Experimental study on failure characteristics of slabbing failure model specimen and rockburst mechanism

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Abstract. Rockburst is a common dynamic disaster in underground engineering under high ground stress. A large number of rockburst examples show that there is a strong correlation between the instability failure of slab cracking surrounding rock and rockburst during the excavation process of hard and brittle surrounding rock. Seven cracks were made in a 150 mm × 150 mm × 35 mm granite cube sample, the lengths of cracks were reduced from the free face to the inside according to a certain proportion. The granite is cut to form a slab-like structure with the same thickness, and the slab cracking sample model was made. The uni-axial compression test was carried out on the cracking samples. Combined with the numerical simulation results, the crack initiation, propagation characteristics and failure process of the cracked rock samples were analyzed, and the relationship between the instability of the slab cracking surrounding rock and rockburst was revealed. The results show that the cracking of surrounding rock plate is easy to induce sudden rockburst disaster, but it also provides the possibility for monitoring and early warning of rockburst disaster. With the increase of the distance between surrounding rock and the excavation face, the failure mode of slab crack structure becomes complex and the degree of failure increases gradually. It is found that there are three types of failure mechanism in the process of slab rockburst formation. The rock slab on the sample that is a certain distance from the excavation frontage is the first to rupture. The failure of the rock slab far away from the excavation free face is relatively rapid, and its fracture mechanism is more complex, with the largest degree of damage, resulting in a large number of rock blocks and cuttings. The slabs close to the excavation face are mainly bent and broken, forming large blocks or slab-like blocks. Once the rock slab is bent and broken at the face of excavation, the slab-like rock block formed at the face of excavation and the inside of surrounding rock will pop out at a high speed instantly, resulting in a rockburst disaster. The results reveal the process of rockburst of slab cracking hard rock structure under high stress condition, which can provide a scientific basis for the prevention and control of rockburst.

1. Introduction
Rockburst is a common dynamic disaster in underground engineering under high ground stress. In underground engineering such as roadway and chamber, stress concentration is easy to occur around the roadway, and the elastic strain energy in rock mass is released suddenly and violently under certain conditions, resulting in the phenomena of spalling, spalling, ejection and throwing. The study of rockburst mechanism is the core problem of rockburst, and how to reveal the "invisible and intangible" evolution process of rockburst is one of the key scientific problems of rock mechanics. A large number of rockburst examples show that there is a strong correlation between the instability failure of slab cracking surrounding rock and rockburst during the excavation process of hard and brittle surrounding rock, and the slab cracking failure provides a "material basis" for the occurrence of rockburst. Therefore, the study of the failure process of slab cracking surrounding rock is helpful to understand the occurrence mechanism of slab cracking buckling rockburst on the one hand, and can
provide important precursor information for the occurrence of rockburst on the other hand, which has important guiding significance for improving the accuracy of rockburst prediction and taking scientific and effective rockburst prevention and control strategies.

Scholars have carried out relevant research and put forward many opinions on the relationship between slabbing failure and rockburst. Ortlepp et al. [1] considered that slabbing failure is a manifestation of strain type rockburst in hard rock. Diederichs [2] believed that the slabbing failure of surrounding rock occurs before the strain type rockburst, and the nearly parallel rock plate produced by the cracking failure produces unstable deformation (buckling instability), which creates conditions for the sudden release of the strain type rockburst energy. According to the study of Zhao et al. [3], with the increase of depth, the failure mode can change from slabbing failure to severe rockburst. He et al. [4] proposed the evolution model of rockburst plate-like structure, and divided the process of rockburst into vertical plate cracking, vertical plate buckling deformation and rockburst failure. Zhou et al. [5] regard the cracking failure of surrounding rock slab as a precursor phenomenon of rock burst, and believed that the accurate interpretation of the precursor information of rock burst contained in the cracking failure of surrounding rock slab is the key to reasonably evaluate and accurately predict the risk of rock burst in deep buried tunnels. Gong et al. [6] used the large-size true triaxial test system to carry out simulation tests on red sandstone samples with prefabricated pores, analyzed the evolution process and failure characteristics of rockburst, and revealed the mechanism of rockburst induced by spalling damage. Du et al. [7] carried out true triaxial unloading tests, and the results show that the occurrence of collapse and rockburst is closely related to rock type and stress path. Si et al. [8] believed that the failure characteristics of tunnel sidewall are related to the shape of tunnel. The spalling failure is the main failure form of the D-shaped hole wall, while the failure of the circular hole wall is more serious, causing a rockburst disaster.

In order to further understand the mechanism of rockburst caused by plate cracking buckling in deep tunnels, scholars have carried out research on the instability process of surrounding rock with plate cracking. Zhou et al. [9,10] used high-strength gypsum to make model samples with cracks, and analyzed the laws of crack expansion and instability failure of plate cracking model samples. Zhou et al. [11] analyzed the strength, crack distribution, crack initiation and evolution rules of fractured rock mass under unilateral confined compression, and studied the formation mechanism of plate cracking from a microscopic perspective. The above research results have greatly enriched the understanding of the relationship between rockburst and slabbing failure of hard rock. However, the current research mainly focuses on the simulation test of similar materials, and the research on the instability process of cracked surrounding rock under high stress is rare. In addition, the relationship between the slabbing failure of surrounding rock and rockburst needs to be further studied.

Based on this, the slab cracking sample model was made of granite, and uniaxial compression experiments were carried out on the slab cracking sample. Combined with the numerical simulation results, the crack initiation, propagation characteristics and deformation and failure process of the crack containing sample were analyzed, and the correlation between the slabbing cracking failure process of surrounding rock and rockburst was revealed.

2. Experimental design
The experimental design includes two steps: crack sample preparation and rockburst simulation. Firstly, rock samples with multiple prefabricated cracks were made to simulate the slab cracking failure characteristics of tunnel surrounding rock in the field. Secondly, the stress adjustment process of tunnel surrounding rock is simulated by loading, and then the rockburst is induced during the stress adjustment process. Uniaxial loading experiments were carried out on samples with prefabricated cracks, and the failure process of samples was captured by means of high-speed camera.

2.1. Sample preparation
Seven cracks were made in the 150mm×150mm×35mm granite cube sample with ultra-high pressure water knife cutting machine, and the granite was cut into a plate-like structure with the same thickness to make the granite slab cracking sample model, as shown in Fig. 1. The length of fissure 1 to fissure 7 decreases successively according to the geometric sequence. The length of fissure 1 is 110mm, and the
The common ratio is 1.5. The width of a single crack is 1.5mm and the distance between the cracks is 10mm. Three samples were made for the test, and the samples were numbered HGS-1, HGS-2 and HGS-3.

![Figure 1. Specimen of tunnel rockburst](image)

2.2. Experimental process
The loading equipment is the type of RLW-3000 servo control testing machine, which can realize uniaxial and biaxial loading. The maximum horizontal load is 1000kN, and the maximum vertical load is 3000kN. Uniaxial loading was carried out on the specimen by using the rock loading testing machine, and the loading rate was 0.3mm/min until the specimen was destroyed. In the experiment, the image and video data of granite sample model destruction were recorded by using the stereo observation system composed of CCD high-speed camera, high-definition video monitoring system and digital camera. The test equipment is shown in Fig. 2.

![Figure 2. Experimental site](image)

3. Evolution of failure process of plate cracking specimen
The typical failure characteristics of granite slab cracking samples were analyzed by continuously photographing the failure process of plate cracking samples with rapid photography equipment. Fig. 3 shows the typical photos of the failure process of the granite prefabricated crack specimen (HGS-1). The main characteristics of the failure process of the specimen are as follows: For a long time, there is no obvious phenomenon on the surface of the sample. Near the peak load, a tensile crack appeared on the rock slab located in the middle of the prefabricated crack area, and a tensile crack gradually appeared on the adjacent rock slab to the right after continuous loading. With the generation of the tensile crack, the sample appeared the phenomenon of small particle ejection (see Figs. 3b and c). Then in a short period of time, cracks spread on each rock plate, and the rock plate located in the middle was peeled off, the rock plate near the empty surface was broken off on the left, the rock plate on the right was destroyed instantly, and a large number of rocks and debris were ejected, resulting in rock burst disaster, as shown in Figs. 3d–f. According to the photos taken, it takes about 3s from the beginning of the tensile macro cracks to the final rockburst disaster. It can be seen that during the
failure of the slab cracking sample, the cracks first appear on the rock slab in the central position, and then the rock slabs in each position are destroyed rapidly in a very short time, resulting in a rockburst disaster.

Figure 3. Failure process of HGS-1 specimen: (a) Quiet period; (b) Tension crack; (c) Particle ejection occurred; (d) Massive particle ejection; (e) Schist stripping; (f) Rockburst

Fig. 4 shows the failure morphology of three prefabricated fracture samples HGS-1, HGS-2 and HGS-3. According to Fig.4 and the failure process of the sample, the failure mode and failure degree of the rock plate at different positions of the cracked sample were analysed. It should be pointed out that, the left side of the sample is taken as the free face of the hole excavation. According to the distance from the excavation free face, the slab structure formed by fracture cutting granite is divided into short distance, medium distance and long distance. (1) The length of the rock slab near the excavation free face is long, and the long rock slab is easy to bend and break under the action of pressure. After bending and breaking, a number of rock blocks are formed, and the damage degree is relatively small. (2) In the process of failure, cracks first appear in the medium distance rock slab, which may occur tensile or shear failure. These rock slabs with a certain distance from the excavation free face produce splitting or shear failure, and the failure form is relatively single. The rock blocks formed after splitting or shear failure are mostly stripped in the form of flakes. (3) Due to the small length of the rock plate far from the open surface, the failure formation is complex and the failure degree is high under the action of high stress. The debris produced by the failure of the rock slab at this location is the main source of ejection during the rockburst process. It can be seen that the farther away from the excavation free face, the more complex the failure mode of rock slab structure, and the greater the degree of failure.

Figure 4. Morphology of three prefabricated crack samples after destruction: (a)HGS-1; (b)HGS-2; (c)HGS-3

4. Variation characteristics of principal strain curve in shear failure process
According to the design of the experimental scheme, the sample model was established by using FLAC3D software, and the uniaxial compression experiment was carried out with 17000 loading steps. The characteristics of crack propagation and damage evolution during the failure process of cracked plate specimens were further revealed.

Fig. 5 shows the damage evolution characteristics of fracture samples. As can be seen from Fig. 5a, when the number of loading steps is 13200, there is no crack in the sample, and there is basically no damage. After loading to step 13700, cracks first appear in the middle of the prefabricated crack area, and corresponding damage gradually increases, resulting in an obvious damage area, as shown in Fig. 5b. As the loading continues, the crack propagates further at the crack tip or between the cracks, and the internal damage of the specimen intensifies. The damage area gradually expands to the left and right sides, and the damage area gradually increases (see Fig. 5c ~ e). After loading up to 17000 steps, it can be seen that the damage is mainly concentrated in the prefabricated crack area (see Fig. 5f).

![Figure 5](image)

**Figure 5.** Damage evolution characteristics of fracture specimen: (a) Step13200; (b) Step13700; (c) Step14100; (d) Step14700; (e) Step15200; (f) Step17000

5. Discussion

(1) Relationship between cracking of surrounding rock slab and rockburst

On the one hand, the experimental results show that the granite samples are damaged in the prefabricated crack area, the crack further expands, and the internal damage intensifies, resulting in a rockburst disaster. This proves the relationship between rockburst and slab cracking, that is, slab cracking is easy to induce a rockburst disaster. On the other hand, the experimental results show that the cracks first appear in the middle area of the prefabricated cracks in the granite specimen, and the cracks are some distance away from the left blank surface. This means that the rock will be destroyed at a certain distance from the excavation free face before the rockburst, which has a certain degree of concealment. However, from the perspective of monitoring and early warning, it can be used as the precursor information of rockburst disaster in the surrounding rock of slab cracking structure. Zhou et al. [5] pointed out that the cracking failure of surrounding rock slab is a precursor phenomenon of rockburst, and the information contained in it needs to be studied deeply and quantitatively. Hu et al. [12] further pointed out that in the process of hard and brittle excavation, slab cracking can be used as the precursor or precursor information of rockburst, but slab cracking does not necessarily lead to a rockburst, which is specifically related to factors such as in-situ stress level, local stiffness of surrounding rock and post-peak behavior. By using microseismic equipment to monitor the surrounding rock and capture the signal generated by the internal rupture of the surrounding rock, it can provide a method for the monitoring and early warning of the slab cracking rockburst disaster.

(2) Size effect of slab structure in the process of slabbing rockburst

The experimental results show that the failure mode and degree of the slab cracking structure formed in the surrounding rock are related to the distance from the excavation face. With the increase of the distance between the surrounding rock and the excavation face, the failure mode of the slab
crack structure becomes complex and the failure degree gradually increases. This may be related to the size effect of the plate structure. The height of the rock slab decreases gradually from the excavation face. During uniaxial compression, the rock slab should be in a one-dimensional compression state, resulting in a three-dimensional compression stress zone near the upper and lower ends of the rock slab (Fig. 6). The larger the height of the slab, the closer the stress zone is to the one-dimensional stress state; on the contrary, the smaller the height of the slab, the overall three-dimensional stress zone is affected. As the height of the rock slab decreases, the influence of the three-dimensional compression stress zone at the upper and lower ends of the rock slab becomes more and more significant, thus making the failure mode of the rock sample more complex [13].

![Figure 6](image.png)

**Figure 6.** Stress distribution and failure mode in condition of uniaxial compressive

(3) Mechanism of slab rockburst

There are three types of failure mechanisms in the formation of slab rockburst. (1) Bending and breaking. The slabs close to the excavation face are mainly bent and broken, forming large blocks or slab-like blocks. Most of the large rock ejected in the rockburst process comes from the vicinity of the excavation face. (2) Tensile or shear failure. This kind of failure mainly occurs on the rock slab at the middle distance from the excavation face. In the first case, the fracture develops towards the wall of the cave in the form of tensile fracture and forms a thin rock block. Second, there is a weak plane in the direction of oblique intersection with the direction of tangential stress in the rock mass. Under the action of tangential stress, shear failure occurs along the weak face of the tunnel wall, forming a massive rock block [14]. (3) Tensile and shear coupling failure. This kind of failure mainly occurs on the rock slab far away from the excavation free face, which is relatively rapid, complex mechanism, large degree of damage, and produces a large number of rock blocks and cuttings.

According to the above analysis, the mechanism of slab rockburst can be summarized as follows: Compared with the short-distance and long-distance rock slab, the rock slab in the middle distance from the excavation free face begins to produce macro damage. Then, the rock slab far away from the excavation free face is destroyed rapidly, and the rock slab near the excavation free face is bent and broken, forming a large number of rock blocks and cuttings. Once the rock slab is bent and broken at the face of excavation, the slab-like rock block formed at the face of excavation and the inside of surrounding rock will pop out at a high speed instantly, resulting in a rockburst disaster.

6. Conclusion

(1) There is a close relationship between slab failure of surrounding rock and rockburst. The slab cracking surrounding rock is easy to induce a sudden rockburst disaster, but it also provides the possibility for the monitoring and warning of the rockburst disaster.

(2) Size effect exists in slab structure during the process of slab rockburst. With the increase of the distance between the surrounding rock and the excavation face, the failure mode of the slab crack structure becomes complex and the failure degree gradually increases.

(3) There are three types of failure mechanisms in the formation of slab rockburst: bending failure, tensile or shear failure, tensile and shear coupling failure. The rock slabs close to the excavation face are mainly broken by bending, the rock slabs in the middle distance from the excavation free face appear a
single type of tension or shear failure, and the rock slabs far away from the excavation face have complex tension-shear coupling failure.

Acknowledgments

This study is supported by the National Natural Science Foundation of China (51904105, 52074123), Hebei province graduate innovation funding projects (CXZZBS2021098, CXZZBS2020136), Science and technology research project of colleges and universities in Hebei Province (QN2020221).

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