

Article

Dynamic Responses and Failure Characteristics of Deep Double U-Shaped Caverns under Disturbing Loads

Lisha Liang *, Xibing Li and Zhixiang Liu

School of Resources and Safety Engineering, Central South University, Changsha 410083, China;
xbli@csu.edu.cn (X.L.); liulzx@csu.edu.cn (Z.L.)

* Correspondence: lls1994@csu.edu.cn

Abstract: The instability of double-cavern structure subjected to dynamic disturbances is a key issue for deep rock engineering. To investigate the dynamic responses of deep double U-shaped caverns, comprehensive analyses are conducted by Particle Flow Code (PFC2D), and the influences of incident directions of stress wave, cavern clearances, and cavern height ratios are discussed. The results indicate that the decreasing cavern clearance aggravates the static stress concentration on the intermediate rock pillar. When the stress wave is horizontally incident, the presence of the incident side cavern reduces peak tangential stress and kinetic energy on the non-incident side cavern; the higher the incident side cavern, the less damage on the non-incident side cavern. A vertically incident stress wave causes more severe damage in the intermediate rock pillar compared to a horizontally incident stress wave; the smaller the cavern clearance, the more violent the rockburst in the intermediate rock pillar. Comparatively, the cavern with a lower height exhibits more severe failure at the adjacent sidewall compared to the cavern with a higher height. This work can provide guidelines for disaster prevention of deep double-cavern structures.

Keywords: double U-shaped cavern; dynamic disturbances; failure characteristics; numerical simulation; PFC2D



Citation: Liang, L.; Li, X.; Liu, Z. Dynamic Responses and Failure Characteristics of Deep Double U-Shaped Caverns under Disturbing Loads. *Appl. Sci.* **2024**, *14*, 4543. <https://doi.org/10.3390/app14114543>

Academic Editor: Tiago Miranda

Received: 2 May 2024

Revised: 23 May 2024

Accepted: 23 May 2024

Published: 25 May 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In deep excavation, the cavern is located at a high in situ stress level, and subjected to various dynamic disturbances, leading to the occurrence of unconventional disasters such as rockburst, spalling, and zonal disintegration [1–3]. Exploring the mechanisms of dynamic disasters is quite important for deep engineering.

To investigate the failure characteristics of the caverns under the coupled static–dynamic loading condition, many studies have been conducted by laboratory experiment. He et al. [4] developed a dynamic true-triaxial experimental system to simulate the impact rockburst, and reproduced the rockburst process on the rock specimens with a circular hole. They concluded that the damage extent under dynamic loading is more severe than that under static loading. Su et al. [5] analyzed the failure characteristics around the circular opening by using an improved true-triaxial test system, and explained the failure mechanism of the remotely triggered rockburst from an energy perspective. Wu et al. [6] captured the strain rockburst process of the circular opening under dynamic impact loading by using the biaxial Hopkinson pressure bar equipment and high-speed camera. They found that the lateral pressure is an important factor for the range of strain concentration zone around the cavern, and the severity of strain rockburst decreases with increasing lateral pressure. He et al. [7] analyzed the dynamic response around a horseshoe-shaped opening under blast loading and pointed out that the loading direction significantly affects the crack propagation around the opening.

Due to the limitation of the testing device, it is difficult to replicate the complex geological and stress conditions of practical engineering by laboratory experiments. With

the rapid development of computer technology, numerical methods such as the finite element method (FEM), the finite difference method (FDM), and the distinct element method (DEM) have extensively been used to investigate the dynamic response and failure characteristics of underground engineering under dynamic disturbance [8–10]. Saiang [11] and Qiu et al. [12] studied the blast-induced dynamic response of U-shaped caverns by PFC (Particle Flow Code) and FLAC (Fast Lagrangian Analysis Code) and analyzed the influence of cavern depth and blasting position on the dynamic response of surrounding rock. Wang et al. [13] investigated the damage characteristics around the cavern under multiple explosion sources by LS-DYNA3D and found that the crack density in the middle part of the two explosion sources is much higher than other rock masses. Mitelman and Elmo [14] compared the blast damage around the cavern with different rock strengths and pointed out that the higher rock strength would increase the durability of the cavern but decrease the wave attenuation rate on the surrounding rock. Kuili and Sastry [15] concluded that the discontinuities accelerate wave attenuation in the surrounding rock, and the stress wave with higher frequency induced large displacements around the boundary of the cavern. Manouchehrian and Cai [16] simulated the dynamic failure of deep caverns under coupled static–dynamic loads by using ABAQUS and found that the presence of fault leads the rock failure to become more violent.

With the development of underground engineering, double-cavern or even multi-cavern structures became common designs [17,18]. When the distance between adjacent caverns is much larger than the cavern size, the influence of adjacent caverns can be neglected, and they can be treated as a single-cavern structure [19]. However, in practical engineering, the limited space and complex geological conditions result in the limited spacing between adjacent caverns. Thus, the stability of the caverns would be affected by neighboring caverns. On the one hand, the interaction effect between caverns exacerbates static stress concentration in the surrounding rock [20]. On the other hand, multiple scattering occurs around the caverns as the disturbing stress waves pass through the multi-cavern structure [21]. Therefore, the dynamic response around the caverns becomes more complex compared to single-cavern structures, and the stability of the multi-cavern structure under dynamic disturbance has attracted the attention of many scholars. Liu et al. [22] and Balendra et al. [23] calculated the steady-state response around double circular caverns under the S waves and P waves by the wave function expansion method, and pointed out that the space between caverns and frequency of the incident wave have considerable influence on the dynamic responses around the caverns. Lu et al. [24] investigated the effects of incident angle and wave number on the twin circular subjected to P-wave. However, the existing research mainly focused on the dynamic response of double circular caverns, and the studies of the non-circular caverns were confined to a single structure. Further investigation of the dynamic responses and failure characteristics of double non-circular caverns is needed, especially for unequal caverns.

This paper aims to understand the dynamic responses around the deep double U-shaped caverns under disturbing load. A two-dimensional numerical simulation model with double U-shaped caverns under coupled static–dynamic loading was established by PFC2D, and the dynamic stress concentration and energy evolution around the caverns were investigated. Moreover, the influences of cavern clearance, cavern height ratio, and disturbing direction on the dynamic response and failure modes of surrounding rock were investigated systematically. This will provide a theoretical basis for disaster prevention and control of deep double-cavern structures.

2. Numerical Model

As one of the explicit discrete element methods (DEMs), PFC2D (Particle Flow Code in two dimensions) of the company Itasca Consulting Group can observe the fracturing process indirectly, and has been widely used to simulate the failure behavior of rock materials [25]. In the PFC2D, the contact bond, parallel bond, and flat-joint model are the main bonding approaches to simulate the cementation between particles. Comparatively,

the flat-joint model can mimic the grain interlocking of polygonal grain structure and replicate the mechanical parameters and crack propagation characteristics of real rocks effectively [26–28]. Therefore, the flat-joint model was applied to establish the numerical models in this study. In this study, the mechanical parameters of the surrounding rock were calibrated by the red sandstone from Linyi, Shandong Province, China, and the corresponding macroscopic mechanical parameters of experimental results and numerical results are shown in Table 1. The calibrated microscopic parameters of the numerical model are illustrated in Table 2, which have been validated in our previous work [29].

Table 1. Macro-mechanical parameters of surrounding rock.

Mechanical Parameters	Density (kg/m ³)	Elastic Modulus (GPa)	Poisson's Ratio	Uniaxial Compressive Strength (MPa)	Brazilian Tensile Strength (MPa)
Experimental results	2440	18.60	0.21	97.60	4.87
Numerical results	2440	18.74	0.21	97.38	4.91

Table 2. Micro-parameters of PFC2D model.

Microscopic Parameters	Values	Microscopic parameters	Values
Particle density, ρ (kg/m ³)	2711	Effective modulus, E_c (Gpa)	18.34
Particle minimum radius, r_{min} (m)	0.03	Stiffness ratio, k_n/k_s	2.0
Particle radius ratio, r_{max}/r_{min}	2.0	Tensile strength, σ_c (MPa)	8.25 ± 0.83
Number of elements	2	Cohesion strength, c (MPa)	45.60 ± 4.56
Porosity	0.1	Friction angle, φ (°)	46
Local damping coefficient	0.0	Friction coefficient, μ	0.50

A numerical model with the geometry of 20×15 m was established by PFC2D, and two U-shaped caverns were set up in the middle of the model, as shown in Figure 1. In this section, the geometric dimensions of cavern 1 (left) and cavern 2 (right) are $w_1 = w_2 = 2.5$ m and $h_1 = h_2 = 3.75$ m, and the buried depth of the surrounding rock is 1000 m. According to the stress field of China, the horizontal and vertical principal stresses can be obtained by [30]:

$$\begin{cases} \sigma_v = 0.02532H + 0.8177 \\ \sigma_h = 0.01766H + 1.0583 \end{cases} \quad (1)$$

where H represents the buried depth of the cavern. According to Equation (1), the vertical stress $\sigma_v = 26.1$ MPa and the horizontal stress $\sigma_h = 18.7$ MPa are applied to the model through the particle boundary. To eliminate the reflected waves on the model boundary, the viscous boundary is set up [31].

When the disturbance wave source is relatively close to the cavern, the dynamic disturbance can be regarded as a cylindrical stress wave. Conversely, when the disturbance wave source is far from the cavern, the curvature of the incident wave can be neglected; thus, the dynamic disturbance can be simplified as a plane stress wave [32]. In this study, we take the blasting load as an example, and the incident stress wave is simplified to a triangular plane wave [33,34]. When $t < t_r$, it belongs to the loading stage of the incident wave, and when $t_r < t < t_s$, it belongs to the unloading stage of the incident wave. The mathematical expression of the incident stress wave can be expressed as the following:

$$P(t) = \begin{cases} 0, & (t < 0) \\ \frac{t}{t_r} P_d, & (0 \leq t < t_r) \\ \frac{t_s - t}{t_s - t_r} P_d, & (t_r \leq t < t_s) \\ 0, & (t \geq t_s) \end{cases} \quad (2)$$

where P_d is the amplitude of the incident wave; t_r and t_s are the rising time and total duration of the incident wave, respectively. In this study, the rising time $t_r = 2$ ms, and the total duration $t_s = 10$ ms.

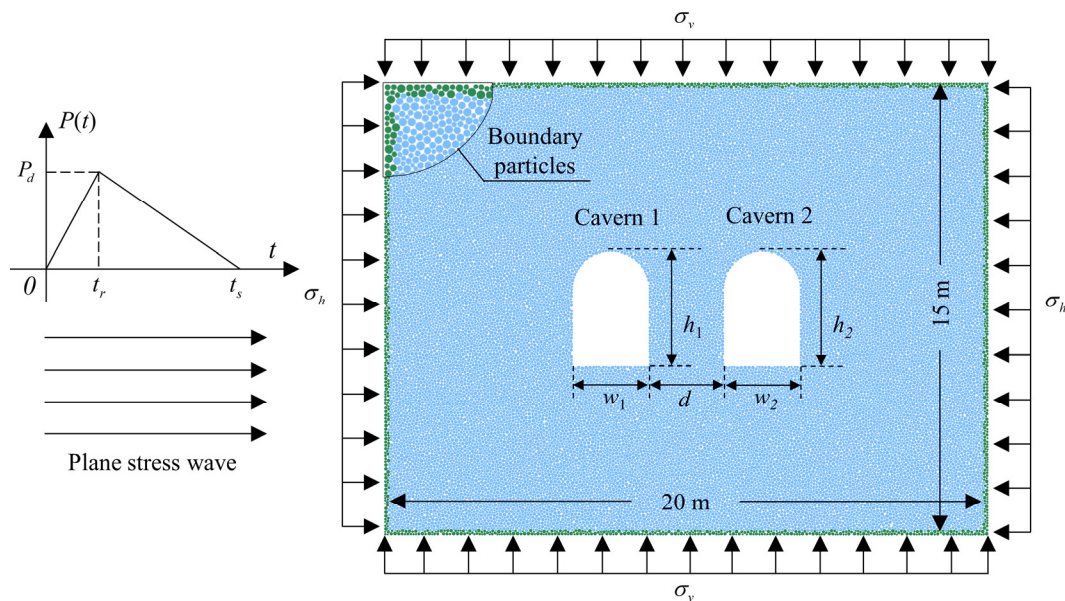


Figure 1. The model of double U-shaped caverns under horizontally incident wave.

In order to investigate the evolution of stress and energy around the double U-shaped caverns under coupled static–dynamic loading, eight measurement circles were set at the midpoints of the crown (A1, A2), the sidewalls (B1, B2, C1, C2), and the floor (D1, D2) of two caverns. The radii of the measurement circles are 0.25 m, and the layout scheme is illustrated in Figure 2, where the blue circles represent the measurement circles.

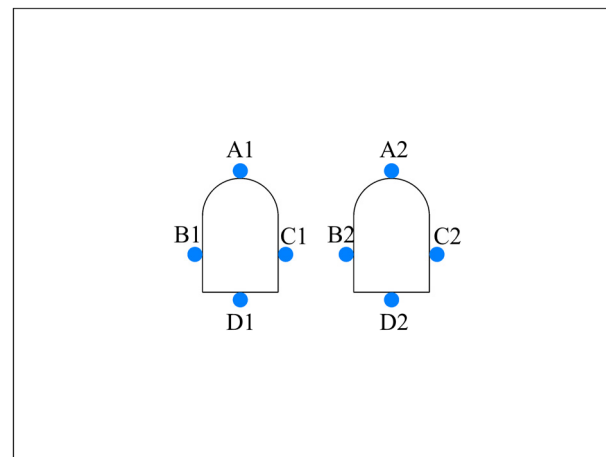


Figure 2. The layout of measurement circles around the two caverns.

3. Numerical Simulation Results and Analysis

3.1. Failure Characteristics of the Double U-Shaped Caverns under Horizontally Incident Wave

As a plane P-wave is incident from the left side of the model horizontally, there are certain differences of the wave propagation process around caverns 1 and 2, leading to distinct variations in their stress evolution processes. When the cavern clearance d is 2.5 m and the stress wave amplitude P_d is 15 MPa, the evolution processes of the tangential stress at different positions of the two caverns are illustrated in Figure 3. When the stress wave propagates to the caverns, dynamic compressive stress concentrations occur at both

the crown and floor areas of both caverns. The peak tangential stresses at the crowns of caverns 1 and 2 are 60.0 and 57.4 MPa, respectively, while the peaks at the floor are 39.8 and 32.0 MPa, respectively. By comparing, the dynamic stress concentration at the roof and floor of the incident side cavern (cavern 1) is more significant than that at the non-incident side cavern (cavern 2). Furthermore, the incoming stress wave results in dynamic tensile stress concentrations at the sidewalls. However, due to the existence of static compressive stress induced by in situ stress, the sidewall areas remain under compression. As shown in Figure 3b, the stress wave diffraction leads to a period of dynamic compressive stress concentration at the B2 position before the occurrence of dynamic tensile stress concentration.

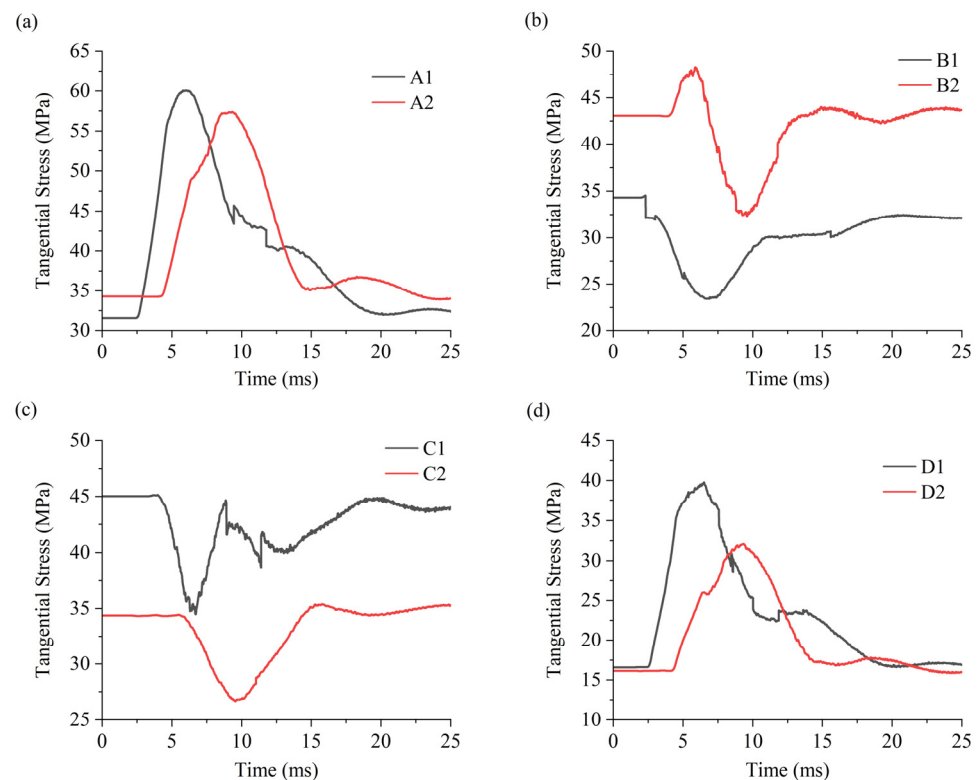


Figure 3. The evolution process of tangential stress at different positions of the caverns under horizontally incident stress wave: (a) midpoints of crown; (b) midpoints of facing-wave sidewall; (c) midpoints of back-wave sidewall; (d) midpoints of floor.

Figures 4 and 5 depict the evolution processes of strain energy and kinetic energy at different positions of the two caverns under dynamic disturbances, respectively. Comparing Figure 3 with Figure 4, it can be found that the evolution pattern of strain energy is similar to the evolution pattern of tangential stress at the same position. The strain energy accumulates at the cavern crown and floor, and the peak strain energies at the crown and floor areas of cavern 1 are higher than those at cavern 2. Comparing the peak value of kinetic energy at different positions of the two caverns, it is found that the maximum peak kinetic energy occurs at position B1, and the corresponding value is 2.8 kJ, significantly higher than the peak kinetic energy at position B2. This indicates that the presence of the incident side cavern weakens the reflection of stress waves on the facing-wave side of the non-incident side cavern. For the back-wave side of the caverns, the peak kinetic energy at position C1 is also significantly higher than that at position C2, suggesting that the presence of cavern 2 intensifies the particle vibration of the surrounding rock on the incident side cavern's back-wave side.

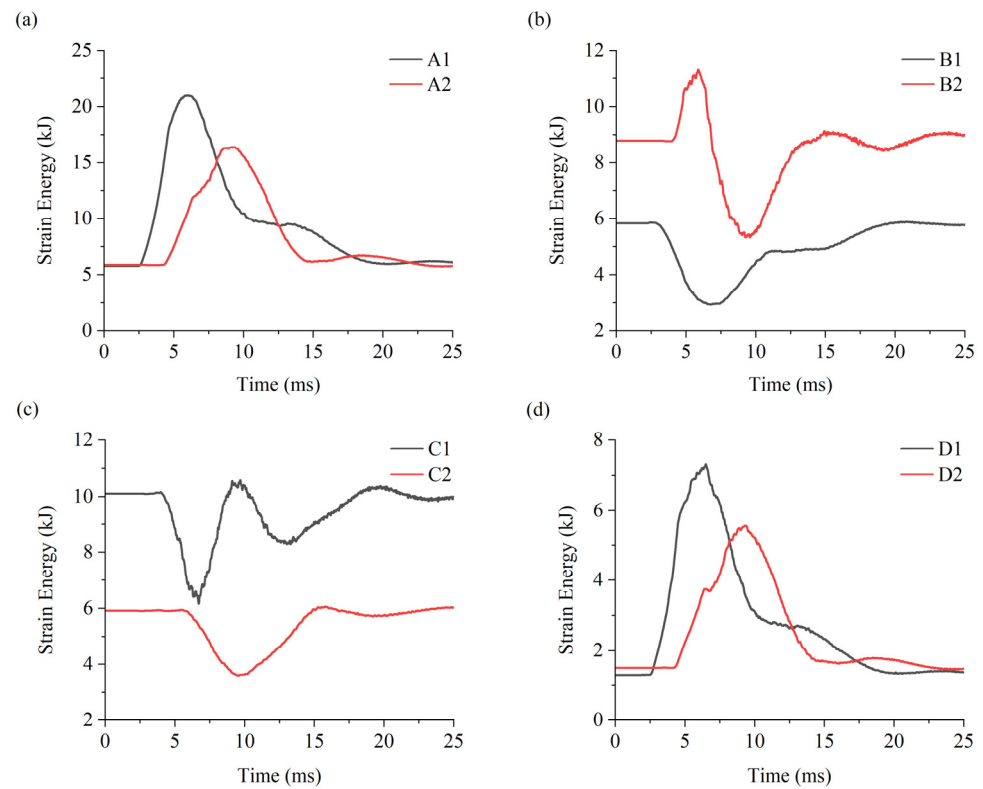


Figure 4. The evolution process of strain energy at different positions of the caverns under horizontally incident stress wave: (a) midpoints of crown; (b) midpoints of facing-wave sidewall; (c) midpoints of back-wave sidewall; (d) midpoints of floor.

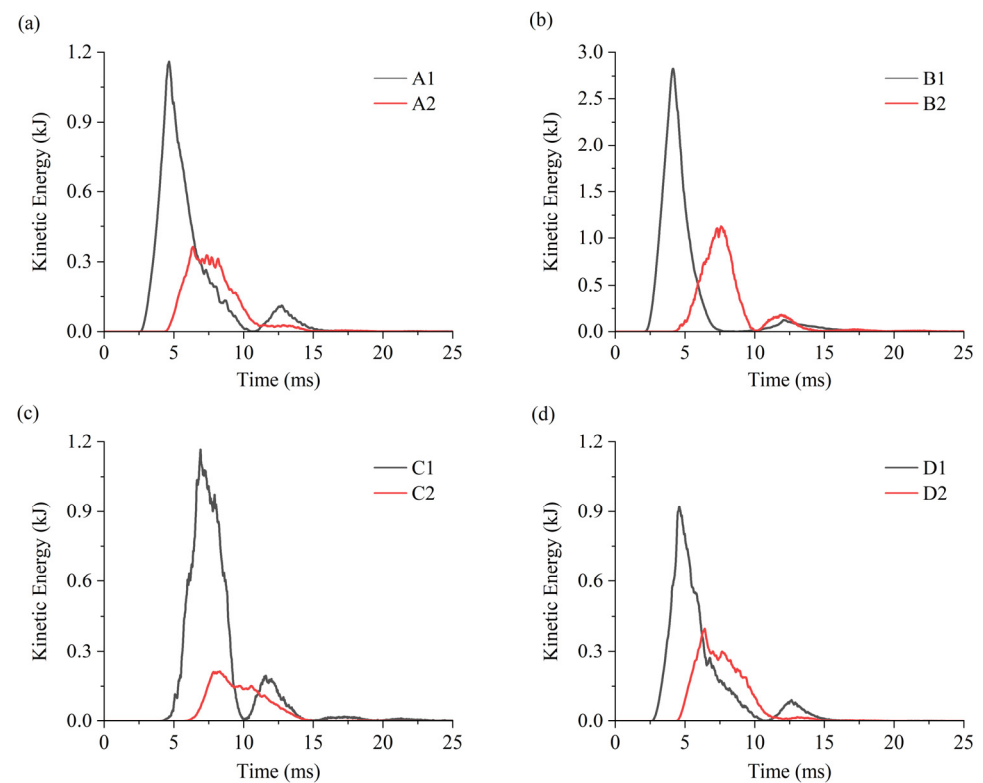


Figure 5. The evolution process of kinetic energy at different positions of the caverns under horizontally incident stress wave: (a) midpoints of crown; (b) midpoints of facing-wave sidewall; (c) midpoints of back-wave sidewall; (d) midpoints of floor.

Previous studies have indicated that cavern clearance is a critical factor for the stress distribution in surrounding rock. Three cavern clearances of $d = 1.25$, 2.50 , and 3.75 m were specified to explore the influence of the clearance between caverns on the stress field of surrounding rock, and the corresponding ratios of the cavern clearance to cavern width (d/w_1) equal to 0.5 , 1.0 , and 1.5 , respectively. The static tangential stresses at key points around the caverns under the in situ stress field are presented in Table 3. With decreasing cavern clearance, the tangential stresses at the crown and floor decrease, while the tangential stresses at the midpoints of both sidewalls increase. Notably, the tangential stress at the adjacent sidewall is higher than that at the non-adjacent sidewall, which indicates that the compressive stress concentration occurs in the middle of two caverns. The result is consistent with the analytical solution of Wang et al. [35]; they also found that the hoop stress at the middle pillar decreases with increasing cavern spacing.

Table 3. Tangential stress at cavern boundary under in situ stress field.

Cavern Clearance	Midpoint of Crown (A1)	Midpoint of Floor (D1)	Midpoint of Adjacent Sidewall (C1)	Midpoint of Non-Adjacent Sidewall (B1)
Single cavern	38.2 MPa	19.3 MPa	29.7 MPa	30.0 MPa
3.75 m	33.7 MPa	17.2 MPa	35.3 MPa	30.2 MPa
2.50 m	32.9 MPa	16.1 MPa	43.1 MPa	34.4 MPa
1.25 m	29.9 MPa	15.2 MPa	59.6 MPa	36.5 MPa

When the dynamic disturbance is superimposed and the stress wave amplitude is $P_d = 60$ MPa, the distributions of microcracks and the macroscopic failure modes of surrounding rock with different cavern clearances are shown in Figure 6. The red segments represent the tensile microcracks, and the blue segments represent shear microcracks. The crack number represents the total microcracks in the numerical model.

As the incident stress wave propagates to the boundary of the caverns, the reflected tensile stress wave causes the generation of an amount of microcracks around the facing-wave sidewall of cavern 1, leading to macroscopic failure resembling spalling. When $d = 3.75$ m, there is a small amount of microcracks on the back-wave side of cavern 1 and the facing-wave side of cavern 2, with the intermediate rock pillar remaining stable and no macroscopic failure occurring. With decreasing cavern clearance, the number of microcracks in the intermediate rock pillar continuously increases. When the clearances between caverns are 1.25 m and 2.50 m, macroscopic failures occur on both sides of the rock pillar, with the severity of failure being more significant at $d = 1.25$ m. The presence of the incident side cavern weakens the dynamic stress concentration at the crown and floor of the non-incident side cavern. Moreover, according to the distribution of tangential stress around the cavern under in situ stress field (Table 3), the static tangential stress at the cavern floor decreases with decreasing cavern clearance. Thus, macroscopic failures mainly concentrate on the floor of cavern 1, and the damage extent around the floor of cavern 1 decreases with decreasing cavern clearance, especially as $d = 1.25$ m, where there is no macroscopic damage on the cavern floor. The smaller the cavern clearance is, the more stable the cavern floor is.

As shown in Figure 6, the failure modes of the intermediate rock pillar between the two caverns varies with the various cavern clearances. Figure 7 illustrates the tangential stress and kinetic energy evolution processes of B2 (the midpoint of the facing-wave sidewall of cavern 2) under various cavern clearances. Because of the diffraction of the stress wave, the tangential stress at the B2 position first increases to the positive peak value. The smaller cavern clearance results in a higher peak tangential stress, and the microcrack density around the facing-wave sidewall of cavern 2 also increases. Subsequently, the reflected tensile wave accelerates the propagation and coalescence of the microcracks in the intermediate rock pillar. The smaller the cavern clearance is, the greater the macroscopic failure that occurs at the intermediate rock pillar. The residual kinetic energy implies

the failure intensity of the surrounding rock. As presented in Figure 7b, when $d = 1.25$ m, the residual kinetic energy reaches 12.4 kJ, which is significantly higher compared to $d = 2.50$ and 3.75 m. This indicates that the damage severity of the intermediate rock pillar intensifies with decreasing cavern clearance.

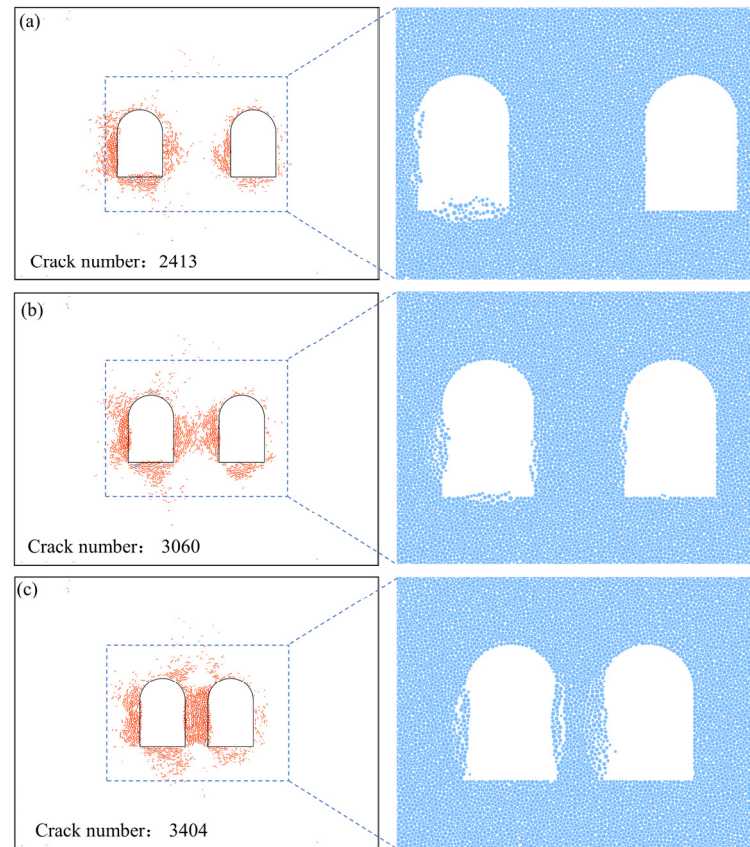


Figure 6. Failure patterns of surrounding rock under horizontally incident stress wave under different cavern clearances: (a) $d = 3.75$ m; (b) $d = 2.50$ m; (c) $d = 1.25$ m.

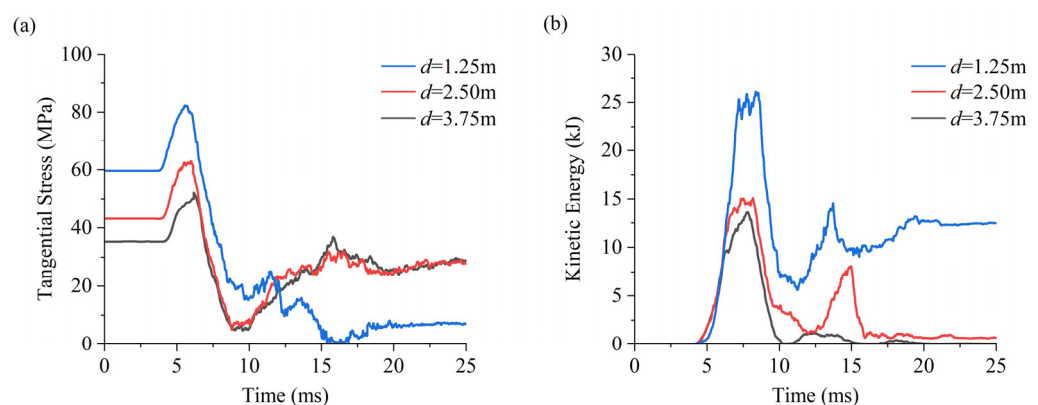


Figure 7. The evolution process of kinetic energy at B2 under different cavern clearances: (a) tangential stress; (b) kinetic energy.

3.2. Failure Characteristics of the Double U-Shaped Caverns under Vertically Incident Stress Wave

The direction of incident stress waves is a critical factor for the dynamic response of the cavern. When the dynamic disturbances originate from the vertical direction, the caverns exhibit different failure characteristics compared to those under horizontally incident stress waves. In this section, a vertically incident triangular plane stress wave was applied at the model bottom, with stress wave parameters $t_s/t_r = 5$, $t_r = 2$ ms. The dynamic response

and failure characteristics of deep double U-shaped caverns under the vertically incident stress waves were investigated by monitoring the stress and energy at key points around the caverns.

When a plane stress wave is incident vertically, the identical geometric dimensions and symmetric arrangement of caverns 1 and 2 along the model center result in an approximately symmetrical distribution of the overall stress field of the model. Taking cavern 1 as an example, when the amplitude of the incident stress wave P_d is 15 MPa, the evolution of tangential stress at the sidewalls (B1, C1) and the midpoint of the floor (D1) of the cavern is depicted in Figure 8. The vertically incident stress wave causes the dynamic tensile stress concentration at the cavern floor, and as the cavern clearance decreases, the reduction extent of tangential stress at the midpoint of the floor decreases. Dynamic compressive stress concentration occurs at the sidewalls of the cavern, and as the cavern clearance decreases, the corresponding peak tangential stress increases. Comparing the tangential stress at B1 and C1, it is noted that their evolution processes are similar, but the peak tangential stress at C1 is greater than that at B1, indicating more significant stress concentration in the right sidewall of cavern 1 compared to the left sidewall. When the cavern clearance is 1.25 m, the final tangential stress at point C1 significantly decreases compared to the initial stress, indicating significant damage and failure in the right sidewall of cavern 1.

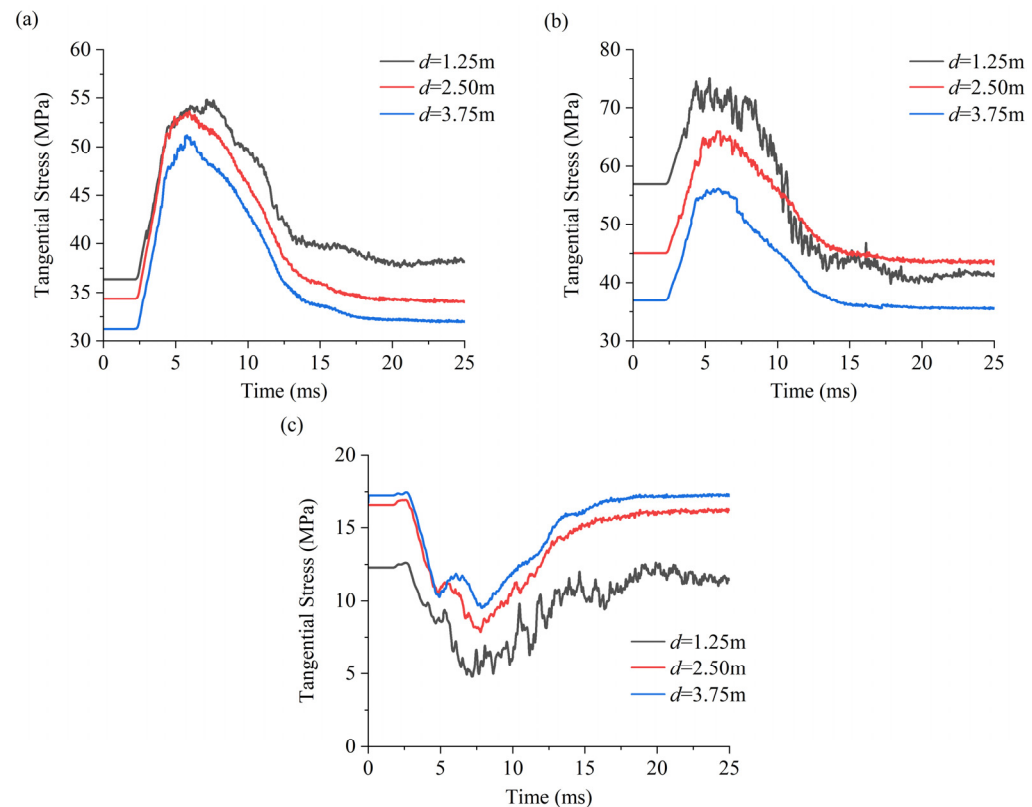


Figure 8. The evolution process of kinetic energy at different positions of the caverns under vertically incident stress wave: (a) midpoint of the left sidewall (B1); (b) midpoint of the right sidewall (C1); (c) midpoint of the floor (D1).

To further investigate the damage characteristics of the surrounding rock under vertically incident stress waves, the stress wave amplitude rises to $P_d = 60$ MPa. The damage modes around the cavern with different cavern clearances ($d = 1.25, 2.50$, and 3.75 m) under vertically incident stress waves are depicted in Figure 9. As the stress waves are vertically incident, the stress wave reflects at the cavern floor, generating numerous tensile micro-cracks parallel to the free surface around the cavern floor, and the spalling phenomena can be observed. As the lateral pressure coefficient is less than 1.0, the in situ stress field

causes the static stress concentrations at the cavern sidewalls. When the vertical stress wave propagates to the sidewalls, dynamic compressive stress concentration occurs at the sidewalls. Combined with the initial static compressive stress, dynamic compressive–shear failure occurs in the sidewalls, generating a large number of rock fragments. Moreover, the damage degree of the adjacent sidewall is more severe than that of the non-adjacent sidewall. As the cavern clearance decreases, stress concentration intensifies in the intermediate rock pillar, and the arch-shaped surfaces generated on the rock pillar boundaries deepen gradually. When the cavern clearance decreases to 1.25 m, the density of microcracks in the intermediate rock pillar increases significantly, the failure surfaces on both sides interconnect, and the rock pillar undergoes overall instability failure.

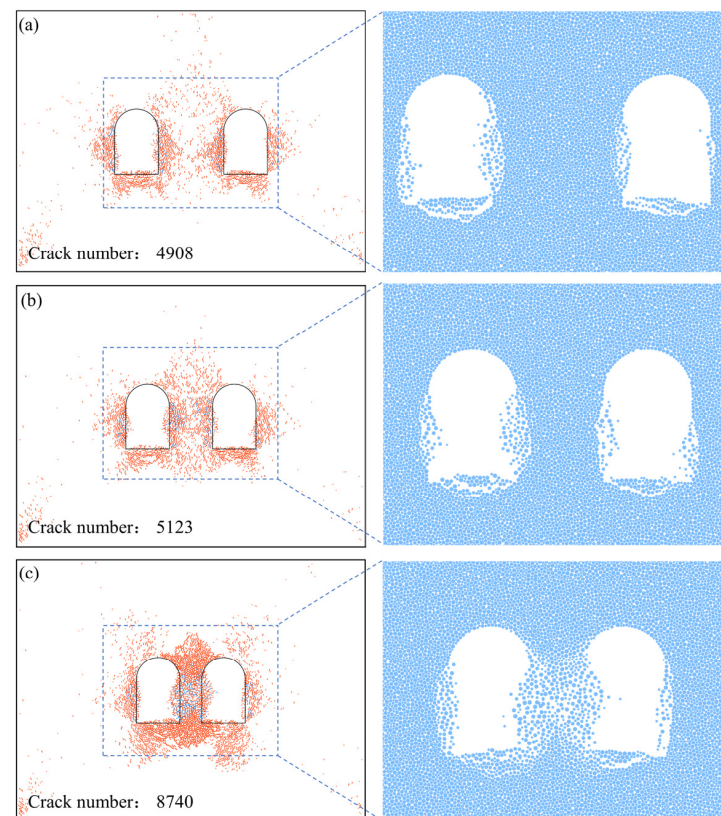


Figure 9. Failure modes of surrounding rock under vertically incident stress wave ($P_d = 60$ MPa): (a) $d = 3.75$ m; (b) $d = 2.50$ m; (c) $d = 1.25$ m.

Taking the midpoint of the right sidewall of cavern 1 (C1) as an example, the evolution process of the kinetic energy of the intermediate rock pillar under vertically incident stress waves is illustrated in Figure 10. When the cavern clearances are 2.5 and 3.75 m, the kinetic energy at point C1 increases first and then decreases over time. When the kinetic energy descends to a certain level, corresponding failure occurs. Due to the static stress of the rock, a certain amount of strain energy is accumulated in the intermediate pillar. As the failure occurs, the release of stored strain energy induces an increase in kinetic energy at C1, reaching a steady state ultimately. When the cavern clearance is 3.75 m, the residual kinetic energy during the failure process mainly derives from the external dynamic disturbances, with a relatively smaller proportion from the release of stored strain energy. With decreasing cavern clearance, the accumulated strain energy in the intermediate rock pillar increases, and the proportion of released strain energy in residual kinetic energy rises. Particularly, when the cavern clearance is 1.25 m, the residual kinetic energy at the periphery of the rock pillar (C1) far exceeds the energy carried by the incident stress wave, and the released strain energy induces the violent rockburst in the intermediate rock pillar.

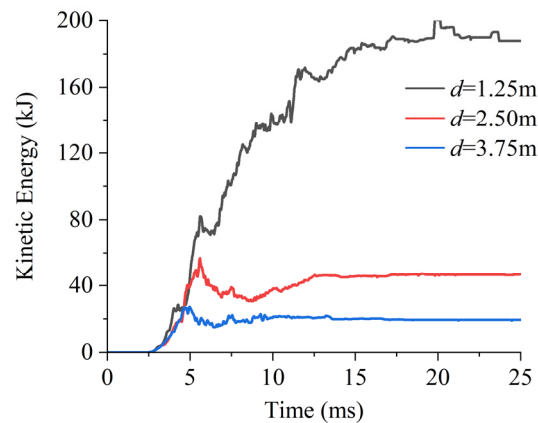


Figure 10. Kinetic energy evolution process of C1 under vertically incident stress wave.

Since the incident direction of the stress wave is consistent with the maximum principal stress direction, the number of microcracks of the model under the vertical incident stress wave is higher than that under the horizontal incident stress wave. The arch-shaped surfaces both formed on the intermediate rock pillar under different incident directions. However, when the stress wave is incident horizontally, the failure around the periphery of the intermediate pillar is caused by the reflected tensile stress wave, and the failure process is relatively gentle, accompanied by less residual kinetic energy. This phenomenon is similar to the pillar failure observed by Esterhuizen et al. [36]. As shown in Figure 11a, an hourglass-shaped pillar formed in a stone mine of the Eastern and Midwestern United States due to spalling. When the stress wave is vertically incident, the failure process around the intermediate pillar becomes more severe, and the rockburst can be observed, especially for the small cavern clearance. A similar failure phenomenon was recorded by Zvarivadza and Sengani [37]. They observed the occurrence of pillar burst induced by earthquake, accompanied by the ejection of a large number of rock blocks (Figure 11b).

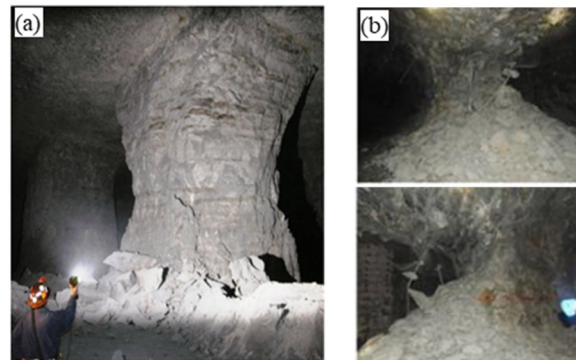


Figure 11. Failure modes of rock pillar in practical engineering: (a) hourglass-shaped pillar [36]; (b) the rock pillar after pillar burst [37].

3.3. Failure Characteristics of the Double U-Shaped Caverns with Different Height Ratios

In practical engineering, the different engineering requirements and geological conditions contribute to the differences in the geometric dimensions of adjacent caverns. Three cavern height ratios (h_1/h_2) of 0.67, 1.0, and 1.33 were specified in this section to explore the effect of height ratios on the failure characteristics of the caverns. The width of two caverns and the height of cavern 2 remain constant ($w_1 = w_2 = 2.5$ m, $h_2 = 3.75$ m), while the corresponding heights of cavern 1 are $h_1 = 2.5$, 3.75, and 5.0 m.

The unequal caverns cause the distribution of the static stress field of the model to be non-symmetrical. Figure 12 presents the strain energy density distribution of double U-shaped caverns with different cavern height ratios under in situ stress field. When

$h_1/h_2 < 1.0$, the strain energy density on the left side of the middle rock pillar is higher than that on the right side, and when $h_1/h_2 > 1.0$, the accumulated strain energy on the right side of the rock pillar is higher. Although the geometric dimensions of cavern 2 remain constant, the low-strain-energy-density area around the floor will increase with the increase in the cavern height ratio, and the low-strain-energy-density area around the cavern floor with smaller height–width ratio is more significant.

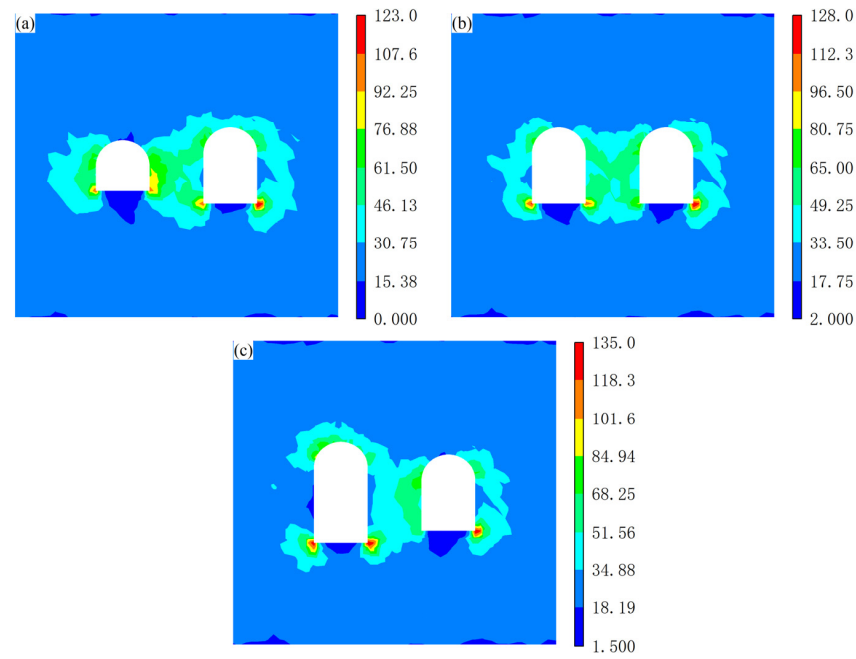


Figure 12. Strain energy density distribution of double U-shaped caverns with different cavern height ratios under in situ stress field (unit: kJ/m^3): (a) $h_1/h_2 = 0.67$; (b) $h_1/h_2 = 1.0$; (c) $h_1/h_2 = 1.33$.

When the stress wave is incoming horizontally ($P_d = 60 \text{ MPa}$), the failure modes with different cavern height ratios are illustrated in Figure 13. As the cavern height ratio (h_1/h_2) increases from 0.67 to 1.33, the number of microcracks on the incident side of cavern 1 increases. When $h_1/h_2 = 1.0$ and 1.33, macroscopic failure occurs in the facing-wave side of cavern 1, and the damage extent and depth of $h_1/h_2 = 1.33$ are greater than $h_1/h_2 = 1.0$. The damage pattern on the facing-wave side of cavern 2 exhibits an opposite trend with the increase in the cavern height ratio. The larger the cavern height ratio h_1/h_2 , the smaller the damage extent on the facing-wave side of cavern 2. For the cavern floor, when $h_1/h_2 < 1.0$, macroscopic failure occurs only at the floor of cavern 2. When $h_1/h_2 > 1.0$, the floor of cavern 2 remains stable, with macroscopic failure occurring only at the floor of cavern 1. These results indicate that under the horizontally incident stress waves, the higher the incident side cavern, the relatively more stable the non-incident side cavern.

When the stress wave is vertically incident, the damage modes of double U-shaped caverns with different cavern height ratios are depicted in Figure 14. There are differences in the damage pattern between the two caverns when the heights of the two caverns are inconsistent. The spalling occurs at the floor areas of both caverns due to stress wave reflection. When h_1/h_2 is equal to 1.0, the damage degree of the floor areas of both caverns is roughly equal; otherwise, more microcracks with larger depths are generated near the floor of the cavern with a smaller height–width ratio. The dynamic stress concentration occurs at the sidewall areas of the caverns. The stress concentration in the sidewalls adjacent to each cavern is more significant compared to those non-adjacent, and macroscopic failure occurs in the sidewalls of both caverns under different height ratios. With increasing height ratio of caverns, the initial strain energy density at the left sidewall of cavern 2 increases, and the depth of damage in the left sidewall of cavern 2 also increases. As $h_1/h_2 < 1.0$, the damage depth in the right sidewall of cavern 1 is greater than that in the left sidewall of

cavern 2, but when $h_1/h_2 > 1.0$, the damage depth in the left sidewall of cavern 2 surpasses that in the right sidewall of cavern 1.

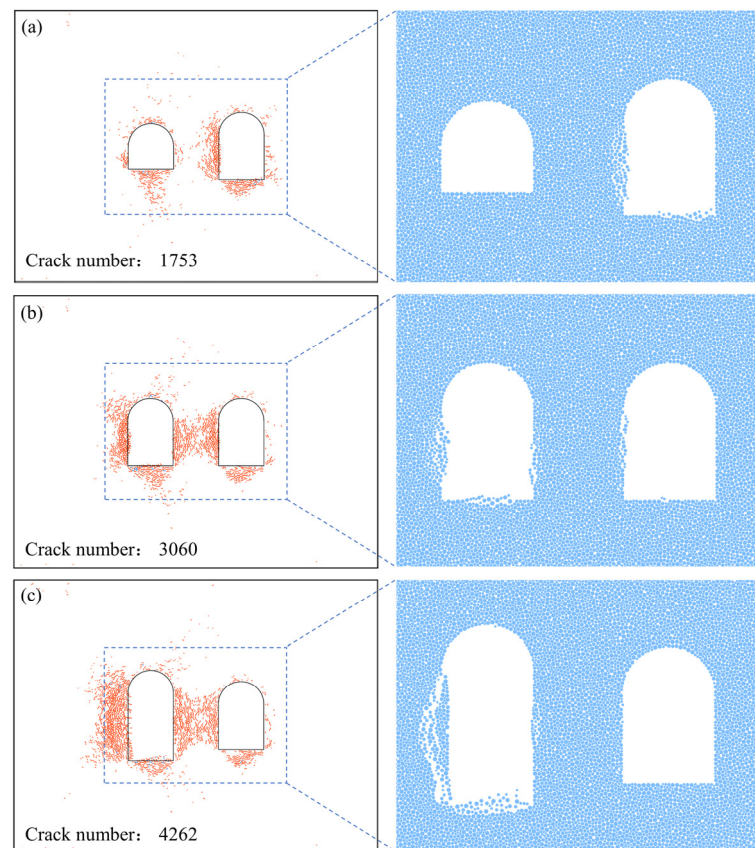


Figure 13. Failure patterns of the caverns with different cavern height ratios under the horizontally incident stress wave: (a) $h_1/h_2 = 0.67$; (b) $h_1/h_2 = 1.0$; (c) $h_1/h_2 = 1.33$.

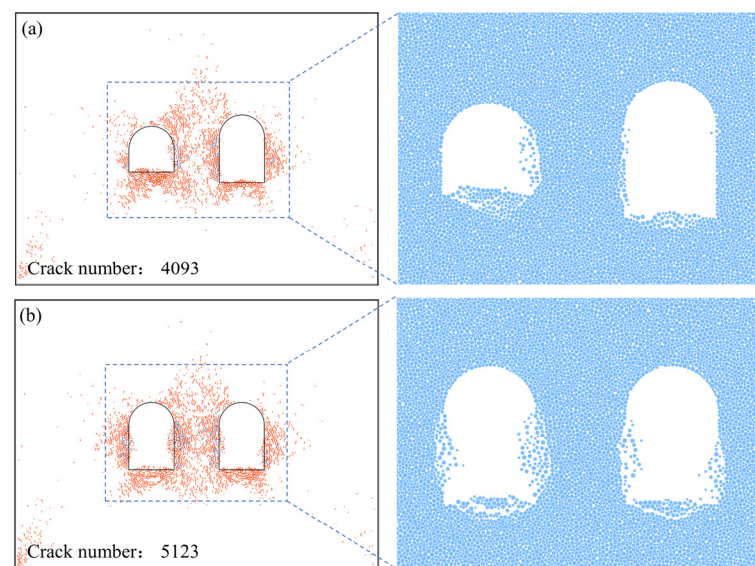


Figure 14. Cont.

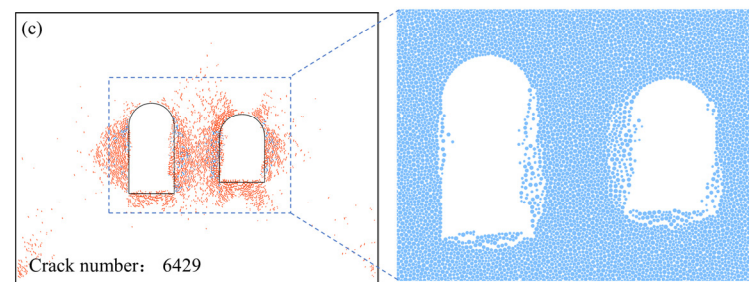


Figure 14. Failure pattern of the caverns with different cavern height ratios under the horizontally incident stress wave: (a) $h_1/h_2 = 0.67$; (b) $h_1/h_2 = 1.0$; (c) $h_1/h_2 = 1.33$.

4. Conclusions

This paper investigated the dynamic responses and failure characteristics of deep double U-shaped caverns under dynamic disturbances by PFC2D, and the influences of stress wave incident direction, cavern clearance, and cavern height ratio on the surrounding rock were analyzed. The conclusions are as follows:

- (1) The cavern clearance has a significant effect on the static stress field around the caverns. When the lateral pressure coefficient is less than 1.0, tangential stresses on roof and floor areas of the caverns decrease with reducing cavern clearance. In contrast, tangential stresses on sidewalls increase with decreasing clearance, and the compressive stress concentration at the adjacent sidewalls is higher than that at non-adjacent sidewalls.
- (2) When the stress wave is horizontally incident, the presence of the incident side cavern reduces peak tangential stress and kinetic energy on the non-incident side cavern, resulting in less damage on the non-incident side cavern. With decreasing cavern clearance, more significant stress concentration occurs in the intermediate rock pillar, and the damage extent in the facing-wave side of cavern 2 increases.
- (3) A vertically incident stress wave causes more severe damage in the intermediate rock pillar compared to a horizontally incident stress wave. The smaller the cavern clearance, the more violent the rockburst in the intermediate rock pillar.
- (4) The failure characteristics of the caverns vary with the cavern height ratio. When the stress wave is horizontally incident, the higher the incident side cavern, the more stable the non-incident side cavern. When the stress wave is vertically incident, the cavern with lower height exhibits more severe failure at the adjacent sidewall compared to the cavern with higher height.

Author Contributions: Methodology, software and writing, L.L.; Validation and funding acquisition, X.L.; Writing—review and editing, Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural science Foundation of China, grant number 51927808.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ortlepp, W.D. The behaviour of tunnels at great depth under large static and dynamic pressures. *Tunn. Undergr. Space Technol.* **2001**, *16*, 41–48. [[CrossRef](#)]
2. Li, T.B.; Ma, C.C.; Zhu, M.L.; Meng, L.B.; Chen, G.Q. Geomechanical types and mechanical analyses of rockbursts. *Eng. Geol.* **2017**, *222*, 72–83. [[CrossRef](#)]

3. Su, G.S.; Chen, Y.X.; Jiang, Q.; Li, C.J.; Cai, W. Spalling failure of deep hard rock caverns. *J. Rock Mech. Geotech. Eng.* **2023**, *15*, 2083–2104. [\[CrossRef\]](#)
4. He, M.C.; Ren, F.Q.; Liu, D.Q. Rockburst mechanism research and its control. *Int. J. Min. Sci. Technol.* **2018**, *28*, 829–837. [\[CrossRef\]](#)
5. Su, G.S.; Feng, X.T.; Wang, J.H.; Jiang, J.Q.; Hu, L.H. Experimental study of remotely triggered rockburst induced by a tunnel axial dynamic disturbance under true-triaxial conditions. *Rock Mech. Rock Eng.* **2017**, *50*, 2207–2226. [\[CrossRef\]](#)
6. Wu, W.X.; Gong, F.Q.; Ren, L.; He, L. Strain rockburst failure characteristics and mechanism of high stress circular hard rock tunnel triggered by dynamic impact load. *Int. J. Rock Mech. Min. Sci.* **2023**, *171*, 105575. [\[CrossRef\]](#)
7. He, C.L.; Chen, D.Y.; Xiao, J.G.; Lu, L.; Guo, Z.X. Experimental study of crack propagation and failure around a horseshoe tunnel during nearby blasting. *Int. J. Rock Mech. Min. Sci.* **2021**, *139*, 104628. [\[CrossRef\]](#)
8. Guo, Y.; Huang, L.; Li, X. Experimental and numerical investigation on the fracture behavior of deep anisotropic shale reservoir under in-situ temperature. *Energy* **2023**, *282*, 128969. [\[CrossRef\]](#)
9. Yue, F.; Liu, B.; Zhu, B.; Jiang, X.; Chen, L.; Liao, K. Shaking table test and numerical simulation on seismic performance of prefabricated corrugated steel utility tunnels on liquefiable ground. *Soil Dyn. Earthq. Eng.* **2021**, *141*, 106527. [\[CrossRef\]](#)
10. He, M.; Ding, M.; Yuan, Z.; Zhao, J.; Luo, B.; Ma, X. Numerical simulation of rock bursts triggered by blasting disturbance for deep-buried tunnels in jointed rock masses. *Comput. Geotech.* **2023**, *161*, 105609. [\[CrossRef\]](#)
11. Saiang, D. Stability analysis of the blast-induced damage zone by continuum and coupled continuum–discontinuum methods. *Eng. Geol.* **2010**, *116*, 1–11. [\[CrossRef\]](#)
12. Qiu, J.D.; Li, D.Y.; Li, X.B.; Zhu, Q.Q. Numerical investigation on the stress evolution and failure behavior for deep roadway under blasting disturbance. *Soil Dyn. Earthq. Eng.* **2020**, *137*, 106278. [\[CrossRef\]](#)
13. Wang, G.Y.; Cao, A.S.; Wang, X.Y.; Yu, R.; Huang, X.; Lin, J.J. Numerical simulation of the dynamic responses and damage of underground cavern under multiple explosion sources. *Eng. Fail. Anal.* **2021**, *120*, 105085. [\[CrossRef\]](#)
14. Mitelman, A.; Elmo, D. Modelling of blast-induced damage in tunnels using a hybrid finite-discrete numerical approach. *J. Rock Mech. Geotech. Eng.* **2014**, *6*, 565–573. [\[CrossRef\]](#)
15. Kuili, S.; Sastry, V.R. A numerical modelling approach to assess the behaviour of underground cavern subjected to blast loads. *Int. J. Min. Sci. Technol.* **2018**, *28*, 975–983. [\[CrossRef\]](#)
16. Manouchehrian, A.; Cai, M. Analysis of rockburst in tunnels subjected to static and dynamic loads. *J. Rock Mech. Geotech. Eng.* **2017**, *9*, 1031–1040. [\[CrossRef\]](#)
17. Mwakipunda, G.C.; Msimba, M.M.; Ngata, M.R.; Yu, L. Recent advances on carbon dioxide sequestration potentiality in salt caverns: A review. *Int. J. Greenh. Gas Control* **2024**, *133*, 104109. [\[CrossRef\]](#)
18. Liu, X.Y.; Xu, D.P.; Jiang, Q.; Ma, X.D. Excavation response and reinforcement practice of large underground caverns within high-stress hard rock masses: The case of Shuangjiangkou hydropower Station, China. *Tunn. Undergr. Space Technol.* **2024**, *147*, 105698. [\[CrossRef\]](#)
19. Fu, J.Y.; Yang, J.S.; Yan, L.; Abbas, S.M. An analytical solution for deforming twin-parallel tunnels in an elastic half plane. *Int. J. Numer. Anal. Methods Geomech.* **2015**, *39*, 524–538. [\[CrossRef\]](#)
20. Zeng, X.; Lu, A.; Zhang, N. Analytical stress solution for an infinite plate containing two oval holes. *Eur. J. Mech. A Solids* **2018**, *67*, 291–304. [\[CrossRef\]](#)
21. Hasheminejad, S.M.; Avazmohammadi, R. Harmonic wave diffraction by two circular cavities in a poroelastic formation. *Soil Dyn. Earthq. Eng.* **2007**, *27*, 29–41. [\[CrossRef\]](#)
22. Liu, Q.; Wang, R. Dynamic response of twin closely-spaced circular tunnels to harmonic plane waves in a full space. *Tunn. Undergr. Space Technol.* **2012**, *32*, 212–220. [\[CrossRef\]](#)
23. Balendra, T.; Thambiratnam, D.P.; Koh, C.G.; Lee, S.-L. Dynamic response of twin circular tunnels due to incident SH-waves. *Earthq. Eng. Struct. Dyn.* **1984**, *12*, 181–201. [\[CrossRef\]](#)
24. Lu, S.; Yao, Y.; Jia, Y.; Sun, J.; Ji, L.; Zhang, Z. Dynamic response of twin circular unlined tunnels subjected to blasting P waves. *Front. Earth Sci.* **2022**, *10*, 941070. [\[CrossRef\]](#)
25. Potyondy, D.O.; Cundall, P.A. A bonded-particle model for rock. *Int. J. Rock Mech. Min. Sci.* **2004**, *41*, 1329–1364. [\[CrossRef\]](#)
26. Potyondy, D.O. A flat-jointed bonded-particle material for hard rock. In Proceedings of the 46th U.S. Rock Mechanics/Geomechanics Symposium, Chicago, IL, USA, 24–27 June 2012.
27. Bahaaddini, M.; Sheikhpourkhani, A.M.; Mansouri, H. Flat-joint model to reproduce the mechanical behaviour of intact rocks. *Eur. J. Environ. Civ. Eng.* **2021**, *25*, 1427–1448. [\[CrossRef\]](#)
28. Wu, S.C.; Xu, X.L. A study of three intrinsic problems of the classic discrete element method using flat-joint model. *Rock Mech. Rock Eng.* **2016**, *49*, 1813–1830. [\[CrossRef\]](#)
29. Liang, L.S.; Li, X.B.; Zhu, Q.Q.; Peng, S.Y.; Si, X.F. Stress distribution and failure characteristics around U-shaped caverns with different height-to-width ratios under biaxial compression. *Eng. Fail. Anal.* **2024**, *156*, 107800. [\[CrossRef\]](#)
30. Sun, Y.; Tan, C.X. An analysis of present day regional tectonic stress field and crustal movement trend in China. *J. Geomech.* **1995**, *1*, 1–12. (In Chinese)
31. Lysmer, J.; Kuhlemeyer, R.L. Finite dynamic model for infinite media. *J. Eng. Mech. Div.* **1969**, *95*, 859–877. [\[CrossRef\]](#)
32. Lu, S.; Zhou, C.; Zhang, Z.; Jiang, N. Particle velocity response of surrounding rock of a circular tunnel subjected to cylindrical P-waves. *Tunn. Undergr. Space Technol.* **2019**, *83*, 393–400. [\[CrossRef\]](#)

33. Yang, J.H.; Xia, Y.Y.; Chen, Z.Z.; Chen, D.; Pei, Y.Y.; Zhu, W.H. Dynamic behavior of road high cutting rock slope under the influence of blasting for excavation. *Procedia Earth Planet. Sci.* **2012**, *5*, 25–31. [[CrossRef](#)]
34. Yang, C.; Zhou, K.; Zhang, Q.; He, M.; Gao, F.; Xiong, X.; Pan, Z.; Topa, A. Rockburst prevention by microwave destressing: A numerical investigation. *Geomech. Geophys. Geo-Energy Geo-Resour.* **2024**, *10*, 38. [[CrossRef](#)]
35. Wang, H.N.; Gao, X.; Wu, L.; Jiang, M.J. Analytical study on interaction between existing and new tunnels parallel excavated in semi-infinite viscoelastic ground. *Comput. Geotech.* **2020**, *120*, 18. [[CrossRef](#)]
36. Esterhuizen, G.S.; Dolinar, D.R.; Ellenberger, J.L. Pillar strength in underground stone mines in the United States. *Int. J. Rock Mech. Min. Sci.* **2011**, *48*, 42–50. [[CrossRef](#)]
37. Zvarivadza, T.; Sengani, F. Performance of bolt-reinforced and fibre shotcreted in-stope pillars in rockburst prone areas. In Proceedings of the ARMA US Rock Mechanics/Geomechanics Symposium, Seattle, DC, USA, 17–20 June 2018.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.