Research Article

Experimental Investigation of Unloading-Induced Red Sandstone Failure: Insight into Spalling Mechanism and Strength-Weakening Effect

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To study the effect of excavation unloading on hard rock failure, a series of true-triaxial compression tests, biaxial compression tests, and true-triaxial unloading compression tests (two different unloading rates) at different confining pressures was conducted on red sandstone cube samples. The strength and failure characteristics and their relationship for red sandstone unloading at different unloading rates and confining pressures were analyzed. Based on the test results, the effects of the unloading rate and confining pressure on the strength and failure characteristics of hard rock were explored, and a reasonable explanation for unloading-induced spalling in hard rock tunnels was presented. The results show the stress-strain curve of highly stressed red sandstone exhibits a stress step during unloading, and the higher the unloading rate, the lower the stress level required for a stress step. The rock strength-weakening effect induced by unloading was confirmed. The mechanical properties of red sandstone become more unstable and complicated after unloading. After the red sandstone is unloaded to a two-dimensional stress state, with increasing confining pressure, the strength increases first and then decreases; the failure mode changes from a low-confining pressure tensile-shear failure to a high-confining pressure tensile failure; and the geometries of the slabs change from large thick plates and wedges to medium- and small-sized thin plates. At equal confining pressures, the higher the unloading rate, the lower the strength (i.e., the strength-weakening effect is more pronounced), the thinner the slab, and the lower the confining pressure required for the failure mode to change from tensile-shear failure to tensile failure. The unloading rate and confining pressure affect the strength and failure characteristics by affecting the crack initiation type and propagation direction in hard rock. For deep hard rock tunnels with high unloading rate and axial stress, neglecting the effects of unloading rate and axial stress will lead to a dangerous support design. For deep hard rock ore, if the maximal horizontal principal stress exceeds the critical confining pressure, the mining surface should be perpendicular to the direction of the minimal horizontal principal stress. The results of this study are of great engineering significance for guiding deep hard rock tunnel construction and mining.

1. Introduction

Deep rock mass is in the original three-dimensional (3D) geo-stress environment and exhibits generally a stable state without failure before excavation. After its excavation, the stress environment changes from 3D to two-dimensional (2D, such as those of tunnels and caverns) or one-dimensional (such as those of pillars). During excavation, the rock mass experiences the unloading of confining pressure. The confining pressure at the excavation surface is reduced to

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zero, which results in a significant decrease in the strength of the rock mass and, eventually, its failure. For hard rock, when the concentrated stress around the excavation surface exceeds the strength of the surrounding rock, brittle failure of varying severity will occur, such as spalling and rockburst [1–10]. Studies have shown that the rock mass strength and failure mode depend mainly on the confining pressure [11–15]. Generally, the strength of rocks increases gradually with increasing confining pressure, indicating an evident positive correlation. The failure mode changes with the change in the confining pressure, thereby transitioning from a tensile failure at low confining pressure to a shear failure at high confining pressure [16–19]. The harder the rock, the higher its strength, and the more significantly the failure mode is affected by the confining pressure [20]. In addition to the influence of the confining pressure on rock failure, the magnitude of the unloading rate caused by excavation will affect the rock failure. Many studies have shown that the unloading effect degrades rock, which leads to different degrees of damage inside the rock [21–25], and altered mechanical properties of the rock. The influence of the unloading effect on the rock failure is related to the unloading rate during excavation; and it is generally believed that the higher the unloading rate is, the more significant the influence is 26–30. For high-stress hard rock, the greater the unloading rate during excavation, the more severe the failure. Hard rocks are more likely to experience rockburst at high unloading rates, and nonviolent spalling is more likely to occur at relatively low unloading rates [31, 32].

However, excavation causes the hard rock to transition from a 3D to a 2D stress state. The confining pressure of the vertical excavation surface is unloaded, while the confining pressure parallel to the excavation surface (such as the axial stress of tunnels, roadways, and caverns) is not unloaded. After the excavation, the confining pressure parallel to the excavation surface and tangential stress affect simultaneously the deformation and failure of the surrounding rock. Experimental research results have shown that a confining pressure parallel to the excavation surface affects the strength and failure mode of the surrounding rock, such as the severity of the hard rock failure [33–35]. Currently, traditional conventional triaxial unloading tests are mainly used to study the effect of the unloading rate on the strength and failure of hard rock. After unloading the confining pressure, the samples are in a uniaxial compression state, which differs from the 2D stress state of the rock surrounding the deep tunnel. In fact, during the excavation process, the hard rock is simultaneously affected by the confining pressure parallel to the excavation surface and the unloading rate. Therefore, when studying the effect of unloading on the strength and failure of hard rock, the effects of the confining pressure and unloading rate should be considered simultaneously.

In this study, a series of true-triaxial compression tests (TCTs), biaxial compression tests (BCTs), and true-triaxial unloading compression tests (including true-triaxial unloading compression tests at a low unloading rate (TLU) and at a high unloading rate (THU)) was performed on red sandstone cube samples to analyze the effects of the unloading rate and confining pressure on hard rock failure. Through a detailed analysis and summary of the test results, the strength and failure characteristics and their relationship for red sandstone unloading at different unloading rates and confining pressures were determined. Therefore, the effects of the unloading rate and confining pressure on the strength and failure characteristics of hard rock were revealed, and a reasonable explanation for unloading-induced spalling in hard rock tunnels (or caverns) is presented in this paper.

2. Experimental Method

2.1. Rock Description and Sample Preparation. The red sandstone used in this experiment originates from Linyi, China. This sandstone has a uniaxial compressive strength (UCS) of 97.5 MPa, a uniaxial tensile strength (UTS) of 3.9 MPa (ratio of UCS to UTS is approximately 25), an elastic modulus of 18.6 GPa, a density of 2.43 g/cm³, and a longitudinal wave velocity of 3108 m/s, and it exhibits a moderate rockburst tendency 36, 37. Thus, the red sandstone is a typical hard rock with high strength and strong brittleness. Visually, the red sandstone is reddish-brown with a uniform texture, no evident structural weak surface, and medium-fine-grained sand-like texture, as shown in Figure 1(a). A thin section of the red sandstone was examined under a polarizing microscope, and the microstructure of the red sandstone was recorded under plane- and orthogonally polarized light, as shown in Figures 1(b) and 1(c). The red sandstone is mainly composed of quartz (42%), K-feldspar (5%), zeolite (8%), plagioclase (35%), calcite (9%), and opaque minerals (1%) 38.

In this study, the red sandstone was processed into cube samples (50 mm × 50 mm × 50 mm), as shown in Figure 1(d). The six faces of the cube samples were polished to obtain parallel faces with deviations within the range of ±0.05 mm and perpendicular adjacent faces within angle deviations within the range of ±0.25°. In addition, the six faces were evenly coated with Vaseline before the test, to mitigate the end effect.

2.2. Test Equipment. The employed TRW-3000 rock true-triaxial test system (Figure 2) consists of six independent loading systems, and the X, Y, and Z directions can be independently loaded to obtain unequal 3D stress conditions. The maximal loading capacity in the horizontal X and Y directions is 2000 kN, and the maximal loading capacity in the vertical Z direction is 3000 kN. During the test, the deformation in the three directions was measured with an extensometer, and then the strain in the corresponding direction was calculated based on the deformation. Thus, the TRW-3000 rock true-triaxial test system can realistically simulate a deep geo-stress environment and an excavation unloading process of rock mass.

(i) TCT: first, the test machine loading device was used to perform simultaneous true-triaxial loading on the cube samples at a loading rate of 1 kN/s in the X, Y, and Z directions. Subsequently, the load was maintained for 5 min after the set confining
pressure level was reached. In the next step, the loads in the X and Y directions remained constant, while the load in the Z direction continued to increase at a loading rate of 1 kN/s until the sample finally suffered overall failure; the loading was then stopped. A schematic of the loading path is shown in Figure 3(a).

(ii) BCT: first, the Y and Z directions of the testing machine loading device were used to load the cube samples at a loading rate of 1 kN/s. When the load in both directions reached the set confining pressure level, the load was maintained for 5 min. Subsequently, the load in the Y direction was maintained constant, while the load in the Z direction increased at 1 kN/s until the sample finally suffered overall failure, and the loading was stopped. A schematic of the loading path is shown in Figure 3(b).

(iii) TLU (or THU): first, the X, Y, and Z directions of the testing machine loading device were used to perform true-triaxial loading on the cube samples at a loading rate of 1 kN/s. After the load in the three directions reached the set confining pressure level, it
remained constant for 5 min. Subsequently, the loads in the $Y$ and $Z$ directions remained constant, while the load in the $X$ direction decreased at an unloading rate of 0.2 kN/s (or 10 kN/s). After the unloading, the loads in the $Y$ and $Z$ directions were kept constant for 5 min. Subsequently, the $Y$-direction load remained constant, while the $Z$-direction load increased at 1 kN/s until the sample suffered overall failure, and the loading stopped. A schematic of the loading path is shown in Figure 3(c).

2.3. Experimental Scheme. To study the effects of the unloading rate and confining pressure on the strength and failure characteristics of hard rock during unloading, two unloading rates (0.2 and 10 kN/s) and seven confining pressure levels (5, 10, 20, 30, 40, 50, and 60 MPa) were applied in the true-triaxial unloading compression tests (including TLU (unloading rate of 0.2 kN/s) and THU (unloading rate of 10 kN/s)). In addition, TCTs and BTCs were conducted at seven confining pressure levels to compare their results with those of the TLU and THU. To simplify the test scheme, the confining pressures in both horizontal directions were equal. The specific experimental scheme is as follows:

3. Test Results and Analysis

Based on the test scheme in Section 2.2, the TCTs, BCTs, TLU, and THU were conducted on cube samples at different confining pressures. To reduce the influence of accidental errors on the test results, tests with large differences in the results were repeated. In the subsequent analysis, only the test results with a peak strength close to the average peak strength are presented owing to the limited manuscript length.

3.1. Stress-Strain Curve. In this study, only the $Z$ direction stress-strain curve ($\sigma_z - \epsilon_z$) was analyzed. Figure 4 shows the $Z$ direction stress-strain curve for each test. For the TCTs (Figure 4(a)), the stress-strain curves exhibit a significant yielding stage before the peak strength, and the curves do not drop rapidly when the stresses increase to the peak strength. Thus, the brittleness of the red sandstone is significantly reduced in the 3D stress state. As the confining pressure increases, the elastic modulus increases. For the BCTs (Figure 4(b)), the stress-strain curves are similar to the uniaxial compressive stress-strain curve of a cylindrical sample. When loaded to the peak strength of the corresponding confining pressure, the curves drop rapidly and show strong brittleness. With increasing confining pressure, the elastic modulus increases first and then decreases. For the TLU and THU (Figures 4(c) and 4(d)), as the confining pressure increases, the elastic modulus increases first and then decreases, and some stress-strain curves include a stress step during the unloading process. For example, when the unloading rate is 0.2 kN/s and the confining pressure exceeds 30 MPa, the strain increases continuously during unloading, and a stress step is formed in the curve. The higher the stress level during unloading, the longer the stress step (Figure 4(c)). When the unloading rate is 10 kN/s, the stress-strain curves show a significant stress step at a confining pressure of 20 MPa, and the sample experiences overall failure during the unloading process at a confining pressure of 60 MPa (Figure 4(d)). In addition, according to Figures 4(a)–4(d), the stress-strain curves of the TCTs are smooth, and the differences in the stress-strain curves at different confining pressures are small. For the BCTs, TLU, and THU, the stress-strain curves at different confining pressures are quite different and rough, and the higher the unloading rate, the more evident the difference.

It can be concluded that, in the 3D stress environment, the crack propagation and coalescence of red sandstone are relatively stable; the plasticity is improved; and the mechanical properties remain relatively stable. In the 2D stress environment, particularly for red sandstone in an unloading process, the cracks are prone to unstable propagation and coalescence, and the mechanical properties are unstable. The higher the unloading rate, the lower the stress level required.
for significant deformation. As a result, the mechanical properties of hard rock experiencing unloading become more complicated.

3.2. Strength Properties. Owing to the large difference in the peak strength at some confining pressures, the tests were repeated. The peak strength observed during each test at different confining pressures is shown in Table 1. Accordingly, the relationship between the peak strength of each test and confining pressure was determined (Figure 5). For the TCTs, the peak strength increases significantly with increasing confining pressure; however, the higher the confining pressure is, the smaller the positive slope is (Figure 5(a)). For the BCTs, TLU, and THU, the peak strength increases with increasing confining pressure when the confining pressure is below 30 MPa; however, the positive slope decreases gradually. When the confining pressure...
increases from 30 to 40 MPa, the peak strength experiences a small decrease. When the confining pressure is over 40 MPa and continues to increase, the peak strength decreases continuously with gradually increasing negative slope. By comparing the peak strengths of the BCTs, TLU, and THU, it can be observed that the peak strength distribution of the

### Table 1: Peak strength of each test at different confining pressures.

| Confining pressure (MPa) | 5  | 10 | 20 | 30 | 40  | 50 | 60 |
|-------------------------|----|----|----|----|-----|----|----|
| Peak strength of TCT (MPa) | 121.1 | 158.5 | 215.3 | 258.5 | 296.0 | 337.7 | 357.7 |
| Peak strength of BCT (MPa) | 70.7 | 84.6 | 95.5 | 104.0 | 111.4 | 93.4 | 88.5 |
| Average                 | 70.7 | 84.6 | 99.8 | 104.7 | 102.0 | 94.6 | 89.5 |
| Peak strength of TLU (MPa) | 64.3 | 76.2 | 112.3 | 120.3 | 105.4 | 76.5 | 85.4 |
| Average                 | 64.3 | 76.2 | 95.7 | 97.2 | 103.5 | 91.9 | 85.4 |
| Peak strength of THU (MPa) | 68.1 | 77.2 | 93.3 | 97.6 | 114.3 | 89.2 | 60.0 |
| Average                 | 68.1 | 77.2 | 89.6 | 87.7 | 90.4 | 84.7 | 72.2 |

![Figure 5: Relationship between the peak strength and confining pressure: (a) TCT, (b) BCT, (c) TLU, and (d) THU.](image)
samples undergoing unloading processes at equal confining pressures is more discrete, particularly when the confining pressure is close to 30–40 MPa (Figures 5(b)–5(d)).

The previously presented results indicate that the peak strength increases monotonously with increasing confining pressure when the hard rock is in a 3D stress state (the two confining pressures are equal). There is a critical confining pressure for a hard rock in a 2D stress state, and the peak strength increases first and then decreases with increasing confining pressure (i.e., the peak strength is maximal at the critical confining pressure). The peak strength of the hard rock undergoing unloading is more unstable. It can be concluded that when the axial stress is below the critical confining pressure, the higher the axial stress, the higher the strength of the surrounding rock for deep hard rock tunnels. When the axial stress is greater than the critical confining pressure, the greater the axial stress, the lower the strength of the surrounding rock. Therefore, the axial stress should be considered in the support design of deep hard rock tunnels, and immediate support should be provided after excavation. For deep hard rock ore, if the maximal horizontal principal stress is higher than the critical confining pressure of the ore, the minimal horizontal principal stress should be unloaded during mining to reduce the strength of the ore and improve the mining efficiency.

To investigate the influence of the unloading rate and confining pressure on the strength of red sandstone further, the average peak strength is used in the following analysis. Figure 6 shows the relationship between the average peak strength and confining pressure for each test. The peak strength of the TCT is significantly higher than that of the BCT, TLU, and THU at equal confining pressures; in addition, the higher the confining pressure, the greater the difference in the peak strength. The peak strengths of the BCT, TLU, and THU increase first and then decrease with increasing confining pressure, and the critical confining pressures are within 30–40 MPa. Their peak strength difference is relatively small at the same confining pressure, particularly when the unloading rate is low. Hence, the transformation of the red sandstone stress state from 3D to 2D is the main reason for its strength reduction. That is, the confining pressure increases (or decreases) by the same value, and the strength increase (or decrease) is much higher in the 3D than in the 2D stress state, particularly when the unloading rate is high. For example, the confining pressure of the BCT decreases from \( \sigma_y = 60 \) to 10 MPa, thereby resulting in a decrease in the peak strength of 4.9 MPa, while the confining pressure of the TCT decreases from \( \sigma_y = \sigma_c = 50 \) MPa to \( \sigma_y = 50 \) MPa and \( \sigma_c = 0 \) MPa, which results in a reduction in the peak strength of 243.1 MPa.

Figure 7 presents the relationship between the peak strength and unloading rate at different confining pressures. The order of the peak strengths at a specific confining pressure is approximately as follows: BCT > TLU > THU. Within the range of the confining pressure variation investigated in this study, the peak strength difference between the BCT and TLU is small; however, their difference is more significant at a low than at a high confining pressure. The possible reason for this result is that the unloading rate of the TLU is very low, and its impact is limited. Consequently, its influence becomes weaker relative to the confining pressure at a high confining pressure. However, at a high unloading rate, the strength difference between the BCT and THU is relatively evident at a high confining pressure. This indicates that the high unloading rate exhibits a significant strength-weakening effect on the hard rock under high confining pressure.

In summary, the unloading rate and confining pressure affect the strength of red sandstone, and the effect of the confining pressure on the strength is significantly greater than that of the unloading rate. Therefore, the decreasing confining pressure caused by excavation is the most important reason for the decrease in the strength and failure of hard rock. A low unloading rate has no significant effect on
the strength of hard rock, whereas a high unloading rate does a significant strength-weakening effect on hard rock at a high confining pressure.

3.3. Failure Characteristics. The failure characteristics (including failure geometry and failure mode) of the samples in the TCTs, BCTs, TLU, and THU at different confining pressures are shown in Figures 8–11, respectively. In general, the failure characteristics of the BCT, TLU, and THU are similar and differ significantly from those of the TCT. The specific failure characteristics of each test are as follows:

(i) Failure geometry. As shown in Figure 8, at a low confining pressure, the samples of the TCT are severely broken, and the slabs are mostly long and columnar. With increasing confining pressure, the fragmentation of the sample is reduced, and the blockiness and thickness of the slabs increase continuously. At high confining pressure, the slabs are large wedges. For example, at $\sigma_y = \sigma_x = 60$ MPa, only three large wedge-shaped slabs are formed (Figure 8(g)). As shown in Figures 9–11, the size of most slabs produced by the BCT, TLU, and THU in the X (thickness) direction is shorter than those produced in the Y and Z directions (blockiness). Thus, slabs that are approximately parallel to the Y-Z plane are dominant. At a low confining pressure, the slabs are thick, their blockiness is large, the degree of fragmentation is relatively low, and their geometries are mainly plate and wedge shapes. With increasing confining pressure, the slabs become thinner; their blockiness decreases; and the degree of fragmentation becomes more severe. At a high confining pressure, the fragmentation of the samples is severe; the thickness and blockiness of the slabs are significantly reduced; and the slabs become mainly plate-shaped, with a low thickness and low blockiness. Furthermore, owing to the effect of the unloading rate, the failure geometry of the samples at equal confining pressures is different in the BCT, TLU, and THU. The higher the unloading rate, the smaller the blockiness, the thinner the slabs, and the more severe the fragmentation of the samples. Within the investigated confining pressure range, the difference in the failure geometries of the BCT and TLU is not significant, whereas that of the failure geometries of the BCT and THU is remarkable. Hence, a high unloading rate promotes the fragmentation of red sandstone and the formation of thin plate-shaped slabs; thus, the red sandstone is more prone to spalling.

(ii) Failure mode. As shown in Figure 8, at a low confining pressure, the samples of the TCT experience mainly columnar splitting and conjugate shearing of
multiple fracture surfaces along the direction of the maximal principal stress (i.e., Z direction). At a moderate confining pressure, the failure mode of samples is an inclined shear failure with multiple fracture surfaces, and at a high confining pressure, the failure mode is an inclined shear failure with a single fracture surface. As shown in Figures 9–11, in general, as the confining pressure increases, the friction powder on the surface of the slabs decreases in the BCT, TLU, and THU. Thus, the shear failure becomes gradually weaker with increasing confining pressure. At a low confining pressure, the friction powder on the surface of the slabs near the unloading surface of the BCT is not significant, and the dominant failure mode is tension. Moreover, a considerable amount of friction powder is generated on the surface of the slabs near the sample center, and the dominant failure mode is shear failure. With increasing confining pressure, the tensile characteristics of the slabs near the unloading surface become more significant, and the friction powder amount on the slab surfaces in the sample center decreases continuously. In particular, when the confining pressure exceeds 30–40 MPa, the shear characteristics become significantly weaker. At a high confining pressure, the slabs near the unloading surface and in the sample center exhibit evident tensile characteristics; i.e., the dominant failure mode of the sample is tensile failure. Owing to the effect of the unloading rate, the TLU and THU have more significant effects on the tensile characteristics of the slabs than the BCT at the same confining pressure. At a high unloading rate (i.e., THU) and at a low and high confining pressure, the dominant failure mode is tensile failure.

The following two conclusions can be drawn: (i) at low confining pressures, hard rock is prone to tensile failure in both 3D (columnar splitting) and 2D (plate-shaped splitting) stress states; in addition, shear failures occur in local areas. With increasing confining pressure, in the 3D stress state, the hard rock failure converts from a multiple-fracture surface tension-shear mixed failure to a single-fracture surface shear failure; the shear characteristics improve continuously, and the degree of fragmentation decreases. In the 2D stress state, the shear characteristics are continuously weakened; the failure state transforms gradually into a thin-plate-shaped tensile failure (i.e., spalling); the range of the tensile failure increases; and the fragmentation is more serious. (ii) The influence of the unloading rate on the failure characteristics of hard rock is related to the magnitudes of the confining pressure and unloading rate. The tensile

![Figure 9: Failure characteristics of BCT at different confining pressures.](image)
characteristics are more evident when the hard rock experiences unloading; thin plate splitting (i.e., spalling) is more likely to occur, and the fragmentation is more serious. The higher the unloading rate and confining pressure, the deeper the range of the hard rock tensile failure. When the unloading rate is low, the effect is not significant. Therefore, the effect of the unloading rate on the hard rock failure manifests itself mainly in enhanced tensile characteristics, which reduces the confining pressure required for a tensile failure in hard rock. That is, the increasing unloading rate accelerates the transition of the failure mode from shear to tensile failure and the change of the slab geometry from a thick plate or wedge to a thin plate.

In summary, after the excavation of high-stress hard rock, if the confining pressure of the parallel excavation surface is low, the tensile failure depth near the excavation surface is shallow, the fracture surface is approximately parallel to the excavation surface, and the slabs are large, thick plates. With increasing confining pressure, the depth of the tensile failure near the excavation surface increases, and the blockiness and thickness of the slabs become smaller and thinner, respectively. Simultaneously, the higher the unloading rate during excavation, the greater the depth of the tensile failure near the excavation surface, and the smaller and thinner the slab blockiness and thickness, respectively. Therefore, for deep hard rock tunnels or caverns, the higher the axial stress and unloading rate during excavation, the higher the possibility of spalling in the surrounding rock, and a rockburst disaster may occur in severe cases. Thus, for deep hard rock ore, mining methods with high unloading rates and unloading the minimal horizontal principal stress enhance ore fragmentation.

4. Discussion

In general, the shear strength of rock material is greater than the tensile strength, and the more evident the shear characteristics, the higher the corresponding strength. This is proved by the TCT results presented herein. According to Section 3, hard rock that experiences unloading exhibits weaker shear characteristics and decreased strength. Figure 12 shows the relationship between the peak strength and failure characteristics of each test. With increasing confining pressure, the failure mode of the TCT shows that the shear failure and the corresponding peak strength increase continuously. The failure modes of the BCTs, TLU, and THU show that the shear failure weakens gradually, and the corresponding peak strength increases first and then decreases. To determine the effects of the unloading rate and confining pressure on the strength and failure characteristics of hard rock, the experimental results in this paper are explained based on crack initiation and propagation.
The reason for rock failure is the macroscopic manifestation of continuous initiation, propagation, and coalescence of internal cracks [39–41]. Hence, the strength and failure characteristics during rock failure are closely related to the initiation, propagation, and coalescence of internal cracks. According to Section 3.3, for the TCT, as the confining pressure increases, the fragmentation of the sample decreases, and the wedge-shaped slab becomes thicker. For the BCTs, TLU, and THU, when the confining pressures are equal, the higher the unloading rate, the more serious the fragmentation of the samples, the more plate-shaped slabs parallel to the unloading surface are produced, and the thinner the slabs. When the unloading rate is constant, the higher the confining pressure, the more severe the fragmentation of the sample, the more plate-shaped slabs parallel to the unloading surface are produced, and the thinner the slabs. The severe fragmentation of the sample indicates that a great number of cracks have been created during the failure, while the great number and thin thickness of slabs parallel to the unloading surface indicate that a great number of cracks have propagated and coalesced in a direction parallel to the 2D stress plane (i.e., the Y-Z plane). It can be concluded that the changes in the confining pressure and unloading rate affect the initiation, propagation, and coalescence of cracks in hard rock.

Regarding the confining pressure, Sahouryeh et al. [42] believed that, in the 2D stress state, the effect of intermediate principal stress will cause the internal cracks of the rock to propagate continuously and coalesce in direction parallel to the 2D stress (i.e., the intermediate principal stress and maximal principal stress) plane, which results in a tensile failure. Cai [43] used a numerical simulation method to study the effect of intermediate principal stress on the surrounding rock failure around caverns. The main reasons for the spalling of rock around the caverns are the minimal principal stress (which is close to zero), the relatively high intermediate principal stress, and rock heterogeneity. The increasing confining pressure in the 2D stress state promotes crack propagation and coalescence in the direction of the 2D stress plane, which results in tensile failure. However, below the critical confining pressure, the confining pressure has a dual effect on the hard rock failure. First, the increasing confining pressure causes the cracks to propagate in the direction of the 2D stress plane, which promotes a tensile failure in the hard rock. Second, an increasing confining pressure increases the frictional resistance required to overcome hard rock fracture [44]; that is, an increasing crack initiation stress delays the hard rock failure [33], which increases the strength. When the critical confining pressure is exceeded, an increasing confining pressure facilitates the propagation of tensile cracks along the 2D plane stress direction, reduces the crack initiation stress, and decreases the strength of the hard rock. In addition, the increasing

![Figure 11: Failure characteristics of THU at different confining pressures.](image-url)
Shear failure is gradually strengthened and the fragmentation becomes less severe.

(a)

Shear failure gradually weakens and fragmentation becomes severe.

(b)

Shear failure gradually weakens and fragmentation becomes severe.

(c)

Figure 12: Continued.
confining pressure causes severe hard rock fragmentation, which is mainly due to the promoted initiation, propagation, and coalescence of more cracks in the hard rock failure process. Therefore, in the 2D stress state, with increasing confining pressure, the strength of the hard rock increases first and then decreases, the shear failure becomes gradually weaker, and the fragmentation becomes more severe. In the 3D stress state, the increasing confining pressure suppresses the initiation and propagation of tensile cracks parallel to the stress plane or in the direction of the maximal principal stress and increases the crack initiation stress. As a result, the rock failure is delayed; the shear failure becomes enhanced; the strength is increased; and fragmentation is reduced.

Regarding the unloading rate, some studies have shown that hard rock exhibits strong tensile fracture characteristics during unloading (verified by the test results in this paper), and tensile cracks will be generated inside the rock. The higher the unloading rate, the more developed the tensile cracks. Therefore, when hard rock under unloading fails, more tensile cracks propagate and coalesce in the direction of the 2D stress plane under the combined effect of the confining pressure and maximal principal stress. Thus, the shear failure is weakened; the strength is reduced (i.e., strength-weakening effect); and the fragmentation becomes severe. Moreover, the higher the unloading rate is, the more significant these effects are.

In summary, the unloading rate and confining pressure affect the strength and failure characteristics by affecting the crack initiation type and propagation direction in hard rock. The influence of the confining pressure on hard rock depends on the stress state. In a 3D stress state, the confining pressure mainly inhibits the initiation and propagation of tensile cracks and increases the crack initiation stress. After unloading to a 2D stress state, the increasing confining pressure promotes mainly the initiation and propagation of tensile cracks parallel to the 2D stress plane. The unloading rate promotes mainly the initiation of tension cracks in hard rock, thereby allowing more tension cracks to propagate and coalesce during hard rock failure, which leads to a strength-weakening effect on the hard rock. Therefore, during the excavation of deep high-stress hard rock tunnels (or caverns), affected by the unloading rate, numerous tensile cracks are generated in the surrounding rock within a certain range around the tunnel. Under the combined action of high tangential and axial stresses, the tensile cracks propagate and coalesce approximately parallelly to the excavation surface, which results in spalling.

5. Conclusions

(1) The order of the peak strengths of the different tests at equal confining pressure is TCT > BTC > TLU > THU. During unloading, the stress-strain curve of red sandstone exhibits a stress step, and its mechanical properties become more unstable and complicated after unloading. After unloading to the 2D stress state, cracks in red sandstone are prone to unstable propagation, and the failure exhibits strongbrittleness. The higher the unloading rate, the greater the difference between the mechanical properties, and the lower the stress level required for a stress step in the stress-strain curve.

(2) A critical confining pressure (within 30–40 MPa) exists after the red sandstone is unloaded to a 2D stress state. With increasing confining pressure, the strength increases first and then decreases (the strength is maximal at the critical confining pressure), and the failure mode changes from a low-confining pressure tension-shear mixed failure to a high-confining pressure tension failure. In addition, fragmentation becomes more severe, and the geometries of the slabs change from large thick plates and wedges to medium- and small-sized thin plates. The change of the red sandstone stress state from 3D to 2D is the main reason for its strength decrease.
(3) The influence of the unloading rate on the failure of red sandstone is related to the magnitudes of the confining pressure and unloading rate. The rock strength-weakening effect induced by unloading was confirmed. At equal confining pressures, the higher the unloading rate, the lower the strength (i.e., the strength-weakening effect is more pronounced), the weaker the shear failure, the more severe the fragmentation, and the easier the formation of thin-plate slabs. Increasing the unloading rate reduces the confining pressure required for the red sandstone failure mode to change from tensile-shear mixed failure to tensile failure. The effect of the high unloading rate on the failure of red sandstone is evident, particularly at high confining pressures, whereas a low unloading rate has no significant effect on the failure of red sandstone.

(4) The unloading rate and confining pressure affect the strength and failure characteristics of hard rock by affecting the type of crack initiation and direction of crack propagation. The effect of the unloading rate causes mainly tension cracks in the hard rock parallel to the unloading surface, which leads to an easier propagation and coalescence of tensile cracks when the hard rock is damaged. In the 2D stress state, the increasing confining pressure promotes the initiation and propagation of tensile cracks parallel to the stress plane. When the confining pressure is below the critical confining pressure, it will increase the crack initiation stress and delay the hard rock failure; in addition, the crack initiation stress decreases when the confining pressure exceeds the critical confining pressure.

(5) A reasonable explanation for spalling in deep hard rock tunnels (or caverns) was provided. During the excavation of deep hard rock tunnels, under the influence of the unloading rate, numerous tensile cracks are generated in the surrounding rock within a certain range around the tunnel. Under the combined action of high tangential and axial stresses, these tensile cracks propagate and coalesce approximately parallelly to the excavation surface, which induces spalling. The greater the unloading rate and axial stress, the greater the failure depth of spalling.

(6) The effects of the unloading rate and axial stress should be considered for deep hard rock tunnels. Neglecting the effect of the unloading rate affects the safety of the support design, particularly at high unloading rates. When the axial stress is lower or higher than the critical confining pressure of the surrounding rock, neglecting the axial stress will lead to a conservative or dangerous support design, respectively. For deep hard rock ore, if the maximal horizontal principal stress exceeds the critical confining pressure, the mining surface should be perpendicular to the direction of the minimal horizontal principal stress to reduce the strength and improve the fragmentation of ore.

**Data Availability**

The data used to support the findings of this study are included within the article.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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