Influence of sidewall size on spalling in deep D-shaped tunnels: An experimental simulation

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Abstract. A series of true triaxial compression tests was performed herein on cubic red sandstone samples containing a D-shaped hole with three sidewall sizes to study the influence of sidewall size on spalling in D-shaped tunnels. The initial horizontal stress of the tests refers to the in-situ stress at 500 m depth. The hole axis was arranged along the direction of the maximum horizontal principal stress. The vertical stress was increased to simulate the increasing surrounding rock stress after tunnel excavation. During the test, a self-made monitoring device was used to monitor and record the failure process of the tunnel models in real time. Furthermore, the spalling process of the D-shaped tunnels with different sidewall sizes was reproduced indoors. The failure process and the stress and fracture characteristics of the tunnel models with three different sidewall sizes were then analyzed and summarized. The effect of the sidewall size on spalling in D-shaped tunnels will be discussed in this paper. The results show that the failure of the tunnel models with different sidewall sizes first occurred on the sidewall near the corner then gradually developed upward and axial along the sidewall with the increase of the vertical stress. The width and the depth of the failure zone gradually increased, and a V-shaped notch was finally formed on the sidewall. No failure occurred on the roof and the floor of the tunnel models. The dominant failure modes were tensile failure. The failure forms were mainly spalling occasionally accompanied by slab ejection. The slabs were shaped in thin plates. The vertical stress that caused the initial failure of the tunnel models gradually decreased with the increasing sidewall size. Furthermore, the ability of the surrounding rock to store elastic strain energy decreased. The tensile characteristics became more prominent, and the size of the plate-shaped slabs increased. In the same stress environment, the greater the sidewall size, the larger the failure width and depth on the sidewall, and the more visible the V-shaped failure zone. The stability of deep D-shaped tunnels can be improved, and spalling can be mitigated by reducing the sidewall size. However, the risk of a rockburst will increase. This finding has an important engineering significance for the optimization design of a tunneling cross-section and the prevention of spalling and rockburst in D-shaped tunnels.

1. Introduction

Mining and tunneling in a deep hard rock have gradually become common phenomena with the increasing demand for resources and underground space. Under high-stress conditions, the failure process of a hard rock is usually controlled by the mechanism of a stress-induced brittle failure, which
results in fractures approximately parallel to the excavation boundary [1]. Studies have shown that this failure usually primarily manifests as spalling [2–5]. However, in severe cases, this failure may appear as a violent slab ejection (i.e., rockburst) [6–11]. These failures have caused a huge security threat to the exploitation of deep resources and the development of underground space, explaining the great attention it has received from researchers of rock mechanics [12–19].

Scholars have conducted many laboratory tests using a reduced-scale tunnel model and obtained many useful results to better understand the process and the mechanism of the stress-induced brittle failure in high-stress hard rock tunnels (e.g., roadways or caverns) [20–26]. These results have provided a theoretical basis for safe construction and spalling (or rockburst) prevention in deep hard rock tunnels. Carter et al. [20] performed uniaxial compression tests on a cuboid granite sample with a circular hole to study the brittle failure around underground caverns and observed that spalling occurred around the hole. Cheon et al. [21] performed a biaxial compression test on the circular tunnel model and found that the failure around the tunnel model can be divided into three grades, namely no failure, visible macro cracks, and heavy spalling. Meanwhile, He et al. [22] performed an impact rockburst simulation on a cuboid sandstone sample with a circular hole and found that the surrounding rock first suffered from spalling under high stress before the impact rockburst occurred under a higher stress. Kusuit et al. [23] performed a uniaxial compression (lateral displacement constraint) test on the cuboid circular tunnel model and found that spalling and slab ejection occurred in the surrounding rock. Gong et al. [24] performed a true triaxial rockburst test simulation using granite cube samples with a circular hole. Consequently, they successfully reproduced the granite rockburst process and observed that the surrounding rock failure showed spalling before the rockburst occurred. The abovementioned studies in the literature primarily investigated spalling or rockburst in circular hard rock tunnels.

In contrast, engineering practice shows that a D-shaped cross-section with advantages of high space utilization rate, less excavation, simple construction technology, and low cost is widely used in underground tunnels, roadways, and caverns. Some scholars performed laboratory tests on spalling and rockburst in D-shaped hard rock tunnels. Zhu et al. [27] performed a simulation test on spalling in deep marble tunnels by building a D-shaped tunnel physical model and studied the evolution process, formation mechanism, and onset conditions of spalling. Luo et al. [9] performed a true triaxial compression test using red sandstone cubic samples with a D-shaped hole, reproduced the spalling process in the D-shaped tunnel, and summarized the spalling characteristics of the sidewall. Pan et al. [28] performed a biaxial compression test on a red sandstone D-shaped tunnel model and studied spalling in the sidewalls. Meanwhile, Zhong et al. [29] processed granite into cube specimens with a U-shaped hole for biaxial compression tests to study the fracture behavior of the surrounding rock with natural fractures. As a result, they pointed out that no splitting and rockburst occurred on the sidewall, but observed slight fracture-induced failure and shear slipping. These studies primarily used tunnel models with the same cross-section in the testing without considering the influence of the cross-section size. However, note that the mechanical properties of a rock have a size effect, and the strength and the failure mode of the surrounding rock are affected by the sidewall size [30–31]. Therefore, the brittle failure (e.g., spalling) of D-shaped tunnels with different sidewall sizes must be studied to provide a theoretical basis for the cross-section optimization.

In this study, brittle red sandstone was processed into cubic samples with a D-shaped hole having different sidewall sizes. True triaxial compression tests were then performed to study the effect of the sidewall size on spalling in D-shaped tunnels. The spalling process of the D-shaped tunnels with different sidewall sizes was reproduced. Furthermore, the stress and failure characteristics of spalling in the D-shaped tunnels with different sidewall sizes were summarized. The influences of the sidewall size on the spalling strength, failure model, and energy storage characteristics of the surrounding rock were discussed based on the experimental results.

2. Experimental procedures

2.1. Sample preparation

Brittle red sandstone was used as the material for the D-shaped tunnel model processing. The red sandstone was described in detail by Gong et al. [4]; hence, it was not further described herein. First,
the red sandstone was cut into cubic samples measuring 100 mm × 100 mm × 100 mm. Next, a D-shaped hole was drilled through the samples to make D-shaped tunnel models. Figure 1 shows that D-shaped tunnel models with three different sidewall sizes were prepared (i.e., sidewall sizes \( h \): 0, 12.5, and 25 mm). We reduced the influence of accidental errors on the test results by smoothing the six surfaces of the sample to control the surface flatness within ±0.05 mm and the deviation of perpendicularity between two adjacent surfaces to be within ±0.25°. Table 1 presents the basic physical and mechanical parameters of the red sandstone.

![Figure 1. D-shaped tunnel model: (a) \( h = 0 \) mm (semicircle); (b) \( h = 12.5 \) mm; and (c) \( h = 25 \) mm.](image)

| P-wave velocity \( v \) (m/s) | Density \( \rho \) (g/cm\(^3\)) | Uniaxial compressive strength \( \sigma_c \) (MPa) | Direct tensile strength \( \sigma_t \) (MPa) | Elastic modulus \( E \) (GPa) | Poisson’s ratio \( \mu \) |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 3180                        | 2.43                        | 97.5                        | 3.9                         | 18.6                        | 0.21                        |

2.2. Test plan

The initial stress during the test refers to the geo-stress at 500 m depth determined by Gong et al., with the vertical stress of 13.5 MPa and the maximum and minimum horizontal principal stresses of 29 and 17 MPa, respectively [4]. The axis of the tunnel models was arranged along the direction of the maximum horizontal principal stress. A true triaxial test machine was used to perform the true triaxial compression tests on the tunnel models with different sidewall sizes. Furthermore, a self-developed monitoring device was used to monitor and record the tunnel model failure in real time (Figure 2). Loading stress path in the tests is described as follows: the three directions (X, Y, and Z) were first loaded to the initial stress at 1 kN/s loading rate; the two horizontal principal stresses were kept constant; and the vertical stress was increased to simulate the stress adjustment process caused by the excavation disturbance. When the sidewall was damaged, the step loading was used in the vertical direction (Z) to ensure the sidewall failure and the integrity of the tunnel model. The vertical stress was kept constant when the sidewall failure penetrated the entire tunnel model in the axial direction (X). Unloading was performed after the failure no longer occurred. Figure 3 illustrates a schematic of the loading stress path.

3. Test results

The true triaxial spalling test simulation was performed on the tunnel models with different sidewall sizes according to the test plan designed in Section 2.2. The loading stress path curves, failure characteristics, and spalling process of each tunnel model were obtained.
Figure 2. Test equipment [9]: (a) true triaxial test machine; (b) true triaxial loading device; (c) micro camera and lighting device; and (d) schematic of the real-time monitoring principle.

Figure 3. Schematic of the loading stress path [32].

3.1. Loading stress path
Figure 4 shows the loading stress path curves of the tunnel models with different sidewall sizes. The three tunnel models all experienced step loading after a failure on the sidewalls. Unloading finally occurred because the failure zone penetrated the axial length of the tunnel models. For the tunnel model with a 0 mm sidewall size (TM-0), step loading was adopted after the vertical stress reached 52 MPa, and the maximum loading stress in the vertical direction was 65 MPa. The beginning of loading to the completion of unloading took 1939 s. For the tunnel model with a 12.5 mm sidewall size (TM-12.5), step loading was applied after the vertical stress reached 50 MPa. The maximum loading stress in the vertical direction was 62 MPa, and the beginning of loading to the completion of unloading took 1510 s. For the tunnel model with a 25 mm sidewall size, step loading was adopted when the vertical stress reached 45 MPa. The maximum stress in the vertical direction was 55 MPa, and the entire test process lasted for 1232 s. Thus, the stress required to begin the step loading application gradually decreased with the increasing sidewall size of the tunnel model. The maximum stress in the vertical direction gradually decreased, and the time required to complete the test continued to decrease. That is,
the larger the sidewall size of the tunnel model, the lower the stress required to cause significant failure and bearing capacity, which resulted in worse tunnel stability.

![Loading path of tunnel models](image)

**Figure 4.** Loading path of the tunnel models with different sidewall sizes: (a) TM-0; (b) TM-12.5; and (c) TM-25.

### 3.2. Spalling characteristics of the tunnel model

Figure 5 shows the overall and local failure of the tunnel models with different sidewall sizes. The local failure is seen from the back of the tunnel models, comprehensively showing the tunnel model spalling. Overall, the three tunnel models were intact, and different degrees of failure only occurred on the holes. The hole sidewalls mainly failed in the tensile mode (i.e., spalling). The larger the sidewall size, the more significant the tensile failure. For TM-0, the tunnel model failure produced a large number of small slabs and debris. The failure depth was shallow, and the V-shaped failure zone was not obvious. The failure degrees on both sides were quite different, and failure occurred on the right side. The failure zone on the right side penetrated the entire tunnel model in the axial direction. On the contrary, no obvious failure was observed on the left side, and only a few fine particles were generated (Figure 5(a)). For TM-12.5, failure occurred on both sides of the tunnel model, and the failure zone on both sides penetrated the entire tunnel model along the axial direction. Some relatively large slabs and a large amount of debris were produced during the tunnel model failure. The fracture surface of the slabs was approximately parallel to the sidewall, and the failure depth was relatively deep. The failure on the right side was more serious than that on the left side, and a relatively obvious V-shaped failure zone was formed on the right side (Figure 5(b)). For TM-25, severe failure occurred on both sides of the tunnel model, but the failure on the right side was more severe than that on the left. The surrounding rock was cut into layered slabs approximately parallel to the sidewall. The slabs were
large, and the failure depth was deep. A clear V-shaped failure zone was formed on the front and rear faces of the tunnel model on the right side. Two cracks of an approximately parallel sidewall were generated on the rear face of the left side (Figure 5(c)). A comparison of Figures 5(a) to (c) showed that the spalling characteristics of each sample hole were different because of the size difference of the sidewalls. The failure difference between TM-0 and TM-12.5 was relatively small, but the sidewall spalling of TM-12.5 was relatively more obvious. The slab size was relatively larger, and the depth and the range of the failure zone were relatively deeper and wider, respectively. The failure difference between TM-12.5 and TM-25 was obvious. The slab size, depth, and range of the failure zone of TM-25 were significantly larger than those of TM-12.5. This result showed that although the sidewall size increased by the same increment, the larger the size, the more severe the failure (i.e., the more significant the reduction in the sidewall stability). In other words, spalling became more severe with the increasing sidewall size (i.e., the larger the slab size, the greater the failure depth and range and the more obvious the tensile failure and the V-shaped failure zone). The fracture surface generated by spalling was approximately parallel to the sidewall. This result depicts that the cracks around the hole propagated and coalesced along the direction of the approximately parallel sidewall because the tangential stress direction was approximately parallel to the sidewall, causing the crack to propagate and coalesce in the direction of the maximum principal stress (i.e., tangential stress) in the compressive stress field. With the increasing sidewall size, the tunnel stability decreased; spalling became more serious; the range and the depth of the failure zone were wider and deeper; and the slab size was larger. The influence of the sidewall size on the strength and failure mode of the surrounding rock will be discussed in detail in Section 4.1.

Figure 5. Picture of the failure of the tunnel models with different sidewall sizes: (a) TM-0; (b) TM-12.5; and (c) TM-25.
3.3. Spalling process of the tunnel model

The failure process of the tunnel models with different sidewall sizes was obtained using the video recorded during the tests (Figure 6). In general, the failure processes of the three tunnel models with different sidewall sizes were roughly similar. Under high-stress conditions, the fracture first occurred on the sidewall near the corner and developed upward and axial along the sidewall. A V-shaped failure zone was eventually formed on the sidewall. In this process, the fracture surface was approximately parallel to the sidewall. The slab geometry was a thin plate. The primary failure form was slab flaking (i.e., spalling). The failure process of each tunnel model was different because of the different sidewall size. For TM-0, the failure form of the surrounding rock was the flaking of small slabs. For TM-12.5 and TM-25, the main failure form was the flaking of large slabs sometimes accompanied by slab ejection (i.e., rockburst). When slabs were ejected in TM-12.5, the failure range was wide (i.e., close to the height of the entire sidewall); the number of slabs was large; and the slab size was large. In contrast, when slabs were ejected in TM-25, the failure range was narrow (i.e., small area of the sidewall near the corner); the number of slabs was small; and the slab size was relatively small. Spalling became more severe, and rockburst was more likely to occur with the increasing sidewall size; however, the severity of the rockburst decreased because the sidewall size of TM-0 was very small, and the maximum vertical stress did not reach the stress conditions required for a rockburst. Therefore, optimizing the sidewall size can improve the stability of the surrounding rock and weaken spalling or rockburst in hard rock tunnels.
Figure 6. Spalling process of tunnel models with different sidewall sizes: (a) TM-0; (b) TM-12.5; and (c) TM-25.

4. Analysis and discussion

The influence of the sidewall size on the strength, failure mode, and energy storage properties of the surrounding rock around the tunnel is discussed herein based on the test results in Section 3.

4.1. Influence of the sidewall size on the strength and failure mode of the surrounding rock

The vertical stress required for the initial failure of the tunnel models with different sidewall sizes can be obtained using the video and the stress path curve recorded during the test (Table 2). The vertical stresses required for the initial failure of TM-0, TM-12.5, and TM-25 were 48.9, 42.7, and 37.6 MPa, respectively. The vertical stress-to-uniaxial compressive strength ratios of TM-0, TM-12.5, and TM-25 were 0.50, 0.44, and 0.39, respectively. The result shows that the vertical stress required for the initial failure of the sidewall of the tunnel model continued to decrease as the sidewall size increased (Figure 7). In Figure 8, the failure of the three tunnel models, in which the maximum vertical stress of TM-25 was 53 MPa, was intercepted with a vertical stress of 53 MPa to further analyze the influence of the sidewall size on the surrounding rock strength. Under the same stress environment, a more severe failure of the surrounding rock and a tensile failure occurred with the increasing sidewall size. Figures 4 and 5 show that the tunnel model failure became more serious and the tensile failure became more significant under a lower vertical stress when the sidewall size was larger. These results indicate that the increase in the sidewall size led to a decrease in the strength of the surrounding rock and was beneficial to the tensile failure occurrence. In other words, the strength and the failure mode of the surrounding rock around the tunnel had size effects, that is, the increase in the sidewall size reduced the stress required for the surrounding rock failure (i.e., the strength of the surrounding rock decreases) and caused a more significant tensile failure.

| Sample no. | Axial stress \( \sigma_x \) (MPa) | Lateral stress \( \sigma_y \) (MPa) | Vertical stress \( \sigma_z \) (MPa) | \( \sigma_z/\sigma_c \) |
|------------|-------------------------------|-------------------------------|-------------------------------|------------------|
| TM-0       | 29                            | 17                            | 48.9                          | 0.50             |
| TM-12.5    | 29                            | 17                            | 42.7                          | 0.44             |
| TM-25      | 29                            | 17                            | 37.6                          | 0.39             |

Table 2. Stress characteristics of the initial failure of the sidewall of each tunnel model.
Figure 7. Vertical stress required for the initial failure of the tunnel models with different sidewall sizes.

Figure 8. Influence of the sidewall size on the failure of the tunnel models (vertical stress: 53 MPa): (a) TM-0; (b) TM-12.5; and (c) TM-25.

Accordingly, scholars performed numerous related studies for the size effect of a rock. Figure 9 shows the relationship between the uniaxial compressive strength and the length-to-diameter ($L/D$) ratio of various rocks. The uniaxial compressive strength gradually decreased with the $L/D$ increase [33]. Du et al. [34] performed uniaxial compression tests on marble samples with three different cross-sectional shapes (i.e., circle, square, and rectangle) and found that the uniaxial compressive strength of each cross-sectional shape sample gradually decreased with the increasing height-to-width ($H/W$) ratio. However, the surrounding rock around the tunnel was generally affected by tangential and axial stresses. Some scholars performed true triaxial unloading tests on rock samples with different $H/W$s to study the size effect. Li et al. [35] performed a true triaxial unloading test on granite samples with...
different $H/W$s and found that the sample’s strength gradually increased with the decreasing $H/W$. Zhao et al. [36] performed a true triaxial unloading test on cuboid granite samples with different $H/W$s and noted that the sample strength gradually decreased as the sample $H/W$ decreased. The samples primarily underwent tensile failure when the $H/W$ was large and shear failure when the $H/W$ was small. Meanwhile, Zhao and He [37] performed a true triaxial unloading rockburst simulation test on granite samples with different height-to-thickness ratios. Consequently, they found that the sample’s strength gradually increased, and the failure mode changed from tensile failure to single-plane shear failure as the height-to-thickness ratio decreased. The abovementioned research showed that the strength and the failure mode of the rock were sensitive to the size effect, which was consistent with the experimental results in this study.

Figure 9. Experimental data of the normalized strength versus $L/D$ (modified from Liang et al. [33]).

4.2. Influence of the sidewall size on the energy storage properties of the surrounding rock

The essence of a rock failure is a result of energy dissipation and release. The higher the amount of energy released in a short time, the more severe the rock failure. For hard rock tunnels, the ability to store elastic strain energy ($U_e$) is the major factor affecting the failure form of the surrounding rock. It is generally believed that the greater the capacity of the surrounding rock to store elastic strain energy, the greater is the possibility of a rockburst [38]. However, studies have shown that the ability of a rock to store elastic strain energy is related to its size. Liang et al. [33] performed uniaxial compression tests on granite cylinder samples with different $L/D$s (setting four different loading rates) to study the influence of $L/D$ on the energy storage characteristics of a rock. Under four loading rates, the stored elastic strain energy in the sample gradually decreased with the $L/D$ increase. That is, the greater the $L/D$ of the sample, the smaller its ability to store elastic strain energy (Figure 10). Zhao et al. [36] studied the influence of $H/W$ on granite rockburst and found that the rockburst becomes more violent as the sample’s $H/W$ becomes smaller. They pointed out that a small $H/W$ is conducive to the energy storage of the sample; hence, more energy is released when the sample is destroyed, resulting in a more severe failure.
Figure 10. Effect of the rock sample L/D on the elastic strain energy [33].

Section 3.3 showed that a rockburst in a tunnel is more likely to occur when the sidewall size is increased. Meanwhile, the severity of a rockburst is weakened, and spalling becomes more serious. A rockburst results from the rapid release of elastic strain energy inside the surrounding rock. The weakening of a rockburst indicates that the releasable elastic strain energy stored in the surrounding rock has decreased. In conclusion, the sidewall size increase reduces the ability of the surrounding rock to store strain energy and is not conducive to the elastic strain energy accumulation, thereby weakening the rockburst. This finding is consistent with the results of Liang et al. [33] and Zhao et al. [36].

In summary, the strength, failure mode, and failure form (flaking or ejection) of the surrounding rock are affected by the sidewall size of the tunnels. Reducing the sidewall size can increase the surrounding rock strength and enhance the tunnel stability. However, it will also increase the capacity of the surrounding rock to store elastic strain energy and increase the risk of a severe rockburst. On the contrary, increasing the sidewall size can reduce the strength of the surrounding rock, thereby resulting in poor tunnel stability, significant tensile failure, and serious spalling. However, the risk of a severe rockburst will be reduced. For high-stress D-shaped hard rock tunnels, the sidewall size can be optimized by meeting the space requirements. The surrounding rock must have a relatively high strength to improve the tunnel stability and reduce spalling. Furthermore, its capacity to store strain energy must not be too strong to reduce the risk of a rockburst. For D-shaped tunnels with a high sidewall rockburst risk, the sidewall size can be appropriately increased to reduce the rockburst risk, but the sidewall support strength must be enhanced to prevent spalling (i.e., increase the strength of the surrounding rock). For D-shaped tunnels with severe sidewall spalling and no (or low) rockburst risk, the sidewall size can be reduced to increase the rock strength to reduce spalling. However, rockburst monitoring must be strengthened, and measures to prevent a rockburst occurrence must be taken. In addition, the size of the two sidewalls of the roadway (cross-section shape is not a D shape) when mining in a deep inclined rock stratum may be different. A high sidewall is prone to severe spalling because of the low strength of the surrounding rock, whereas a low sidewall has a high risk of rockburst because of the strong ability of the surrounding rock to store elastic strain energy. High prestressed bolts should be used to prevent spalling when designing a high sidewall support, while high energy-absorbing bolts should be used for low sidewall support to prevent a rockburst occurrence.

5. Conclusions
The following results were obtained from this study:
(1) The spalling process and characteristics in D-shaped tunnels were obtained under the condition where the vertical stress was the maximum principal stress. The failure of the tunnel models first occurred on the sidewall near the corner and gradually developed upward and axial along the sidewall as the vertical stress increased. A V-shaped notch was finally formed on the sidewall when the width and the depth of the failure zone continuously increased. No failure occurred on the roof and the floor of the tunnel models. The dominant failure mode was tension failure. The primary failure form was spalling occasionally accompanied by slab ejection. The slab geometry was a thin plate.

(2) Spalling of the D-shaped tunnel was significantly affected by the sidewall size. The strength of the surrounding rock, the vertical stress required for the initial tunnel failure, and the ability of the surrounding rock to store elastic strain energy all decreased with the increasing sidewall size. The tensile characteristics also became more prominent; spalling was more serious; and the slab size increased. On the contrary, the risk of a rockburst was reduced. Under the same stress environment, the greater the sidewall size, the larger the failure width and depth on the sidewall and the more obvious the V-shaped failure zone.

(3) For the D-shaped hard rock tunnels, the surrounding rock should have a relatively high strength to reduce spalling and optimize the sidewall size. Moreover, the capacity of the surrounding rock to store strain energy should not be too strong to reduce the risk of a severe rockburst. High prestressed bolts should be used for the high sidewall support to increase the strength of the surrounding rock when designing a tunnel support, while high energy-absorbing bolts should be used for the low sidewall support to reduce the risk of a rockburst.

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