mechanism of rockburst prevention by DPR, that is, the formation of the pressure relief zone weakens the internal structure of the surrounding rock, leading to the release of the originally accumulated elastic strain energy. At the same time, the broken structure of the pressure relief zone also weakens the capacity of the surrounding rock to store elastic energy, thereby reducing the possibility of
Table 1. Schematics of the representative specimen used in the experimental.

| No. | Basic parameters of drillings | Scheme design drawing | Actual specimen photos |
|-----|-------------------------------|-----------------------|-----------------------|
| (a) | Drilling diameter Φ: 3, 5, 8, 10 mm (Huang et al. 2018). | ![Scheme design drawing](image) | ![Actual specimen photos](image) |
| (b) | Drilling diameter Φ: 12 mm (Zhang et al. 2019) | ![Scheme design drawing](image) | ![Actual specimen photos](image) |
| (c) | Drilling diameter Φ: 8, 10, 12 mm; Drilling depth \( l \): 30, 40, 50 mm; Drillings spacing \( d \): 20, 30, 40 mm (Jia et al. 2017) | ![Scheme design drawing](image) | ![Actual specimen photos](image) |
| (d) | Drilling diameter Φ: 8, 12, 16 mm (Zhang et al. 2017). | ![Scheme design drawing](image) | ![Actual specimen photos](image) |

(continued)
inducing rockburst. Therefore, drilling pressure relief can achieve the effect of preventing rockburst.

Actually, the action mechanism model of DPR to prevent rockburst constructed above is only a theoretical hypothesis model, which cannot fully serve the engineering site to optimize the DPR scheme. Based on theoretical analysis, the internal mechanism of rockburst prevention by DPR from the aspect of laboratory tests were further explored, such as the mechanics behavior (Jia et al. 2017; Huang et al. 2018; Zhang

Table 1. Continued.

| No. | Basic parameters of drillings | Scheme design drawing | Actual specimen photos |
|-----|------------------------------|-----------------------|-----------------------|
| (e) | Drilling diameter Φ: 5 mm; Drilling arrangement angle: 0°, 27°, 90° (He, Gong, and Luo 2021). | ![Scheme design drawing](image) | ![Actual specimen photos](image) |

Figure 4. The mechanical behavior characteristics specimen with different drilling parameters: (a) and (d) drilling diameter Φ; (b) and (e) drilling depth l; (c) and (f) drilling spacing d (reproduced from Jia et al. 2017).
et al. 2019), crack evolution (Yang et al. 2013, 2018; Lin et al. 2015; Wong and Lin 2015; Jia et al. 2017; Zeng et al. 2018; Huang et al. 2019; Wu et al. 2019), strain energy evolution (He, Gong, and Luo 2021; He, Gong, Wu, et al. 2021; Wang et al. 2021) of rock specimen with prefabricated drillings.

3. Research progress of laboratory test on the mechanism of rockburst prevention by DPR

3.1. Weakening characteristics of rock mechanical behaviors under different prefabricated drillings

High stress is an important factor inducing deep rockburst disaster (Qi et al. 2019). In addition, the engineering site also confirmed that DPR in high-stress areas can adjust the structure surround rock, reduce the number of stress concentrations caused by excavation disturbances, so as to change the high stress environment that induces rockbursts (Zhang et al. 2019). Therefore, some researchers have explored the mechanism of rockburst prevention by DPR from the weakening mechanism of the mechanical behavior of rock. To better analyze the mechanical behavior of rock after DPR, prefabricated drilled rock specimens were used as the testing specimen in the experiment. Table 1 listed the schematics of the representative specimens used in the experimental.

3.1.1. Influence of drilling spatial size on rock mechanical behaviors

To explore the mechanism of pressure relief in large-diameter drillings, Jia et al. (2017), Huang et al. (2018) and Zhao et al. (2018) explored the influence of drilling space size on drilling weakening rock mechanical properties. It was found that the peak compressive strength ($\sigma_c$) of specimen show a downward trend as the drilling diameter increases, i.e. large diameter drilling can weaken the mechanical behavior of rock more effectively. Taking the experimental results of Jia et al. (2017) as an example, the stress-strain curve and $\sigma_c$ under different drilling diameters were illustrated in Figure 4a and d. With the increase of the drilling diameter, the prefabricated drilled rock is more likely to enter the yield stage during the loading process, and the strength weakening effect is also more obviously. The acoustic emission (AE) characteristics of the specimens under different drilling diameters also confirmed this (Huang et al. 2018). When the diameter of the drilling is larger, the activity of the AE before the peak strength point is more intense, resulting in a weaker bearing capacity of specimen. In all, large-diameter drilling is more effective in weakening the mechanical behavior of rocks. In fact, in terms of the mechanism of DPR, this is because the larger drilling diameter causes more seriously damage to the interior of rock, which leads to a more obvious weakening of the mechanical behavior characteristics of rock. Thereby, it indicated that the larger the pressure relief zone radius was formed around the drilling after large-diameter DPR, which can more eliminate the high stress state of rock mass, reduce the stress concentration and rockburst prone-ness of rock mass. At the same time, it also confirmed that the effectiveness of large-diameter DPR proposed by relevant scholars (Liu et al. 2014).
Figure 5. Representative crack initiation and coalescence in granite sample containing three drillings under uniaxial compression. The ‘—’ and ‘↑↑’ represent the displacement direction of tensile crack and shear displacement, respectively (Lin et al. 2015).
Furthermore, the influence of drilling depth and spacing on the effect of DPR was also investigated (Lin et al. 2015; Jia et al. 2017). Jia et al. (2017) confirmed that the deeper the drilling depth, the better the weaken effect of rock mechanical property (Figure 4b and e). Meanwhile, reducing the spacing between drillings will improve the weakening effect of rock mechanical property (Figure 4c and f). The reason is that with the increase of drilling depth, the pressure relief range will gradually increase. At the same time, with the decrease of the distance between drillings, the pressure relief zones formed by the two drillings overlap lead to a larger pressure relief area. Therefore, the deeper the drilling depth, the smaller the spacing between drillings, and the better the pressure relief effect.

3.1.2. Influence of the number and arrangements of drillings on rock mechanical behaviors

In addition, He, Gong, and Luo (2021) and Zhang et al. (2019) also investigated the weakening effect of the number and arrangements of drillings on rock mechanical properties via uniaxial compression test. It was suggested that the strength weakening effect of the rock increases as the number of drillings increases. He, Gong, and Luo (2021) and Zhang et al. (2019) found that the arrangement of drillings significantly affects the mechanical properties of rocks. For example, when the three drillings are arranged along the horizontal, vertical and triangular, $\sigma_c$ of specimen were reduced by 19.1%, 24.8% and 41.8% respectively compared with the non-drilled specimen (Zhang et al. 2019). He, Gong, and Luo (2021) found that $\sigma_c$ of specimens decreased with the arrangement angle of drillings and loading direction from 90° to 27° (diagonal arrangement) then to 0°. Among them, the effect of reducing $\sigma_c$ of rocks was the best when the drillings were arranged along the diagonal (Figure 10). Besides, He, Gong, and Luo (2021) suggested that the effect of drilling arrangement angle on rock mechanical properties was greater than that of the drilling numbers. The above scholars have explored the mechanism of rockburst prevention by DPR based on the mechanical characteristics of drilling weakening rock.
3.2. Crack evolution mechanism and failure characteristics of rock with prefabricated drilling

As mentioned in Section 2, the formation of pressure relief area is caused by the broken area formed by the development and penetration of cracks in the rock mass around the pressure relief drilling under the action of high stress. The broken zone formed by the crack penetration makes the surrounding rock stress transfer to the deep part, which plays a role of pressure relief in high-stress zone. Therefore, in revealing the mechanism of rockburst prevention by DPR in high-stress areas, related studies have been conducted on the crack evolution mechanism of prefabricated drilled rock from the perspective of micromechanics.

3.2.1. The initiation and coalescence mechanism of cracks around drillings

To investigate the initiation and coalescence mechanism of cracks around drillings, Lin et al. (2015) investigated the crack evolution mechanism of prefabricated drilled granite specimens with different sizes, spacings, and distributions of drillings via uniaxial compression. The test results indicate that three types of typically cracks were initiated around the drilling under the interaction of stress, namely shear cracks, tensile cracks and mixed cracks, as shown in Figure 5. In addition, the crack coalescence modes between multiple boreholes were also determined according to the type of crack initiation, which are tensile crack coalescence pattern and mixed crack coalescence pattern. Based on this, Lin et al. (2015) suggested that the crack-coalescence mechanisms of specimens with drillings primarily determined by the arrangement (rock-bridge angle and length) of drillings. Besides, Huang et al. (2019) explored the cracking process of a granite specimen containing multiple prefabricated drillings via uniaxial test. The test results indicated that the failure mechanism of prefabricated drilled specimens was determined by the number and rock-bridge angle of drillings.

Additionally, on the basis of exploring the mechanism of crack initiation and coalescence around the drilling, the variation of the stress field around the drilling was also investigated. Wu et al. (2019) monitored the crack development and stress distribution of prefabricated drilled rock specimens with the digital image correlation (DIC) technology. The tests results suggested that under uniaxial compression, tensile...
stress first concentrated on the top and bottom of the drilling and gradually became compressive with increasing distance from the drilling boundary. Subsequently, the compressive stress concentration appeared on the sides of the drillings, leading to the

Figure 8. Final failure patterns of specimens with various drilling arrangements. (a) Different drilling diameters; (b) Different numbers of drillings in one row; (c) Different numbers of drilling rows (Zhao et al. 2018).
initiation and development of shear cracks. In final, a macroscopic failure mode combining shear cracks with the slabbing fracture zones was formed in prefabricated drilled red sandstone specimens (Figure 6). The specific calculation flow chart of the deformation of DIC technology is shown in Figure 7. Additionally, Zeng et al. (2018) studied the force field distribution before and during cracking of sandstone specimens with a drilling via uniaxial compression. The results show that the force fields effect the crack initiation and propagation, and the formed cracks also affect the force field distribution.

### 3.2.2. The effect of crack evolution mechanism on the failure characteristics of rock with prefabricated drilling

In addition to the crack initiation and coalescence mechanism around the drilling, the influence of the crack evolution mechanism on failure characteristics of rock with prefabricated drilling has also been paid more attention. For instance, Jia et al. (2017) explored the crack evolution mechanism of rock specimens under different prefabricated drilling diameters and drilling spacing through experiments and particle flow software (PFC). The results presented that as the increase of the drilling diameter, the cracks around the drilling were easier to initiate and develop, and more failure cracks were generated (According to the simulation results of PFC, the number of cracks under different drilling diameters is 1680 \((\Phi = 8 \text{ mm})\), 1714 \((\Phi = 10 \text{ mm})\), and 1756 \((\Phi = 12 \text{ mm})\), respectively). Meanwhile, the crack propagation pattern was clearer, and the corresponding pressure relief effect was also better. This is in accordance with the findings of Zhang et al. (2019). Besides, it was also found that the smaller the drilling spacing, the easier the crack coalesces and penetrates, which makes the number of cracks increase rapidly, and then forms a larger pressure relief zone. In addition, Jia et al. (2017) pointed out that the pressure relief caused by crack penetration is the essential cause of DPR. On this basis, Zhao et al. (2018) continued to explore the crack-dominated failure characteristics of specimen with different drilling arrangements via the PFC numerical simulation software. The test results indicate that for specimens with different drilling diameters, shearing accompanied by splitting is the main failure pattern, while for a row of specimens with different number of drillings, splitting accompanied by shearing is the main failure pattern. However, for specimens with different drilling row numbers, splitting or shearing failure patterns may occur. The final failure patterns of specimens with various drilling arrangements are shown in Figure 8. Furthermore, He, Gong, and Luo (2021) also explored the failure mechanism
of rock specimen with various arrangements of drillings, and the results pointed out that the rock specimens with various arrangement of drillings present three failure models, i.e. the splitting, shearing, and mixed splitting and shearing failure pattern.

3.3. Mechanism of strain energy storage and dissipation of rock under prefabricated drilling

According to the rockburst induction mechanism, rockburts refers to the phenomenon that elastic energy release of surrounding rock during deep engineering excavation or mining of ore bodies under high stress (Bernabé and Revil 1995; Hua and You 2001; Li et al. 2011; Peng et al. 2015; Miao et al. 2016; Qi et al. 2019; Gong, Pan, et al. 2021). The higher the stress of the surrounding rock mass, the more elastic
energy stored (Meng et al. 2016). Therefore, the storage and consumption of elastic energy of surrounding rock play a vital role in the induction of rockburst disasters. However, DPR in deep surrounding rock changes the internal structure of the surrounding rock, enhances the internal energy dissipation and weakens the new energy storage capacity. Based on this, related scholars have explored the mechanism of rockburst prevention by DPR from an energy point of view via laboratory experiments. For instance, Zhu et al. (2015) analyzed the pre-peak stored strain energy characteristics of intact specimens and specimens with defects through uniaxial compression tests, and proposed the conception of energy dissipation index \(X_{U_0}\) to optimize DPR scheme (Table 2). Besides, He, Gong, and Luo (2021) explored the energy evolution characteristics of red sandstone with different prefabricated drillings via uniaxial compression tests. It was found that the prefabricated drilled red sandstone specimens conform to the linear energy storage and consumption laws as non-drilled rock specimens. The specific linear relationship was shown in Figure 9 and the fitting formula was listed in Table 2. Furthermore, according to the linear energy storage and consumption laws of the prefabricated drilled rock specimen, the characteristics of the energy storage coefficient (ESC) and energy dissipation coefficient (EDC) of the prefabricated drilled specimens with different arrangements were also analyzed. It was found that ESC decreases with the increase of the number of drillings. With the angle of drillings arrangement and loading direction from 90° to 27° and then to 0°, ESC first decreased and then increased. When the number of drillings in the specimen is 3 and the arrangement angle and loading direction is 27° (diagonal arrangement), ESC is the smallest, which decreases by 12.94% compared with the non-drilled rock specimen. Besides, ESC represents the capacity of rock to store elastic energy, i.e. the higher ESC, the more the elastic strain energy stored by the rock under high stress, and the greater the severity of failure during critical instability. Herein, He, Gong, and Luo (2021) further explored the relationship between ESC and \(\sigma_c\) of the prefabricated drilled rock specimens, found there is a linear correspondence between ESC and \(\sigma_c\), and suggested that ESC effects the \(\sigma_c\) of the rock (Figure 10).

Figure 10. Relationship between peak compressive strength and compression energy storage coefficient (He, Gong, and Luo 2021).
4. Evaluation of DPR scheme based on different methods

DPR is one of the effective measures to prevent deep high-stress rockbursts. However, there was a new problem appeared in the actual engineering after DPR. For example, when DPR is insufficient, the effect of preventing rockburst will be invalid.

| No. | Evaluation criteria of DPR | Calculation formation | Evaluation criteria model |
|-----|----------------------------|-----------------------|--------------------------|
| 1   | Strength reduction index method (Zhang et al. 2019) | $X_{SRI} = \frac{\sigma_1 - \sigma_2}{\sigma_3}$ | |
| 2   | Local fracture initiation and propagation degree (Zhang et al. 2019) | $X_{LFI} = \frac{\Delta U_1}{U_0} = \frac{U_1 - U_0}{U_0}$ | |
| 3   | Strain energy dissipation index (Zhu et al. 2015) | $X_{SED} = \frac{U_p}{U_0}$ | |
| 4   | Energy impact index (Tan 1992) | $A_{CF} = \frac{U_p}{U_a}$ | |
| 5   | Peak-strength strain storage index (Gong, Yan, Li, et al. 2019) | $W_{ET}^p = \frac{U_p}{U_0}$ | |
Figure 11. Energy evolution curves of specimens with various drilling arrangements. (a) Different drilling diameters, (b) different numbers of drilling holes in one row, (c) different numbers of drilling rows (reproduced from Zhao et al. 2018).
On the contrary, when DPR degree is too large, the pressure relief zone such as the roadway (tunnel) will appear excessive deformation, which causes the failure of the support function of the roadway (Wang et al. 2017). Therefore, evaluating the effect of DPR scheme has become a key issue. At present, engineering analogy and engineering experience methods are mainly used in evaluating DPR schemes. However, due to different engineering geological conditions, the DPR scheme cannot achieve desired results.

To optimize DPR scheme, different indicators have been used to evaluate the DPR scheme’s effect from different perspectives of DPR mechanism, the specific evaluation calculation method as shown in Table 3. For instance, strength weakening degree of rock after DPR is used to evaluate the DPR scheme’s effect. Besides, relevant scholars evaluated the effect of DPR according to the crack evolution mechanism of prefabricated drilled rock. For instance, Zhang et al. (2019) evaluated the effectiveness of the drilling layout scheme by analyzing the crack propagation mechanism around the drilling and the number of cracks in different drilling layout modes. Besides, related scholars also evaluated the effect of DPR from the aspect of energy. For example, Zhu et al. (2015) put forward the concept of energy dissipation index ($X_{U_0}$) according to the energy evolution mechanism of rock before and after DPR. Meanwhile, the different levels of rockburst potential risk areas were divided according to the specific $X_{U_0}$ of surrounding rock. On this basis, Zhao et al. (2018) and Zhang et al. (2019) investigated the effect of preventing rockburst with the number of prefabricated drillings in different arrangement by means of laboratory test and numerical simulation. Their experimental results pointed out that the energy dissipation index decreased with the increase of the number of drillings, i.e. the more of drillings, the better the effect of preventing rockburst. In addition, Zhao et al. (2018) also constructed and fitted the relationship between diameter, number, row number of drillings and $X_{U_0}$, energy impact index ($A_{CF}$), as shown in Figure 11. It can be observed that $X_{U_0}$ has a nonlinear growth relationship with the diameter and number of drillings, while $A_{CF}$...
has the opposite change law. Additionally, it also found that $X_{U_0}$ increases linearly with the increase of the number of drilling rows, while $A_{CF}$ has no obvious change. It can be inferred that large diameter and multiple rows of drillings can effectively enhance the energy dissipation and weaken the rockburst proneness of rock. From the aspect of rock energy storage and dissipation, He, Gong, Wu, et al. (2021) accurately calculated the peak-strength strain energy storage index ($W_{ET}^P$) of prefabricated drilled rock specimens with different arrangements. Besides, combined with the corresponding relationship between the failure characteristics and $W_{ET}^P$ of rock specimens, it was found that $W_{ET}^P$ can be used to quantitatively describe the failure intensity characteristics of rock specimen, i.e. $W_{ET}^P$ can quantitatively evaluate the rockburst proneness of prefabricated drilled rock specimens. Based on this, it was found that the $W_{ET}^P$ of prefabricated drilled specimens reduced by 23.2%~70.2% than that of non-drilled rock specimen. In addition, it was found that $W_{ET}^P$ decreased with the increased of the number of drillings. As the arrangement angle and the loading direction changed from $90^\circ$ to $27^\circ$ and then to $0^\circ$, $W_{ET}^P$ first decreased and then increased. Furthermore, combined with the corresponding relationship between $W_{ET}^P$ and $\sigma_c$, He, Gong, Wu, et al. (2021) also pointed out that the drilling arrangement has a more significant effect on weakening the rockburst proneness of rock mass than that of drilling numbers (Figure 12).

The evaluation methods mentioned above were based on the internal mechanism of rockburst prevention by DPR. Actually, there are still some limitations in evaluating and optimizing DPR scheme from the perspective of weakening the mechanical properties of rock mass by DPR. For example, there is no unified standard for the degree of rock mass strength weakening after DPR. The number of pressure relief drillings is determined only by experience on site, which may lead to inaccurate pressure relief accuracy. In addition, due to the complexity of rock crack evolution mechanism, most scholars reveal the mechanism of rockburst prevention by DPR from the macro mechanism of crack, but there is few in-depth research on the micro mechanism. Meanwhile, the quantitative evaluation of the effect of DPR based on the crack propagation mechanism has not been realized. Therefore, further research and development are needed to reveal the mechanism of rockburst prevention by DPR based on the surface of crack mechanism. At present, it is reasonable and applicable to evaluate the effect of DPR from the perspective of strain energy. Because the violent occurrence of rockburst is caused by sudden release of elastic energy accumulated in rock in the limit state. In fact, according to the evolution characteristics of strain energy, the process of rock deformation is a process of strain energy input (external work), storing elastic strain energy and dissipating strain energy. Most rockburst discrimination indexes are also defined from the perspective of energy, such as, strain storage index ($W_{ET}$) (Kidbyński 1981), $W_{EF}^P$ (Gong, Yan, Li, et al. 2019), residual elastic energy index ($A_{EF}$) (Gong, Yan, et al. 2018; Gong, Wang, et al. 2021), elastic strain potential energy ($P_{ES}$) (Wang and Park 2001), and energy impact index ($A_{CF}$) (Tan 1992). Moreover, these discriminant indexes have specific evaluation criteria, which can quantitatively evaluate the rockburst proneness. Therefore, it is reasonable to develop the method of evaluating DPR scheme from the aspect of strain energy. In all, quantitative and reasonable evaluation method is an important basis for optimizing DPR scheme.
5. Development trend for revealing mechanism of rockburst prevention by DPR with laboratory testing

With the advancement of deep rock mechanics, great progress and breakthrough have been achieved in understanding of disaster causing by mechanism of deep rockburst, which provides strong support and help for the prevention and control of deep rockburst. In particular, the research and development of new true triaxial testing system makes the laboratory test realize the simulation process induced by rockburst disaster under deep high stress. Therefore, according to the development of current test system, some new prospects may be drawn in the research development trend on the mechanism of rockburst prevention by DPR.

5.1. Developing drilling rig test equipment for real-time DPR simulation test under high static stress

At present, in revealing the mechanism of rockburst prevention by DPR, prefabricated drilled specimens were mostly used to simulate the DPR test, i.e. the method of ‘drilling first, then loading’ is adopted. Essentially, there is a big difference between using prefabricated drilled specimens to simulate the DPR test and the actual DPR under high stress. Because the prefabricated drilling does not consider the effect of the high stress condition of the surrounding rock on DPR results. Besides, prefabricated drillings cannot accurately reflect the changes in the internal strain energy of rock during the process of DPR. In general, the method of prefabricated drilling cannot accurately reflect the mechanism of rockburst prevention by DPR. Therefore, it is necessary to develop a drilling rig test equipment combined
with the laboratory testing system for DPR simulation test under high static stress, i.e. the real-time DPR simulation test of 'loading first, then drilling'. Currently, to simulate the high-stress real-time DPR test, Gong, He, et al. (2022) independently developed the SG4500 drilling rig test equipment, combined with the existing test system to conduct real-time DPR tests under high stress (Figure 13). On this basis, the mechanical behavior characteristics and strain energy evolution mechanism of rock under high stress real-time drilling were further explored, which also confirmed that real-time drilling under high stress can weaken the elastic strain energy storage capacity and rockburst proneness of rock more effectively than prefabricated drilling (Figure 14). Therefore, it is a new idea to develop the drilling rig test equipment combined with the existing laboratory test system to simulate the DPR
5.2. Considering real-time DPR simulation test with cyclic load disturbance factors

In the process of continuous excavation or mining of deep rock mass, the surrounding rock mass near the excavation is subject to periodic stress concentration and stress dispersion disturbances (Su et al. 2016; Su, Feng, et al. 2017), such as the periodic pressure faced by the roadway in the process of coal mining. Besides, Figure 15 illustrates the stress condition of a typical rock unit near the free boundary after excavation. It can be seen that the free boundary after excavation will be continuously disturbed by the excavation ahead. In fact, in the process of implementing DPR measures in the high stress area, the pressure relief surrounding rock area will also be disturbed by the continuous excavation stress. Meanwhile, as mentioned in Section 2, it is under the action of disturbance that it is easier to form cracks around the pressure relief drillings and develop into a pressure relief area. Therefore, it is necessary to consider the influence of cyclic load disturbance on the pressure relief effect in the research on the mechanism of rockburst prevention by DPR. In general, it is a new idea to carry out the compression test of 'high-stress real-time DPR + cyclic load disturbance' in the study of the mechanism of rockburst prevention by DPR.

5.3. Exploring the relationship between the spatial size of drilling and surrounding rock stress field and strain energy evolution under two-dimensional high static stress

Large-diameter DPR technology has been widely applied to engineering sites as a measure to prevent rockburst disasters. At the same time, in the experimental research on
the statistical revealing of the mechanism of DPR to prevent rockburst, it can also be observed that many scholars have also focused on exploring the effect of the spatial size (drilling diameter and depth) of the drilling. However, most of the studies investigating the spatial size effect of drillings have only explored the crack evolution mechanism, strength characteristics and failure characteristics of rocks under different spatial sizes of drillings via uniaxial compression tests. In fact, DPR is a complex free-space three-dimensional expansion problem (Qi et al. 2018). Therefore, it is also necessary to further investigate the change of the surrounding rock stress field around the drilling under the drilling of different spatial size, and to explore the relationship between drillings with different spatial sizes and the evolution of strain energy inside the surrounding rock. With the advance of rock mechanics, the successful development of the multi-functional true triaxial rigid testing machine system also provides the possibility for us to further investigate the mechanism of rockburst prevention by DPR. For instance, Si and Gong (2021) and Si et al. (2022) have conducted the rockburst simulation test of unloading inside the rock under the condition of two-dimensional static stress on the TRW-3000 rock true triaxial testing system (Figure 16). Inspired by this, we can combine the true triaxial testing machine system to carry out real-time DPR simulation tests under two-dimensional stress conditions to further explore the relationship between the spatial size of the drilling and the evolution of stress field and strain energy of surrounding rock.

### 5.4. Combining with the true triaxial testing system to simulate the real-time DPR after rock excavation (‘three-dimensional loading + unloading + real-time DPR’ test)

The rockburst simulation test of the ‘true triaxial loading + unloading’ has been successfully realized (He et al. 2014; Su et al. 2016; Su, Feng, et al. 2017; Gong et al.)
which simulated the rockburst induced phenomenon after rock mass excavation (Figure 17). The stress state change on the sidewall of an underground opening before and after excavation is illustrated in Figure 18. In fact, rockburst is a phenomenon of sudden and violent release of elastic energy after deep rock excavation. If DPR can be performed on the deep rock mass in time after excavation, the elastic energy stored in rock mass can be released and the high stress state of rock mass at the excavation can be weakened, thus achieve the purpose of preventing rockburst. Thereby, if the true triaxial testing system can be combined to simulate the real-time DPR test after rock excavation, i.e. the simulation test of ‘three-dimensional loading + unloading + real-time DPR’, it will more intuitively reveal the effect of DPR on rockburst.

5.5. Focusing energy perspective to reveal mechanism of rockburst prevention by DPR

Rockburst is an energy-driven dynamic disaster, and its essence is the energy release process during the destruction of deep surrounding rock (Li et al. 2019). In fact, the essence of DPR to prevent rockburst is actually to release the elastic energy inside the
rock mass in advance by changing the surrounding rock structure in the pressure relief area, and prevent the rock mass from continuing to store energy (as mentioned Sec. 2). From this point of view, it is more intuitive and reasonable to specifically reveal the mechanism of rockburst prevention by DPR from the aspects of energy. At present, the linear energy storage and energy dissipation laws of intact rock (or coal/concrete) and prefabricated drilled rock have also been confirmed (Gong, Yan, et al. 2018; Gong, Yan, Li, et al. 2019; Gong, Wang, et al. 2021; Gong, Shi, et al. 2022; Luo et al. 2022; He, Gong, and Luo 2021), which provides a basis for quantitatively characterizing and analyzing mechanism of rockburst prevention by DPR from the aspects of energy. For example, the effect of different layouts of prefabricated drillings on the rock ESC and $W_p$ was quantitatively evaluated according to the linear energy storage law (Figures 10 and 12). Actually, the linear energy storage law can also be applied to the DPR simulation test under three-dimensional conditions to quantitatively evaluate the dissipation of energy inside the rock mass before and after pressure relief.

5.6. Calculating and visualizing the energy evolution inside the rock mass based on ‘real-time DPR test + numerical simulation calculation’

At present, the mechanism of rockburst prevention by DPR is mainly explored via laboratory tests. However, due to the limitation of current test equipment, it is impossible to fully reveal the mechanism of rockburst prevention by DPR. For example, (1) the large-scale rock specimens considering the spatial structure cannot be applied to the indoor real-time DPR test. (2) the specific evolution process of the internal strain energy of rock mass before and after real-time DPR cannot be completely visualized. With the development of computer technology, computer numerical simulation software has solved the related problems that cannot be satisfied by laboratory tests. For example, the finite element simulation software FLAC3D, RFPA, IRAZU, 3 DEC and discrete element simulation software PFC are used to analyze the disaster mechanism of engineering. In addition, there are some common problems in the process of using numerical simulation software. For example, the constitutive relationship and material property parameters provided by itself sometimes cannot fully meet the real experimental conditions of the simulation, and it needs to be developed based on the laboratory test data (Liu et al. 2019). Therefore, we can consider the secondary development of numerical simulation software on the basis of laboratory one-dimensional, two-dimensional, and three-dimensional high static stress real-time DPR tests. Then, to realize the visualization of the energy evolution and calculation inside the large-scale rock mass during the DPR process with the secondary developed simulation software.

6. Conclusions

DPR is an effective measure to prevent deep rockburst disasters, of which the implementation effect is obvious. With the advance of rock mechanics, laboratory tests have also succeeded in studying the mechanism of rockburst prevention by DPR. It was verified that DPR can effectively weaken the strength of rock, enhance the
crack evolution mechanism of rock, reduce the storage ability of elastic strain energy and rockburst proneness of rock, which provided theoretical support for the optimization of DPR scheme. However, due to the limitations of current test equipment and test conditions, the research on the mechanism of rockburst prevention by DPR was still not in-depth. Specifically, specimens with prefabricated drilling were mostly used to explore the mechanism of rockburst prevention by DPR, which can’t truly reflect the high-stress state of the rock before real-time DPR. Additionally, the effect of DPR scheme was mostly evaluated from the perspective of the change of rock mechanical behavior. This study introduces the theoretical action mechanism of rockburst prevention by DPR, and comprehensively summarizes and analyzes the experimental research status on the mechanism of DPR preventing rockburst from the aspects of rock mechanical behavior, crack evolution and strain energy storage. Finally, combining with the experimental development conditions of deep rock mechanics, the developing of drilling rig experimental equipment which can realize real-time DPR is proposed. On this basis, ‘three-dimensional high stress + unloading + real-time DPR’ is conceived to reveal the development trend and research direction of DPR mechanism for rockburst prevention and control.

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

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