

Article

Influences of Internal Unloading and Lateral Stress on Rockburst Behavior in Deep Hard Rock Roadways

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Abstract

To explore the effects of internal unloading and lateral stress on rockburst behavior in deep hard rock roadways, rockburst simulation tests were executed utilizing a self-developed internal unloading apparatus. A miniature camera was employed to monitor and record the rockburst evolution process of surrounding rock following internal unloading. Results demonstrate that the rockburst process primarily consists of four stages: the quiet stage, the buckling deformation stage, the rock fragment exfoliation stage, and the V-shaped notch formation stage. As the lateral stress increases from 15.2 MPa to 26.7 MPa, the vertical stress corresponding to the initial failure (σ_{zi}) increased from 64.00 MPa to 74.00 MPa, the fractal dimension of rock fragments decreases from 2.4033 to 2.3459, and the rockburst severity decreases. Under high lateral stress conditions, rock bearing capacity is comparatively high, making it less prone to rockbursts. However, more elastic strain energy accumulates inside the surrounding rock. Consequently, once a rockburst occurs, its intensity is notably greater than that subjected to low lateral stress. This suggests that increasing the lateral stress exerts a strengthening effect on the surrounding rock of the roadway. Numerical simulations were performed to study the crack evolution laws within the surrounding rock. Studies have revealed that internal unloading induces both shear and tensile cracks, but mainly tensile cracks. As the lateral stress increases, the number of shear and tensile cracks induced by internal unloading increases. The internal unloading triggers rock damage, leading to a strength-weakening effect. It becomes more pronounced as lateral stress increases. By comprehensively comparing the effects of internal unloading and lateral stress, the initial failure vertical stress increases with rising lateral stress, demonstrating an overall strength-strengthening effect induced by increasing lateral stress. Therefore, the strength-weakening effect resulting from internal unloading is weaker than that resulting from increasing lateral stress.

Keywords: rockburst; internal unloading; lateral stress; biaxial compression test; fractal dimension; numerical simulation



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1. Introduction

The progressive exhaustion of shallow resources has necessitated a strategic shift in mining operations toward greater depths, accompanied by a continuous expansion in both the quantity and scale of deep underground engineering projects [1–4]. Following excavation unloading, deep in situ stress rock transitions into a biaxial or uniaxial stress

environment. Furthermore, it is inevitably subjected to dynamic disturbances from mining and blasting activities. These factors can trigger an abrupt release of stored energy within high stress rock, ultimately inducing rockburst disasters [5–9]. The stress of rock undergoes a “high stress + unloading + static stress adjustment or dynamic disturbance” process [10]. Under deep complex stress environments, rockburst frequently occurs, posing a severe threat to deep engineering [11–16]. To investigate the rockburst characteristics under “high stress + unloading + static stress adjustment or dynamic disturbance”, Si and Gong [10] pointed out that the fundamental cause of strength-weakening in deep surrounding rock is a conversion of destruction mode, and confirmed that the unloading-induced strength-weakening is a primary trigger for rockburst. Xiao et al. [17] investigated the influence of the pre-cycles on the failure mode of rock samples with pre-formed cyclic loading–unloading damage. Gong et al. [18] reproduced the rockburst process through true-triaxial unloading tests and studied the impact of TBM excavation on rockburst and slabbing. Li et al. [19] explored the effect of intermediate principal stress on strainburst characteristics, and discussed the micromechanisms and energy characteristics of rockburst via experiments and numerical simulation. Ren et al. [20] found that periodic disturbance loading was the most prone to inducing rockburst, and static loading was the least likely to do so, while the rockburst triggered under static loading exhibited the highest intensity. The aforementioned studies have investigated the failure of rock materials under three-dimensional stress, unloading, and stress adjustment or dynamic disturbance. However, deep roadways are artificially excavated spatial structures in underground engineering that possess specific structural responses and spatial distribution characteristics. This constitutes a crucial aspect for laboratory research on the rockburst behavior and induced mechanisms.

To study the spatial structural responses of rockburst in roadways, many academics have executed multitudinous experimental research. For instance, Cheon et al. [21,22] carried out true-triaxial physical model tests to simulate the rockburst process and observed a V-shaped notch. Gong et al. [23] carried out true-triaxial compression tests on 100 mm × 100 mm × 100 mm sandstone specimens containing a non-through circular hole, reproduced the working-face rockburst process under wall-support constraints, and analyzed the characteristics of rockburst pits and rock fragments. Hu et al. [11] monitored the rockburst process under two-dimensional (2D) stress states, indicating that the quiet period, which was characterized by low acoustic emission (AE) counts, high amplitudes, and rapid rise of AE energy, was able to serve as a precursor for forecasting rockbursts. Liu et al. [24] reproduced the rockburst process along the tunnel sidewall and monitored surface strain behavior utilizing the Digital Image Correlation (DIC) technology using granite samples retrieved from the surrounding rock of the Zheduoshan Tunnel. Zuo et al. [25] explored the crack propagation in the surrounding rock of circular tunnels under varying burial depths. The aforementioned studies explored the rockburst behavior of roadways surrounding rock under “biaxial or triaxial stress + static stress adjustment” paths while considering the spatial structural response. However, they overlooked the strength-weakening effect resulting from internal unloading. To study the impact of internal unloading, Gong et al. [26] explored the effect of internal unloading on the stress response of rockburst, and revealed the mechanism of internal unloading in inducing rockburst. Si et al. [27] conducted the experiments and numerical simulations under internal unloading and different external loading rates, studied the stress variation law induced by internal unloading in tunnels, and analyzed the comprehensive effects of internal unloading and external loading rates on rockburst. He et al. [28] conducted real-time internal unloading uniaxial compression tests on red sandstone samples, and investigated the effects of real-time drilling speed and drill diameter on rock mechanical behavior, rockburst characteristics, crack evolution around the borehole, and peak elastic strain energy. However, there have been relatively

few experimental and numerical simulation studies on the impact of lateral stress on the rockburst behavior of roadways under internal unloading conditions. Consequently, it is essential to execute experimental and numerical simulation investigations under different lateral stresses and the “high stress + internal unloading + stress adjustment” path.

In this study, rockburst simulation tests were conducted on 100 mm × 100 mm × 100 mm cubic red sandstone samples. The primary objectives are to investigate the rockburst behavior of roadway surrounding rock, and to analyze the impact of lateral stress on rockburst severity (rockburst or failure severity mainly refers to the range and depth) and intensity (rockburst or failure intensity mainly refers to the speed of rock fragment exfoliation). Based on the experimental results, numerical models were established using the PFC3D6.0 software to observe the damage weakening effect resulting from internal unloading under varying lateral stresses. Furthermore, the crack evolution laws and failure modes of rockburst were analyzed to reveal the rockburst triggering mechanism under internal unloading and difference lateral stresses, thereby providing a theoretical guidance for rockburst prevention and control.

2. Test Plans

2.1. Sample Fabrication

A red sandstone material with moderate rockburst tendency was selected for experiments (rockburst tendency refers to the activity and intensity with which rock is susceptible to rockburst). The mineral composition of the red sandstone material consists of quartz (42% content), plagioclase (35% content), calcite (9% content), zeolite (8% content), K-feldspar (5% content), and opaque minerals (1% content). The red sandstone material was processed into cubic specimens, with a side length of 100 mm. The machining accuracy strictly follows the standards of ISRM. Some basic parameters of the tested sandstone are shown in Table 1.

Table 1. Basic parameters of the tested red sandstone.

Rock Type	Uniaxial Compressive Strength (MPa)	Tensile Strength (MPa)	P-Wave Velocity (m/s)	Density (kg/m ³)	Poisson's Ratio	Elastic Modulus (GPa)
Red sandstone	97.5	2.1	3180	2438	0.21	18.6

2.2. Experimental Apparatus

The primary experimental apparatus includes a rock true-triaxial apparatus (Figure 1a) integrated with a self-developed rock internal unloading apparatus (Figure 1b). A micro-camera monitoring system (Figure 1c) was employed to observe the rockburst process and characteristics of roadway surrounding rock. Figure 1d illustrates the diagram of sample overall stress state and the installation configuration of the micro-camera following internal unloading.

2.3. Experimental Scheme

Biaxial compression experiments were executed on cubic samples following a “2D stress + drilling unloading + stress adjustment” path. The initial in situ stresses were determined according to the Chinese geostress calculation formulas ($\sigma_v = 0.02532H + 0.8177$, $\sigma_{hmax} = 0.02989H + 2.7984$, $\sigma_{hmin} = 0.01766H + 1.0583$). Specifically, the stress state at a depth of 800 m was simulated, yielding calculated values of $\sigma_{hmax} = 26.7$ MPa, $\sigma_{hmin} = 15.2$ MPa, and $\sigma_v = 21.1$ MPa. During the test, the Y- and Z-orientations of true-triaxial apparatus were used for loading. Table 2 lists the experimental stress environment. In the sample nomenclature, “SX” denotes the biaxial compression test on red sandstone

under the aforementioned loading path, while the numbers 15.2, 21.1, and 26.7 correspond to the stress magnitudes of 15.2 MPa, 21.1 MPa, and 26.7 MPa, respectively.

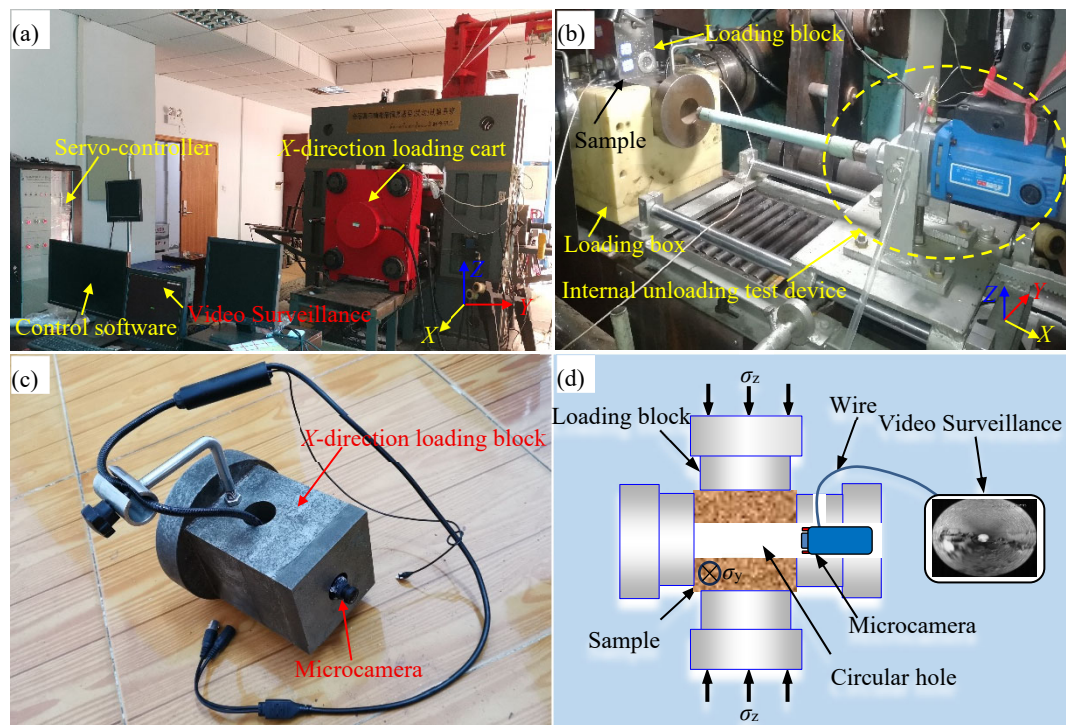


Figure 1. Experimental apparatus: (a) true-triaxial apparatus, (b) self-developed rock internal unloading apparatus and its installation, (c) micro-camera monitoring system, (d) diagram of sample overall stress state and the installation configuration of the micro-camera.

Table 2. Sample nomenclatures and stress environment of the test at a depth of 800 m.

Sample No.	“2D Stress + Internal Unloading + Stress Adjustment” Test	
	Lateral Stress σ_y	Vertical Stress σ_z
SX-15.2-21.1	15.2	21.1
SX-26.7-21.1	26.7	21.1

3. Experimental Results and Analysis

3.1. Stress Path

During the “2D stress + internal unloading + stress adjustment” tests, σ_y and σ_z were first increased to the preset stress values. Subsequently, internal unloading was performed using the self-developed rock internal unloading apparatus over a duration of 45 s. Following a holding period, σ_z was increased to 30 MPa with a constant loading rate of 0.1 MPa/s. Thereafter, σ_z was increased via stepwise loading, with each increment of 2 MPa maintained approximately 1 min. Once severe rockburst occurred, σ_y and σ_z were immediately uninstalled. The experimentally measured stress–time curves are illustrated in Figure 2.

3.2. Rockburst Process in Roadway Surrounding Rock

Following the internal unloading, the evolution of rockburst in specimen SX-15.2-21.1 is illustrated in Figure 3. At 2173.28 s and $\sigma_z = 64.00$ MPa, slight buckling deformation occurred on the left sidewall (Figure 3a). As σ_z increased, the buckling deformation of the left sidewall intensified (Figure 3b). At 2434.92 s and $\sigma_z = 70.37$ MPa, rock fragment exfoliated on the left sidewall (Figure 3c). Upon further increasing σ_z to 74.00 MPa, new rock

fragment exfoliation occurred on the left sidewall, while buckling deformation appeared on the right sidewall (Figure 3d). Buckled rock fragment progressively expanded and opened towards the free surface (Figure 3e). Once the opening displacement reached a critical limit, rock fragment exfoliation ensued (Figure 3f–h). When σ_z reached 76.00 MPa, multiple rock fragment exfoliations continued to occur on both sidewalls, leading to severe failure and symmetric V-shaped notches formation on both sidewalls (Figure 3i–l).

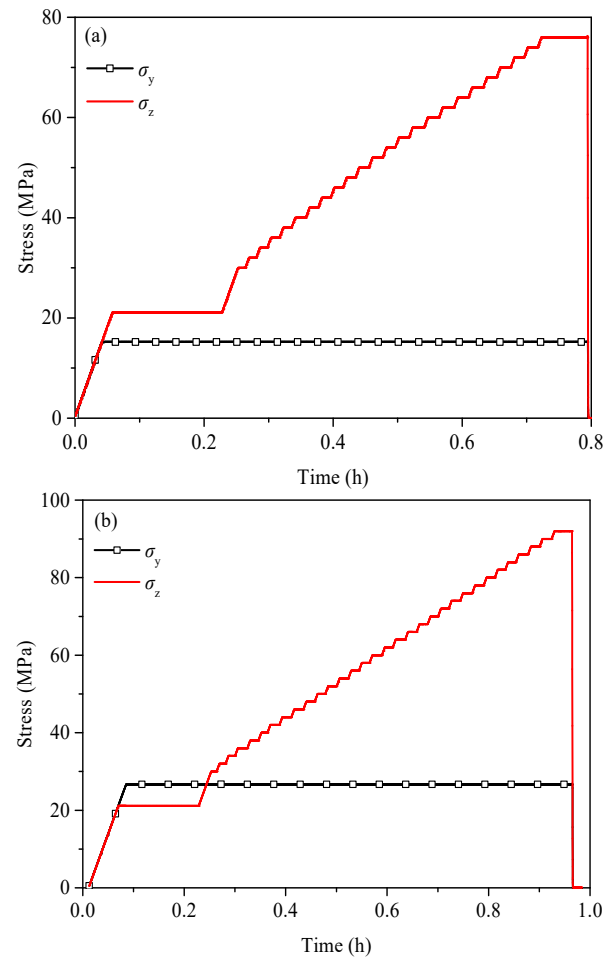


Figure 2. Stress–time curves: (a) Sample SX-15.2-21.1 and (b) Sample SX-26.7-21.1.

The rockburst process in Sample SX-26.7-21.1 under higher lateral stress is presented in Figure 4. At 2624.04 s and $\sigma_z = 74.00$ MPa, slight buckling deformation occurred on the right sidewall (Figure 4a). At $\sigma_z = 78.00$ MPa, left slight buckling deformation occurred, while right buckled rock fragment progressively extended (Figure 4b). At $\sigma_z = 82.00$ MPa, buckled rock fragments further developed towards free surface, concurrent with right sidewall particle ejection (Figure 4c). With a continued increase in σ_z , the buckled rock fragments gradually opened. Once the opening displacement reached a critical limit, rock fragment exfoliation occurred, and right sidewall underwent numerous rock fragment exfoliations (Figure 4d–h). At $\sigma_z = 88.00$ MPa, significant rock fragment exfoliation happened on the left sidewall (Figure 4i). Upon further loading to 90.00 MPa, rock fragment exfoliation occurred on the right sidewall (Figure 4j). Finally, at $\sigma_z = 92.00$ MPa, massive rock fragment exfoliation concurrent with intense particle ejection occurred on the left sidewall, resulting in violent rockburst. Ultimately, V-shaped notches were created (Figure 4k,l).

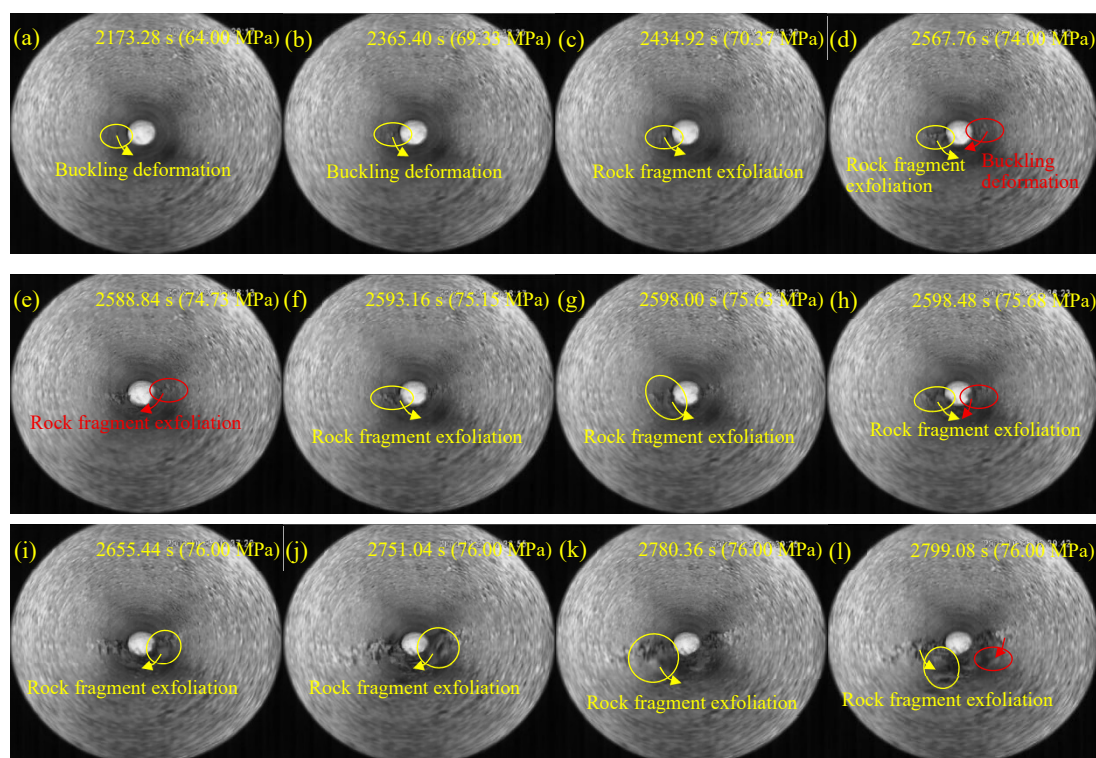


Figure 3. Rockburst process of Sample SX-15.2-21.1.

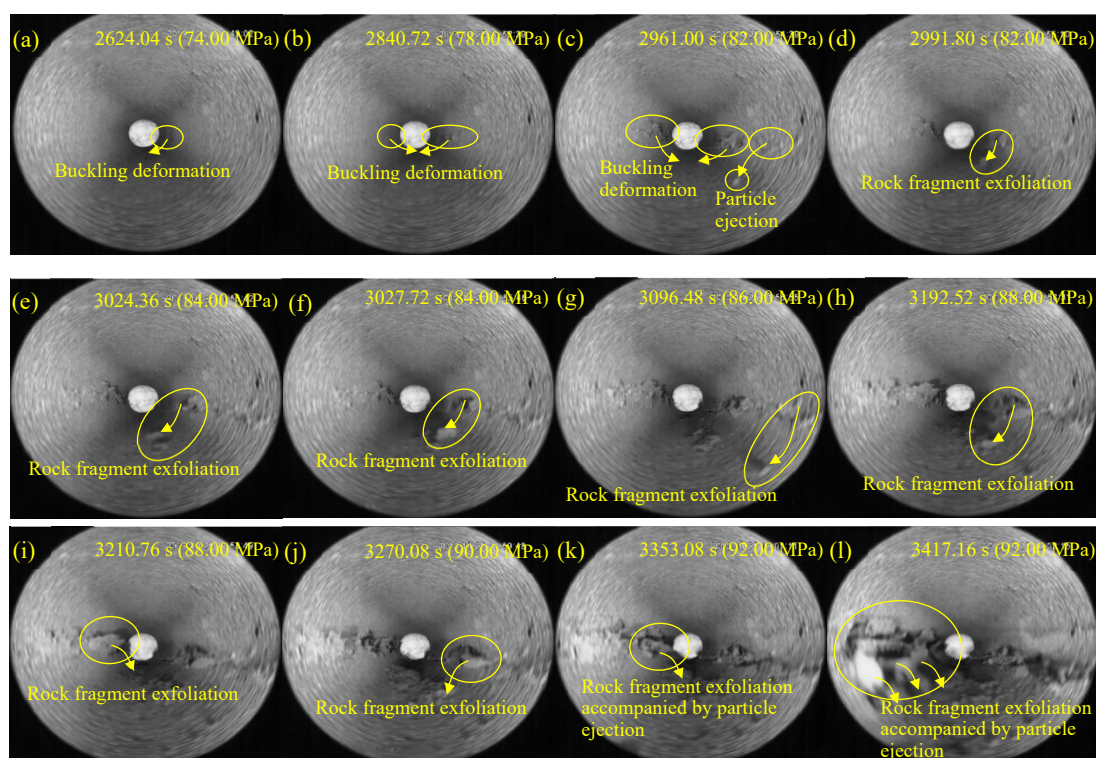


Figure 4. Rockburst process of Sample SX-26.7-21.1.

3.3. Rockburst Characteristics

Figure 5 presents the V-shaped notches in samples SX-15.2-21.1 and SX-26.7-21.1 after the removal of loose rock fragments. It can be observed that V-shaped notches are symmetrically distributed in the central region of both sidewalls. Notably, varying lateral

stresses did not generate remarkable impact on the distribution location of these V-shaped notches. The produced rock fragments are shown in Figure 6. Larger rock fragments display an elongated strip shape characterized by a central thickness that exceeds that of its outer boundaries. Additionally, the rock fragment includes a substantial amount of fine rock particles. Comparative analysis reveals that the dimensions of the larger rock fragments generated from the hole sidewall in Sample SX-26.7-21.1 are greater than those of Sample SX-15.2-21.1.

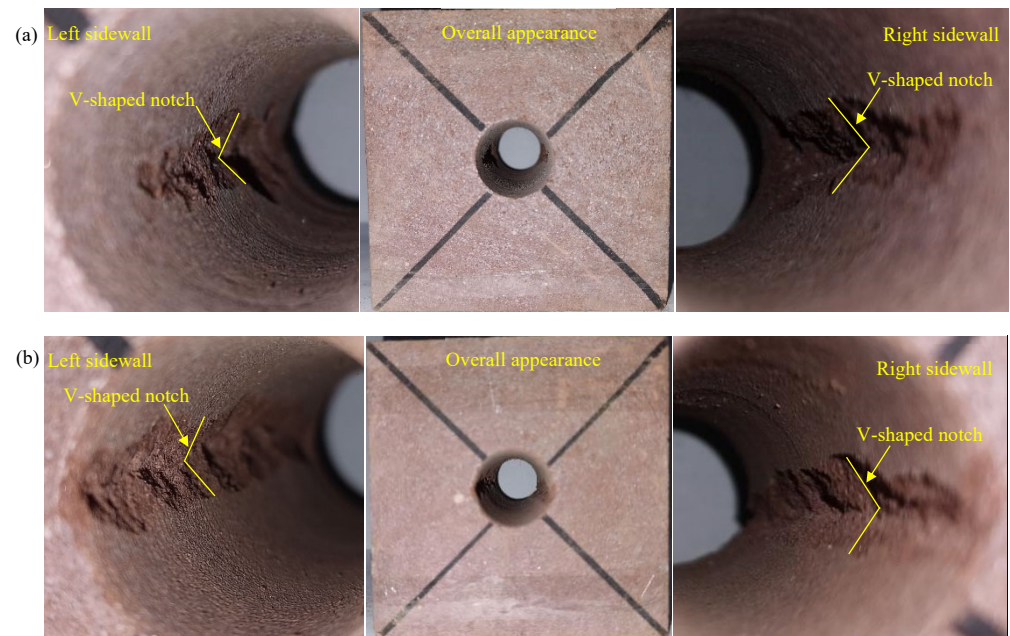


Figure 5. Overall appearance of the samples and V-shaped notches: (a) Sample SX-15.2-21.1 and (b) Sample SX-26.7-21.1.

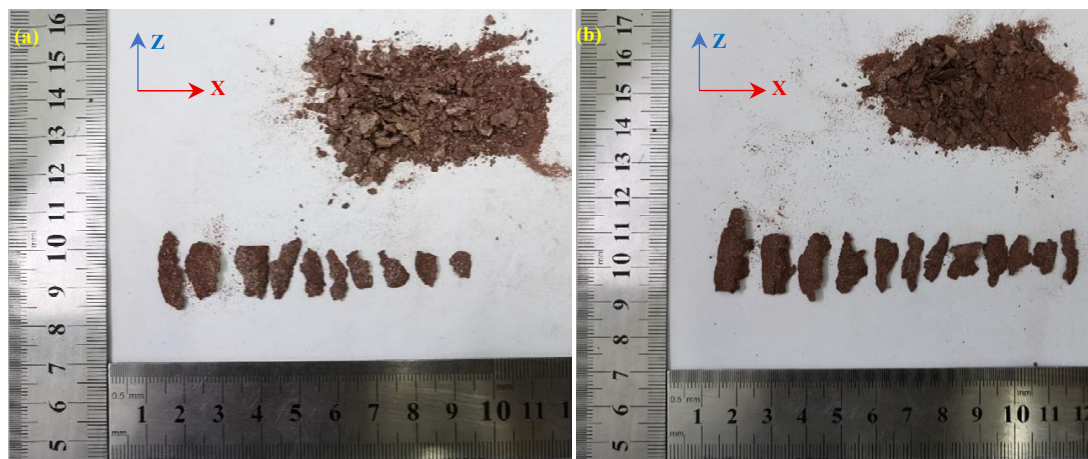


Figure 6. Characteristics of rock fragments: (a) Sample SX-15.2-21.1 and (b) Sample SX-26.7-21.1.

During the tests, the hole sidewall underwent buckling deformation towards the free surface. As the deformation progressed to a critical stage, it resulted in a bulging and folding failure originating from the center. A comparison shows that the bulging failure on a tunnel surface [29] and the buckling and bulging in a horizontal borehole of the Manitoba Underground Research Laboratory (URL) [30] are consistent with the experimental results. The comparative findings demonstrate that the buckling and bulging failure observed from our experiments is highly similar to the rock failures encountered in

actual engineering. To further validate the similarity between the rockburst simulation test and real-world engineering scenarios, comparative analysis was executed based on rockburst pits generated after the sample failure. V-shaped notches were ultimately developed in samples SX-15.2-21.1 and SX-26.7-21.1, which resemble the V-shaped notches generated in the 600 mm diameter borehole at 420 Level of the URL [31], the V-shaped notches formed by tunnel destruction [32], and the V-shaped notches in Jinping II Hydropower Station [33]. Furthermore, these V-shaped notches are distributed on both sidewalls orthogonal to the maximum principal stress orientation. In summary, both the bulging phenomenon during destruction progression and the final V-shaped notches are consistent with field observations of rockburst, and this consistency validates the reliability of the test results.

4. Discussion

4.1. Rockburst Evolution Process of Hole Sidewall Under Internal Unloading

By comparison, the rockburst process of samples SX-15.2-21.1 and SX-26.7-21.1 is similar under different lateral stresses. The process can be split into four stages: the quiet stage, the buckling deformation stage, the rock fragment exfoliation stage, and the V-shaped notch formation stage, as shown in Figure 7. These four stages are described in detail as follows:

- (1) The quiet stage: As the lateral and vertical stresses were loaded to the preset stress environment, no destruction occurred in the surrounding rock. As σ_z further increased, some microcracks were generated. However, no macroscopic failure was observed, as shown in Figure 7a. This stage represents the energy accumulation and incubation phase of the rockburst.
- (2) The buckling deformation stage: As σ_z continuously increased, high elastic strain energy gathered, resulting in a gradual increase in deformation. Upon reaching a certain threshold, macroscopic buckling deformation occurred. As σ_z increased further, buckled rock fragments progressively expanded and opened towards the free surface (Figure 7b). Buckling deformation also propagated along the hole axis.
- (3) The rock fragment exfoliation stage: When the buckled slab extended towards the free surface to a certain extent, it would bulge and fracture from middle. Subsequently, two separated parts of rock fragment continued to open towards the free surface before final spalling occurred, as illustrated in Figure 7c.
- (4) The V-shaped notch formation stage: As σ_z continued increase, different locations and depths within the surrounding rock would repeatedly undergo two or three of the aforementioned stages (quiet, buckling deformation, and rock fragment exfoliation). This repetitive process ultimately resulted in V-shaped notch formation around the hole, as shown in Figure 7d. In practical engineering, corresponding support measures can be implemented based on the evolution process, location, and rockburst characteristics in roadway surrounding rock.

4.2. Effect of Lateral Stress on Rockburst

The failure images of specimens SX-15.2-21.1 and SX-26.7-21.1 under identical vertical stresses ($\sigma_z = 68.00, 72.00$, and 76.00 MPa) were selected for a comparison. Figure 8a–c present the failure severity of Sample SX-15.2-21.1 at $\sigma_z = 68.00, 72.00$, and 76.00 MPa. At $\sigma_z = 68.00$ MPa, slight buckling deformation occurred on the left sidewall, whereas the right sidewall remained intact (Figure 8a). At $\sigma_z = 72.00$ MPa, the left sidewall displayed significant buckling deformation and a small amount of rock fragment exfoliations, whereas the right sidewall showed only slight buckling deformation (Figure 8b). At $\sigma_z = 76.00$ MPa, severe buckling deformation and extensive rock fragment exfoliations were observed on the left sidewall, concurrent with significant buckling deformation and bits of rock

fragment exfoliations on right sidewall (Figure 8c). Figure 8d–f present the failure situation of Sample SX-15.2-21.1 at $\sigma_z = 68.00$, 72.00 , and 76.00 MPa, respectively. No failure was observed at $\sigma_z = 68.00$ and 72.00 MPa, as illustrated in Figure 8d,e. At $\sigma_z = 76.00$ MPa, slight buckling deformation appeared on the right sidewall. However, the left sidewall remained undamaged (Figure 8f). By comparing the failure severity under identical vertical stresses, it is evident that as σ_y rose from 15.2 MPa to 26.7 MPa, the failure severity on both sidewalls gradually decreased. Furthermore, the vertical stress corresponding to the initial failure (σ_{zi}) increased from 64.00 MPa to 74.00 MPa, as shown in Figure 9. These findings demonstrate that increasing σ_y enhances the bearing capacity and stability of unsupported rock, thereby decreasing the rockburst risk and severity.

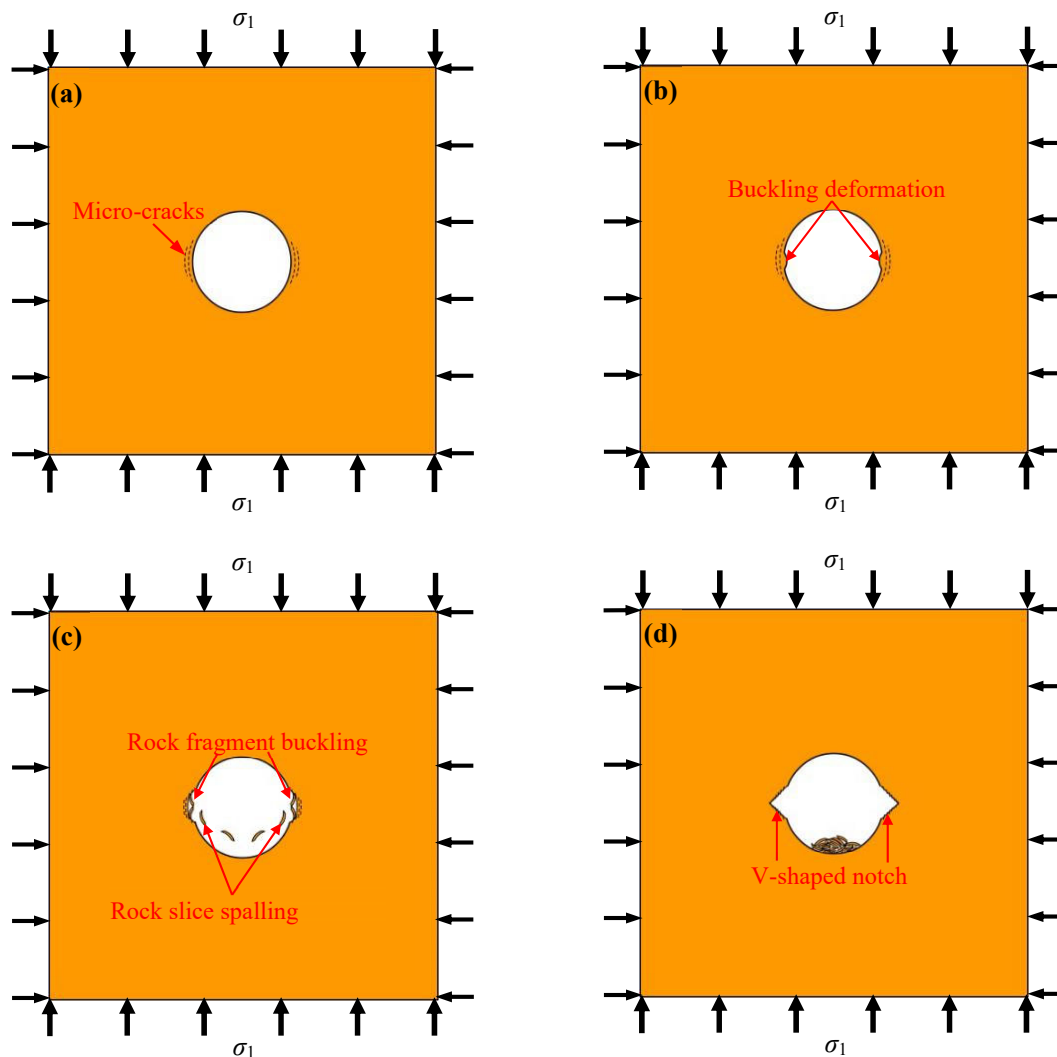


Figure 7. Rockburst evolution process: (a) quiet stage, (b) buckling deformation, (c) rock fragment exfoliation, and (d) V-shaped notch formation.

In addition, an analysis of the failure processes in Figures 3 and 4 reveals a distinct difference in failure dynamic characteristics. The failure process of Sample SX-15.2-21.1 (lower lateral stress) was relatively gradual. In contrast, the failure of Sample SX-26.7-21.1 (higher lateral stress) was much more violent due to the higher stress state. This is evidenced by the particle ejection in Figure 4c and the massive rock fragment exfoliations accompanied by intense particle ejection in Figure 4k,l. It indicates that, while high σ_y increases the bearing capacity and makes the rock less prone to rockburst, it also causes a higher elastic strain energy accumulation. Furthermore, once rockburst occurs, rockburst intensity is

notably greater than that under low σ_y . This demonstrates that an increase in σ_y exerts a strength-strengthening effect in roadways. Therefore, in practical engineering, appropriately increasing the lateral stress (e.g., through active support) can improve the stability and raise rockburst threshold. However, a higher lateral stress enhances the constraint effect on the surrounding rock of roadways, resulting in less deformation and lower energy release. This makes it easier for the surrounding rock to accumulate higher elastic strain energy. The higher lateral stress leads to an increase in the rockburst threshold, resulting in an increase in the rock strength, an increase in stress during rockburst, and a higher accumulation of elastic strain energy in rock. In summary, higher lateral stress results in a lower released energy and a higher accumulated elastic strain energy. Therefore, the elastic strain energy released during rockburst is greater, leading to a more violent rockburst, necessitating targeted prevention and control measures.

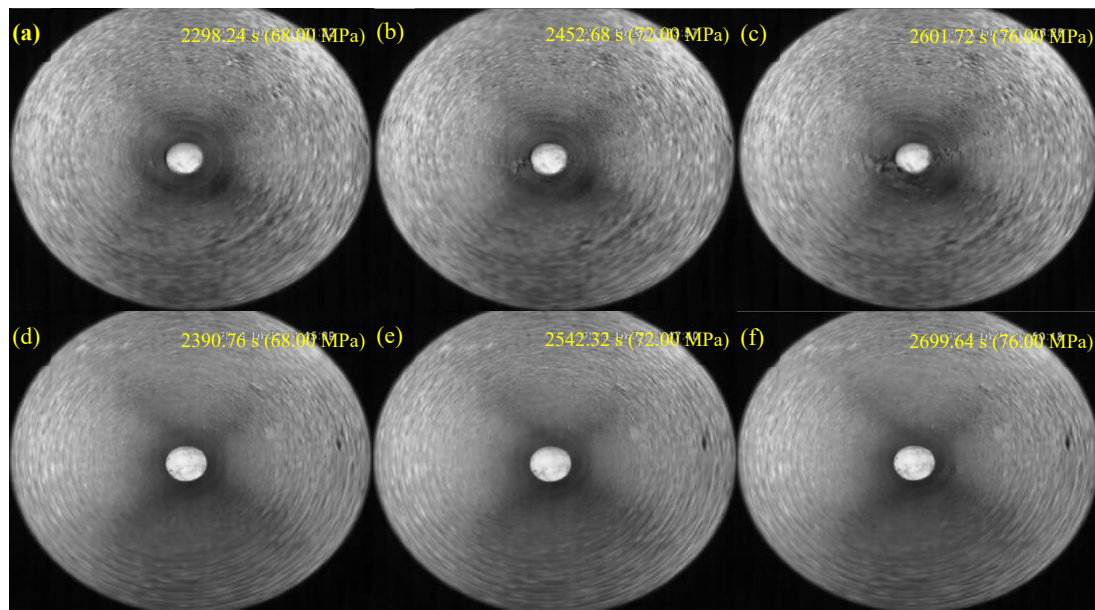


Figure 8. Failure characteristics under three vertical stresses ($\sigma_z = 68.00$ MPa, 72.00 MPa, 76.00 MPa): (a–c) Sample SX-15.2-21.1, (d–f) Sample SX-26.7-21.1.

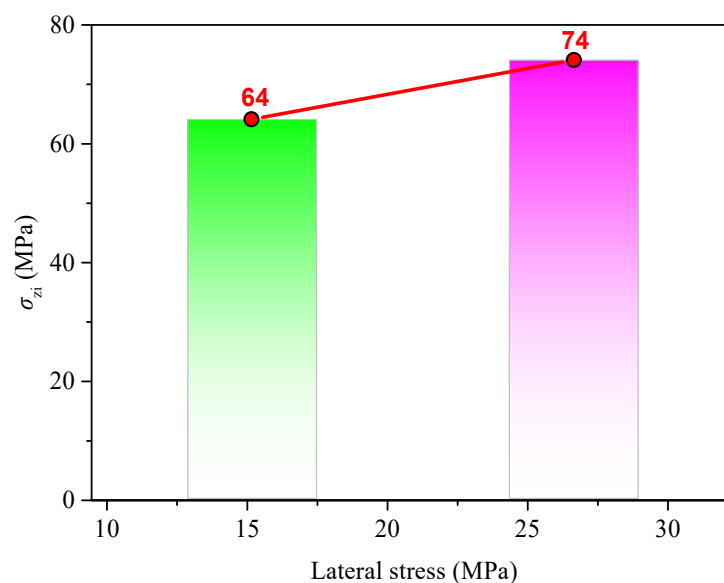


Figure 9. σ_{zi} under different lateral stresses.

4.3. Fractal Behaviors

For studying fractal behaviors, sieves with different particle sizes (15.00, 8.00, 6.70, 4.75, 2.36, 1.00, 0.55, 0.25, 0.075 mm) were used for screening treatment. Rock fragments and their masses within different particle size ranges are shown in Figure 10. Based on fractal theory, the relationship between the size and mass of rock fragments can be represented by Equation (1) [34]:

$$\frac{M(r < R)}{M_T} = \left(\frac{R}{R_L}\right)^{3-D} \quad (1)$$

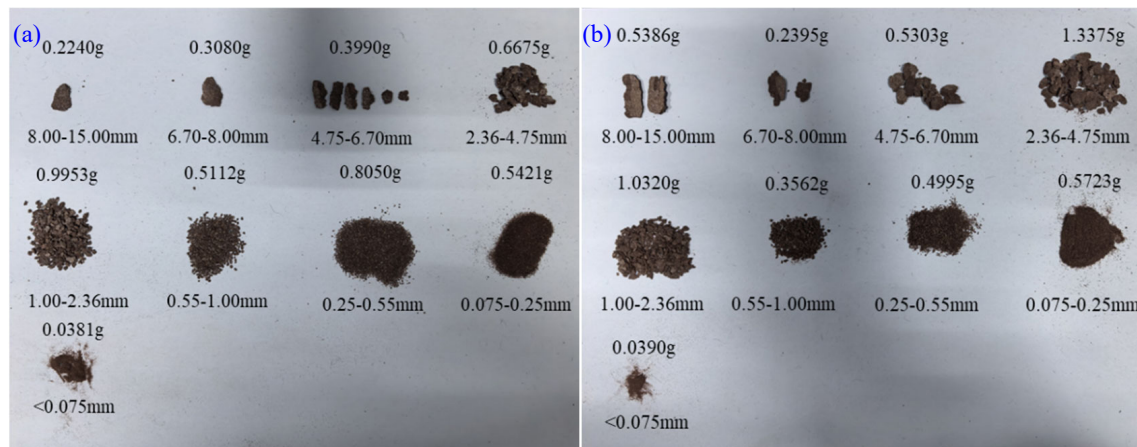


Figure 10. Rock fragments and their masses within different particle size ranges under varying lateral stresses: (a) Sample SX-15.2-21.1, (b) Sample SX-26.7-21.1.

Through mathematical transformation, Equation (2) can be obtained:

$$\ln\left(\frac{M(r < R)}{M_T}\right) = (3 - D)\ln\left(\frac{R}{R_L}\right) \quad (2)$$

where r is the diameter of the rock fragments, R is the mesh aperture of the selected sieve, D is the fractal dimension, M is the mass of the rock fragments under $r < R$, M_T is the total mass of the rock fragments, and R_L is the aperture of the maximum sieve. Based on the mass of the rock fragments within different particle size ranges from Figure 10, $M(r < R)$ and M_T under different lateral stresses were calculated, as listed in Table 3. The correlation between the rock fragment mass and particle size under varying lateral stresses is shown in Figure 11. According to Equation (2), $3-D$ corresponds to the fitted line slope in Figure 11. Consequently, the variation trend of D under different lateral stresses is displayed in Figure 12. As σ_y increased from 15.20 MPa to 26.70 MPa, the D of the rock fragments decreased from 2.4033 to 2.3459. This indicates that higher σ_y leads to lower D . Generally, a larger D signifies higher energy consumption during rockburst and a more thorough degree of fragmentation [35,36]. For Sample SX-15.2-21.1 (lower lateral stress), the failure occurred at a lower stress level. Consequently, accumulated elastic strain energy was lower, leading to a slower buckling deformation and rock fragment exfoliation process. With less kinetic energy released, the rockburst was relatively moderate. The resulting rock fragments were more uniform, leading to a larger D . In contrast, for Sample SX-26.7-21.1 (higher lateral stress), the failure occurred at a higher stress level, meaning higher elastic strain energy was accumulated. The rockburst was more violent, releasing a greater kinetic energy. As a result, the mass of the rock fragments in the larger particle size ranges (8.00–15.00, 4.75–6.70, 2.36–4.75, and 1.00–2.36 mm) was greater than that under low

lateral stress. Overall, the distribution of rock fragments under high lateral stress was more heterogeneous, which resulted in a lower D .

Table 3. M and M_T under different lateral stresses.

R (mm)	R_L (mm)	Sample SX-15.2-21.1		Sample SX-26.7-21.1	
		M ($r < R$) (g)	M_T (g)	M ($r < R$) (g)	M_T (g)
0.075	15	0.0381	4.4902	0.0390	5.1449
0.25	15	0.5802	4.4902	0.6113	5.1449
0.55	15	1.3852	4.4902	1.1108	5.1449
1.00	15	1.8964	4.4902	1.4670	5.1449
2.36	15	2.8917	4.4902	2.4990	5.1449
4.75	15	3.5592	4.4902	3.8365	5.1449
6.70	15	3.8982	4.4902	3.8982	5.1449
8.00	15	4.2062	4.4902	4.3668	5.1449
15.00	15	4.4902	4.4902	5.1449	5.1449

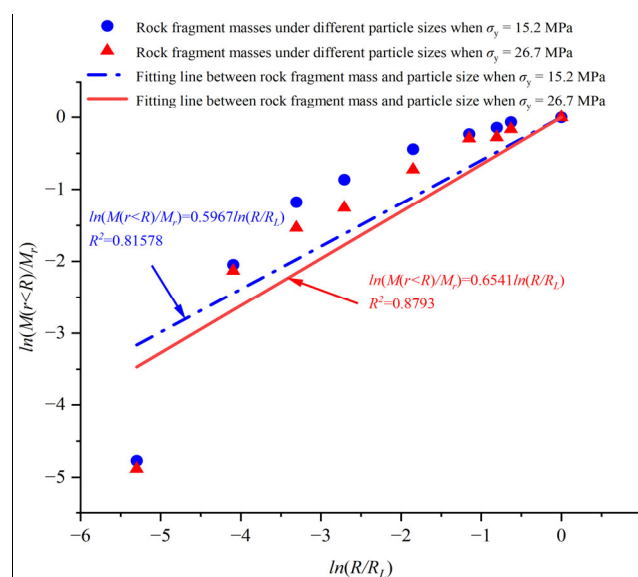


Figure 11. Relationship between rock fragment mass and particle size under varying lateral stresses.

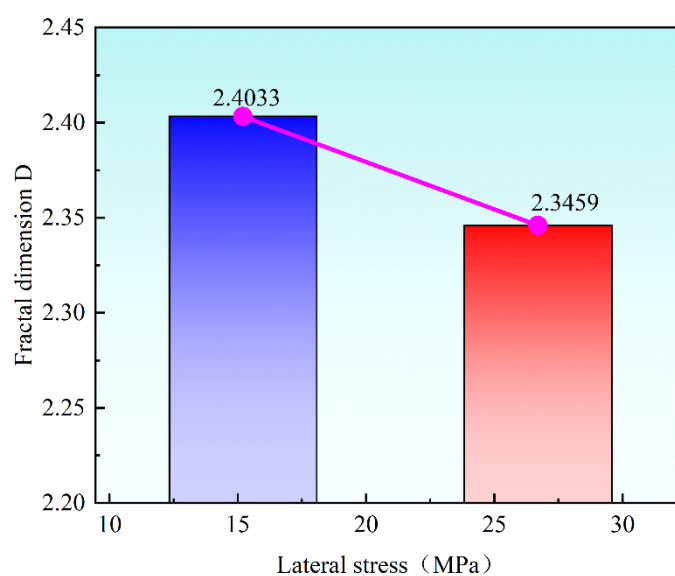


Figure 12. D under varying lateral stresses.

4.4. Numerical Simulation on the Influence Mechanism of Internal Unloading and Lateral Stress on Rockburst

To explore the influence mechanism of internal unloading and lateral stress on the crack evolution process and failure modes in deep rock, numerical simulations were executed utilizing PFC^{3D}. To realize the same characteristics as the rock materials, the parallel bond model (PBM) was chosen as the constitutive model [37]. The macroscopic parameters were derived from the rock samples. Then, the microscopic parameters were adjusted by an iterative back-analysis method based on the observed failure types and other macroscopic mechanical responses. A controlled-variable method was applied to gradually change the parameters until a great agreement with the experimental results was obtained [38]. During this procedure, the microscopic parameters were modified according to the macroscopic mechanical responses found in the experiments, especially the stress–strain curves and failure modes of the specimens. After calibration, the numerical model was verified by uniaxial compression and Brazilian splitting tests. The results indicate that the relative error between the calculated and experimental uniaxial compressive strength is less than 5%. The calibration was stopped when a satisfactory agreement was achieved. Meanwhile, the macroscopic parameters and microscopic parameters were recognized as the final model parameters. The calibrated model can simulate the macroscopic mechanical response and failure features of red sandstone well, showing its good feasibility for other rock materials. The selected partial parameters are listed in Table 4. In simulation, cracks are visualized as black dots. To monitor the stress adjustment and variation patterns, the measure with a diameter of 3 mm tangent to the free surface was established on the hole sidewall. Additionally, the model was rendered semi-transparent to clearly visualize the spatial distribution and quantity of cracks. The configuration of the measure and semi-transparent numerical model is illustrated in Figure 13.

Table 4. Main macro and micro parameters of the parallel bond model.

Macroscopic Parameters		Microscopic Particle Parameters	
ρ	2438 kg/m ³	R_{max}	1 mm
P-wave velocity	3180 m/s	R_{max}/R_{min}	1.66
Uniaxial compressive strength	97.5 MPa	emod	18.6 GPa
Elastic modulus	18.6 GPa	kratio	1.5
		μ	0.4
		pb_coh	46 MPa
		pb_ten	46 MPa
		pb_kratio	1.5
		pb_emod	18.6 GPa

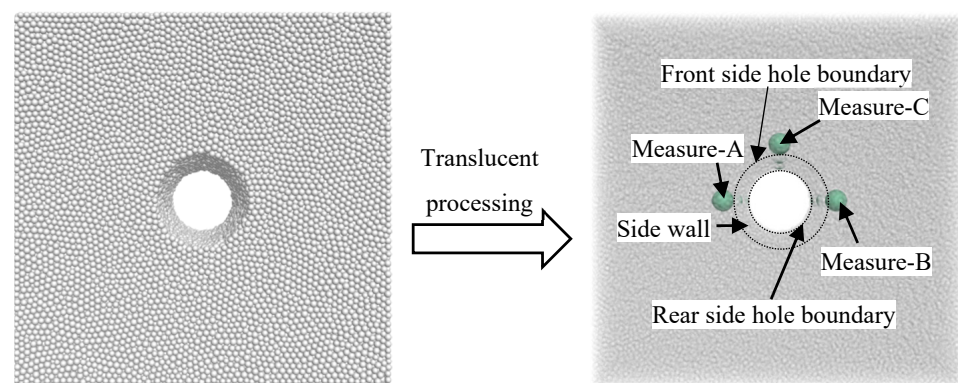


Figure 13. Diagram of numerical model and measure setup.

The rockburst process of Sample SX-15.2-21.1 obtained from numerical simulation is shown in Figure 14. When σ_z reached 64.00 MPa, cracks appeared on both hole sidewalls

(Figure 14a). At $\sigma_z = 68.00$ MPa, particle ejection was observed on both sidewalls, and the fracture surfaces propagated progressively and deepened, as shown in Figure 14b. As σ_z increased to 70.00 MPa and 72.00 MPa, the failure zone gradually expanded and intensified, and the cracks on both sidewalls gradually propagated towards the corners of the model, as illustrated in Figure 14c,d. When σ_z reached 74.00 MPa, the overall oblique shear cracks gradually increased and showed a butterfly shape (Figure 14e). Finally, at $\sigma_z = 76.00$ MPa, V-shaped notches were created, as shown in Figure 14f. The overall process of the simulation tests under different lateral pressure conditions were similar. By comparing the rockburst process of the numerical simulation and indoor tests, it was found that there was a high degree of consistency. Therefore, the numerical simulation can be used to analyze the crack evolution and mechanism of rockburst induced by internal unloading.

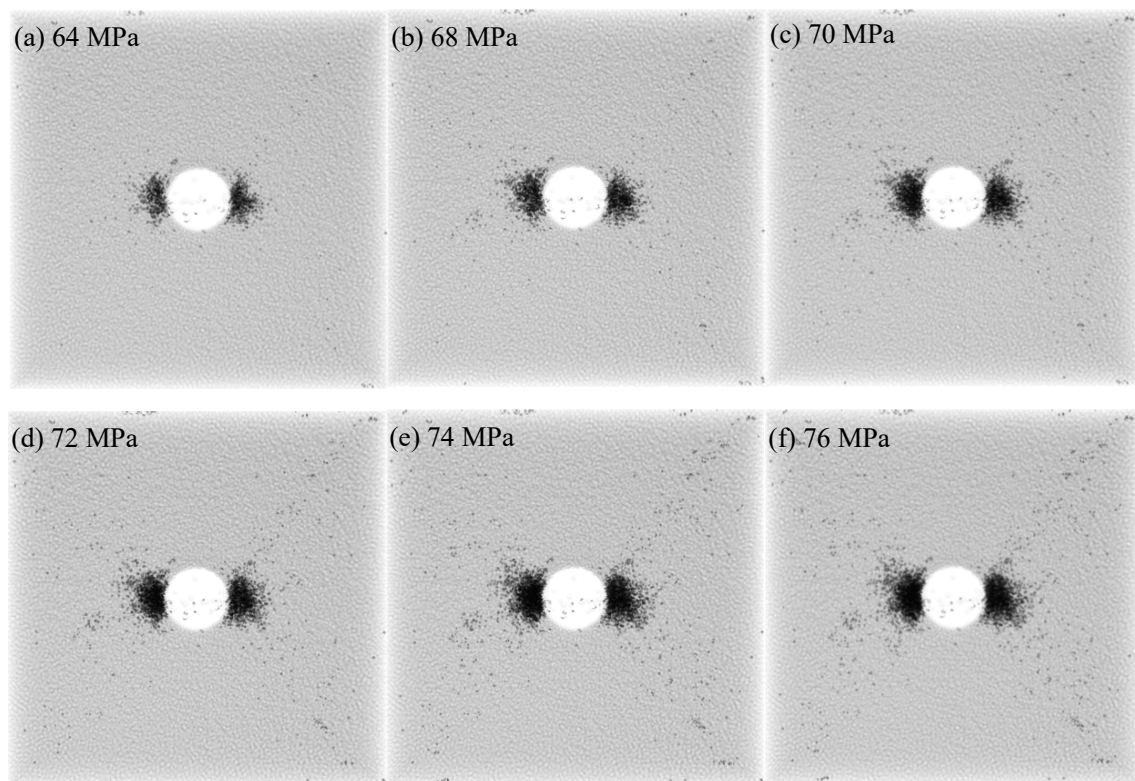


Figure 14. Failure process of numerical model for Sample SX-15.2-21.1.

In the numerical model, process files were saved starting from 30 MPa at intervals of 2 MPa to record the number of cracks generated, as illustrated in Figure 15. With an increase in σ_y , the crack number in Sample SX-15.2-21.1 was greater than that in Sample SX-26.7-21.1, and the difference in crack number between Sample SX-15.2-21.1 and Sample SX-26.7-21.1 gradually increased as the vertical stress increased. The primary reason is that Sample SX-15.2-21.1 has a lower σ_{zi} , and the increase rate of the crack number in the surrounding rock increases. In contrast, Sample SX-26.7-21.1 has a higher σ_{zi} , and the increase rate of the crack number is lower than that of Sample SX-15.2-21.1. This discrepancy in growth rates leads to a progressively widening gap in the crack number between these two models. At $\sigma_z = 76.00$ MPa, Sample SX-15.2-21.1 exhibited more severe failure than Sample SX-26.7-21.1. Figure 16 presents the proportions of shear and tensile cracks for both models at 76 MPa. As σ_y increased from 15.2 MPa to 26.7 MPa, the proportion of shear cracks rose from 68.71% to 70.02%. This demonstrates that an increase in the lateral stress promotes a generation of shear cracks.

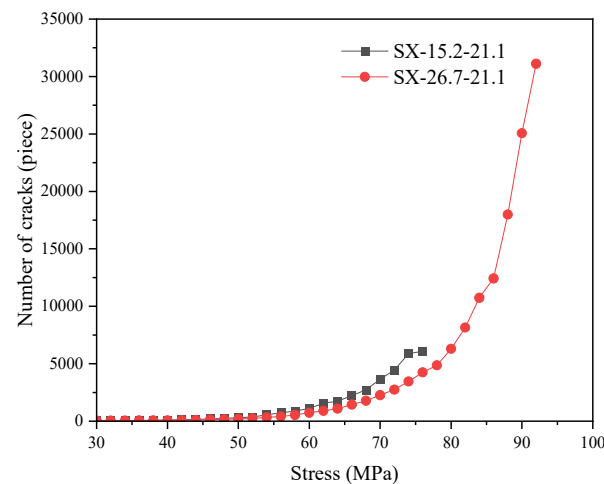


Figure 15. Changes in crack number under different lateral stresses.

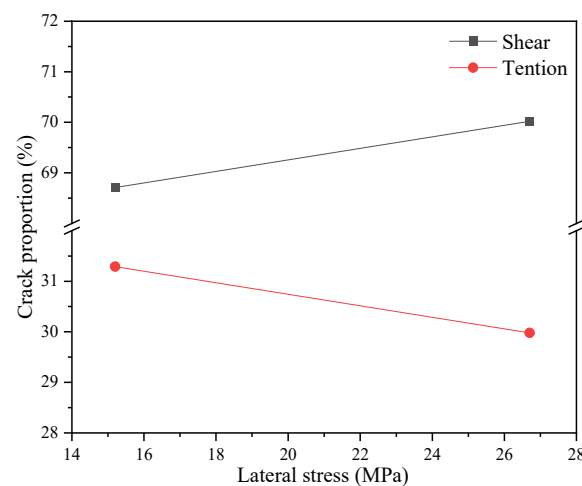


Figure 16. Proportion of shear and tensile cracks under varying lateral stress.

Under different lateral stresses, internal unloading exerts a notable influence on tensile and shear cracks of the model specimens. The crack number immediately after internal unloading is shown in Figure 17. At the lateral stress of 15.2 MPa, the internal unloading induced nine shear cracks and eighteen tensile cracks. When the lateral stress increased to 26.7 MPa, these numbers of shear and tensile rose to 15 and 24, respectively. The results indicate that internal unloading causes a damage and weakening effect. The damage induced by internal unloading is dominated by tensile cracks, with shear cracks being secondary. As the lateral stress increases, internal unloading triggers more severe damage, thereby resulting in a greater strength-weakening effect. With increasing σ_z , the number of cracks at the lateral stress of 15.2 MPa is higher than that at the lateral stress of 26.7 MPa. This demonstrates that the crack increase rate under lower lateral stress is faster with increasing σ_z , and the failure is more severe. Rock strength under high lateral stress is higher. Consequently, the increase in lateral stress exerts a strength-strengthening effect.

To investigate the stress variations of the hole free surface during the numerical tests, measures tangent to the free surface were established. Figure 18 shows the stress evolution recorded by these measures throughout the numerical model experiment. In Figure 18, σ_{Ar} , $\sigma_{A\theta}$, σ_{Br} , $\sigma_{B\theta}$, σ_{Cr} , and $\sigma_{C\theta}$ denote the radial and tangential stresses measured by measures A, B, and C, respectively. Taking Sample SX-15.2-21.1 (Figure 18a) as an example, following the internal unloading, $\sigma_{A\theta}$ and $\sigma_{B\theta}$ increased from 22.6 MPa and 24 MPa to 40.4 MPa and 48.3 MPa, respectively. Meanwhile, σ_{Ar} and σ_{Br} decreased from 15.7 MPa

and 16.3 MPa to 6.3 MPa and 6.4 MPa, respectively. At the hole top, $\sigma_{C\theta}$ increased from 15.7 MPa to 24.2 MPa, while σ_{Cr} dropped from 24.3 MPa to 4.2 MPa. From Figure 18, the σ_{zi} of Sample SX-15.2-21.1 is lower than that of Sample SX-26.7-21.1. For Sample SX-26.7-21.1 (Figure 18b), $\sigma_{C\theta}$ increased from 26.8 MPa to 48.1 MPa after internal unloading. The internal unloading under different lateral pressures leads to a significant disparity in $\sigma_{C\theta}$. With increasing σ_z , $\sigma_{C\theta}$ gradually decreases. However, it remains compressive until the end of the test. In contrast, under lower lateral stress conditions, the stress eventually drops below zero. This indicates a transition from compressive to tensile stress at the hole top [27]. As σ_z increases, stress concentration undergoes corresponding changes. From Figure 18, the variation trend of $\sigma_{A\theta}$ and $\sigma_{B\theta}$ is similar. Taking $\sigma_{B\theta}$ as a representative example for detailed analysis, for Sample SX-15.2-21.1 (Figure 18a), when σ_z reached 57.6 MPa, $\sigma_{B\theta}$ exhibited a decrease from 137 MPa to 130.8 MPa. Similarly, at $\sigma_z = 63.6$ MPa, $\sigma_{B\theta}$ dropped from 148.5 MPa to 145.9 MPa. During this stage, fine microcracks initiated at the location of measure B. When σ_z increased to 69.7 MPa and 71.9 MPa, $\sigma_{B\theta}$ dropped from 155.8 MPa to 135.1 MPa and from 143.2 MPa to 125.7 MPa, respectively. This location generated new microcracks and the microcracks gradually expanded. For Sample SX-26.7-21.1 (Figure 18b), at $\sigma_z = 59.3$ MPa, $\sigma_{B\theta}$ decreased from 138.9 MPa to 132.2 MPa, accompanied by the initiation of fine microcracks at the location of measure B. When $\sigma_z = 69.7$ MPa, $\sigma_{B\theta}$ dropped from 150.8 MPa to 125.4 MPa. As σ_z further increased to 76.6 MPa and 85.7 MPa, $\sigma_{B\theta}$ continued to show moderate declines, falling from 141.3 MPa to 125.4 MPa and from 149.6 MPa to 115.9 MPa, respectively. This indicated that the location generated new microcracks and the microcracks gradually expanded. Notably, when σ_z reached 88 MPa, $\sigma_{B\theta}$ plummeted drastically from 124.6 MPa to 77.9 MPa, and rock fragment exfoliation occurred at the location of measure B (see Figure 4h). Therefore, the stress evolution at the location of measure effectively characterizes the processes of crack initiation, propagation, coalescence, and ultimate macroscopic failure. Specifically, a slight drop in the tangential stress indicates the initiation of microcracks; a moderate decline signifies the generation of new microcracks and their gradual propagation; and a drastic drop marks the coalescence of cracks leading to macroscopic failure.

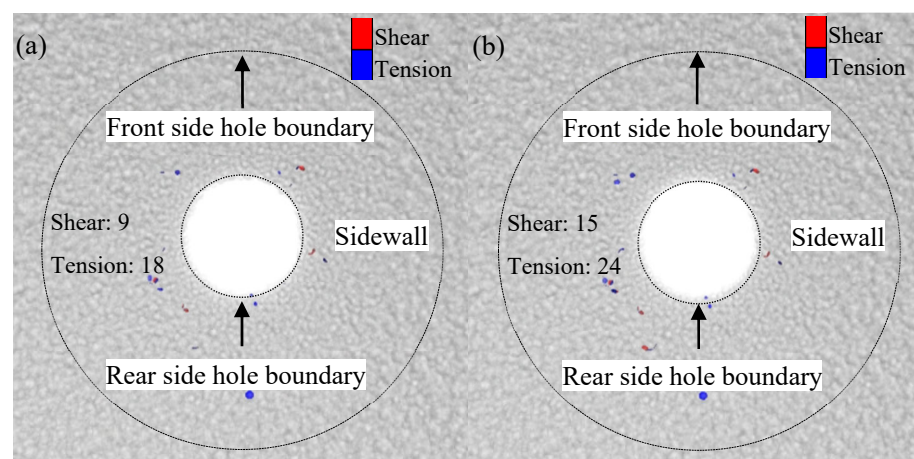


Figure 17. Internal unloading induced rock damage under different lateral stresses: (a) Sample SX-15.2-21.1 and (b) Sample SX-26.7-21.1.

In summary, both experimental and numerical results demonstrate that internal unloading under varying lateral stresses consistently induces an increase in the tangential stress and a decrease in the radial stress at the hole's surrounding rock. This leads to stress concentration and damage initiation, ultimately leading to a strength-weakening effect exacerbated as the lateral stress increases. Conversely, increasing σ_y raises σ_{zi} , exerting

a strength-strengthening effect. A comprehensive comparison of these two mechanisms reveals that, although both samples SX-15.2-21.1 and SX-26.7-21.1 were subjected to internal unloading, the overall mechanical response is dominated by the strength-strengthening effect triggered by increased lateral stress. Therefore, the strength-weakening effect resulting from the internal unloading is weaker than strength-strengthening effect resulting from the increasing lateral stress. In practical engineering, excavation unloading inevitably causes damage, necessitating post-excavation support to enhance its bearing capacity. These findings provide a strong evidence for this practical approach, and demonstrate that applying support to the unloaded surrounding rock significantly improves its stability.

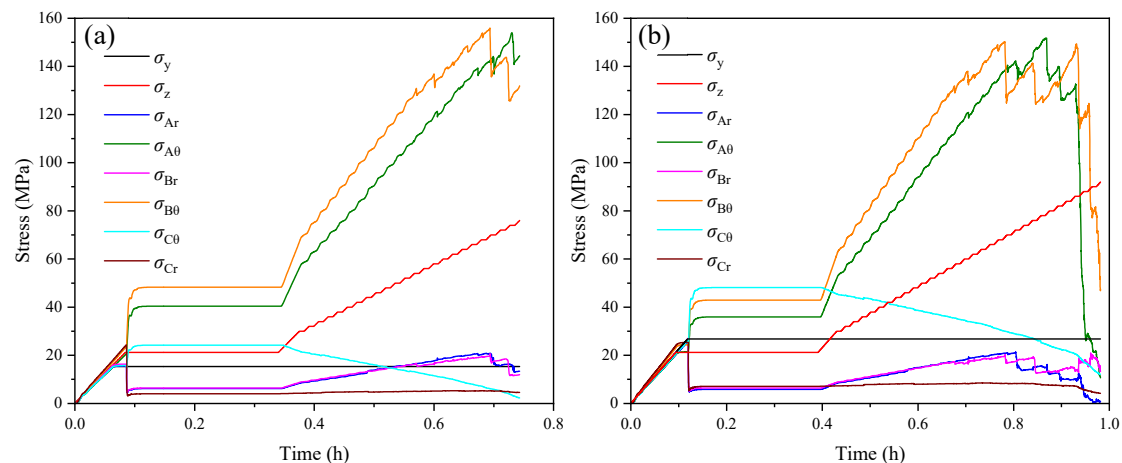


Figure 18. Stress distribution of the hole's surrounding rock: (a) Sample SX-15.2-21.1 and (b) Sample SX-26.7-21.1.

4.5. Limitations of This Research

Natural rock usually exhibits a strong variability in mechanical properties, including heterogeneous strength, stiffness, water content, bedding, and fractures [39–41]. These factors can significantly affect stress redistribution, strain localization, crack propagation, energy accumulation, and sudden failure of rock. In this study, complete rock samples were mainly selected for the rockburst simulation experiments to investigate the effects of lateral stress and internal unloading on rockburst, without considering the influence of heterogeneous strength, stiffness, water content, bedding, and fractures in natural rock. In addition, only 2D stress conditions were studied, and the influence of axial stress was ignored due to the limited experimental conditions. In future research, it is necessary to develop an internal unloading test device under three-dimensional stress conditions, conducting “three-dimensional stress + internal unloading + stress adjustment” tests to study the influence mechanism of three-dimensional stress and internal unloading on rockburst processes and characteristics. On this basis, the effects of heterogeneous strength, stiffness, water content, bedding, and fractures will be comprehensively considered.

5. Conclusions

- (1) Using a self-developed internal unloading testing apparatus, rockburst simulation tests were conducted under varying lateral stresses to replicate the conditions of “high geostress + internal unloading + stress adjustment”. A micro-camera was employed to observe the entire rockburst process, which encompasses four distinct stages: the quiet stage, the buckling deformation stage, the rock fragment exfoliation stage, and the V-shaped notch formation stage.
- (2) As the lateral stress increases from 15.2 MPa to 26.7 MPa, σ_{zi} increases from 64.00 MPa to 74.00 MPa, and D decreases from 2.4033 to 2.3459. Increasing the lateral stress en-

hances the rock bearing capacity and stability even without support, thereby reducing the rockburst risk and severity.

- (3) Following the internal unloading, shear and tensile cracks develop in the surrounding rock, with tensile cracks being predominant. With the increasing lateral stress, the number of shear and tensile cracks induced by internal unloading increases, yet tensile cracks remain dominant. As the vertical stress increases, the total crack number under low lateral stress surpasses that under high lateral stress. This indicates that while internal unloading under high lateral stress triggers more severe damage, the deterioration and failure become more pronounced under low lateral stress as the vertical stress continues to rise.
- (4) Under different lateral stresses, internal unloading can induce damage, which in turn induces a strength-weakening effect. With the increase in lateral stress, the strength-weakening effect due to internal unloading increases. Additionally, increasing the lateral stress results in a rise in σ_{zi} , inducing a strength-strengthening effect. By comprehensively comparing the effects of internal unloading and lateral stress, it was found that σ_{zi} increases as the lateral stress increases, indicating an overall strength-strengthening effect induced by increasing lateral stress.

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