Research Article

Particle Flow Simulation of Failure Characteristics of Deep Rock Influenced by Sample Height-to-Width Ratios and Initial Stress Level under True-Triaxial Unloading

Haoyu Rong¹ ,¹ Guichen Li¹ ,¹ Jiahui Xu,¹ Ruiyang Bi,¹ Yuantian Sun¹ ,¹ Yaqiao Hu,² and Guoliang Bai³

¹School of Mines, Key Laboratory of Deep Coal Resource Mining, Ministry of Education of China, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

²Tongling Nonferrous Metals Group Holdings Co., Ltd. Technology Center, Tongling, Anhui 244000, China

³Tangshan Branch, Ecological Environment Technology Co., Ltd., China Coal Technology and Engineering Group Corp., Tangshan 063012, China

Correspondence should be addressed to Guichen Li; liguichen@126.com

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The micromechanism of the effects of different height/width ratios (H/W) and initial stress levels on unloading characteristics of deep rock was investigated based on PFC3D true-triaxial unloading simulation. The results show that the increase of H/W will increase the movement speed of rock particles and intensify the acoustic emission (AE) activity inside the rock. With the increase of H/W, the failure mode of rock changes from splitting failure to tensile-shear failure. With increasing initial stress level, the particle velocity and overall fragmentation degree of rock increase. However, the increase of lateral stress will limit the coalescence of microfractures and weaken AE activity in the rock. Under unloading condition, the bonds between particles generally crack along the unloading direction, and the tensile effect is more pronounced under the condition of low initial stress level and high H/W. Under unloading condition, the variable energy of rock increases with increasing H/W and initial stress level, and the kinetic energy of rock particles increases with increasing H/W. The increase of initial stress level will increase the kinetic energy of rock particles when H/W is high.

1. Introduction

The instability and failure of surrounding rock caused by excavation unloading effect is a huge problem faced by deep underground engineering. It is important to master the unloading characteristics of deep rock mass, which is necessary to improve the stability of surrounding rock and give full play to the optimal effect of support [1–5].

The mechanical properties of deep rock are affected by its stress environment. The deformation and failure characteristics of rock under different stress levels are different. Qiu et al. [6] investigated the unloading strength, deformation law, and expansion characteristics of marble under different unloading initial damage levels and unloading path and revealed the control effect of unloading initial damage degree and

unloading path. Xu et al. [7] studied the influence of initial stress and unloading rate on the deformation and failure mechanism of Jinping marble under true-triaxial compression. Hou et al. [8] examined the effects of unloading rate on the deformation and failure of surrounding rock under different confining pressures. Zhang et al. and Yin et al. [9, 10] performed test and numerical simulation under different stress levels to investigate the deformation and failure characteristics of rock. Li et al. and Ma et al. [11, 12] carried out laboratory tests and obtained the failure mode and spalling strength of rock under different confining pressures.

The research shows that the deformation and failure characteristics of surrounding rock are not only affected by the change of stress level but also related to the specific size [13–15]. Some scholars have studied the mechanical

TABLE 1: Microparameters of the calibrated PFC3D model.

Microparameter	Description	Calibrated value
$R_{\min}$ (mm)	Minimum particle radius	1.5
$R_{\max}/R_{\min}$	Particle radius ratio	1.66
E_c (GPa)	Effective modulus	15
k^*	Normal-to-shear stiffness ratio	1.5
μ	Particle friction coefficient	0.5
$\bar{E}_c$ (MPa)	Bond effective modulus	15
$\bar{k}^*$	Bond normal-to-shear stiffness ratio	1.5
$\bar{\sigma}_n$ (MPa)	Normal bond strength (mean $\pm$ SD)	30 ± 5
$\bar{\tau}_n$ (MPa)	Shear bond strength (mean $\pm$ SD)	60 ± 5
λ	Bond width multiplier	1

TABLE 2: Test and simulation results.

Method	Uniaxial compression strength (σ_c (MPa))	Young's modulus (E (GPa))	Poisson's ratio (ν)	Sample size ($R \times H$ (mm))
PFC simulation	154.03	22.46	0.16	25×100
Laboratory test	154.27	22.89	0.17	25×100

properties of rocks with different sizes. Mogi and Bažant et al. [16, 17] found that with increasing length/diameter ratio, the rock strength will decrease significantly. Li et al. [18] observed that the macrofailure mode of rock is affected by the change of height/width ratios (H/W). Zhao et al. [19, 20] presented the results of an experimental study on strainburst behaviors of rock with different H/W under the condition of true-triaxial unloading. Li et al. and Chen et al. [21, 22] studied the effects of different H/W on the true-triaxial unloading characteristics of rock. However, these studies only focus on the macrolevel, and the failure mechanism of rock at the microlevel has not been studied. The mesomechanism of the influence of H/W and initial stress on the unloading characteristics of deep rocks is still unclear.

For the macrolevel study of mechanical properties of high-stress rock mass, predecessors have done a lot of basic work. At present, it is necessary to further explore the failure mechanism of deep rock under different conditions from the microlevel. The particle flow code (PFC) discrete element method can conveniently handle discontinuum problems and effectively simulate discontinuous phenomena such as the cracking and separation of a medium, offering an important means for studying the failure mechanism of rock-like media [23–25]. Wu et al. [26] conducted PFC simulation of unloading rockburst test and obtained the microfracture phenomenon and process of rock sample under different stress states. Huang et al. [27] analyzed the strength failure

FIGURE 1: Stress-strain curves obtained from the laboratory test and PFC simulation.

TABLE 3: Initial stress level.

Stress level	σ_1 (MPa)	σ_2 (MPa)	σ_3 (MPa)
S1	40	10	5
S2	50	20	10
S3	60	40	20

behavior and crack evolution mechanism of granite containing noncoplanar holes based on PFC simulation and laboratory tests. Bahaaddini et al. [28] used PFC to numerically investigate the influence of the geometrical parameters of jointed rock masses on the mechanical properties of the joints. Mohammad et al. [29] established a new rock strength criterion based on true-triaxial tests and PFC simulation. Valdez et al. [30] used PFC to study the influence of fracture roughness and microfractures on the mechanical responses of rock joints. The above studies show that the PFC can be used to investigate rock deformation and failure characteristics from the microlevel and that the simulation results are basically consistent with the actual results.

To further explain the mechanical behavior of deep rock, unloading tests were carried out in the present study through PFC3D true-triaxial simulation. The stress-strain relationship, failure modes, and crack evolution process of deep rock under different H/W and initial stress level were analyzed from macro- and microperspectives.

2. Numerical Simulation Scheme

2.1. Construction of a Numerical Model. PFC3D is used in the present study for true-triaxial numerical simulation. The parallel bond model (PBM), a commonly adopted contact model, is selected. In this model, the bond breakage leads to an immediate decrease in the macrostiffness [23, 31], and

FIGURE 2: Numerical model.

hence, the characteristics of rock material failure can be reflected well.

Microparameters are used in PFC3D to characterize the mechanical properties of particles and bonds. Therefore, first, the calculated macroparameters of the sample must be compared with the laboratory test results, then the microparameters must be adjusted, and finally, a set of parameters that make the simulation results consistent with the test results must be determined and used for subsequent simulation calculations. The rock physical and mechanical parameters were obtained by uniaxial compression of granite standard samples. Rock samples tested were granite which is typically hard and brittle rock found in Anhui province. According to the relationship between the macro- and microparameters of the model [32–35], the trial-and-error method is used to calibrate microparameters, the experimental results are matched by continuously adjusting the microparameters, and the obtained microparameters are shown in Table 1.

Table 2 shows the laboratory test results and PFC simulation results. The comparison in Figure 1 reveals that the stress-strain characteristics of the discrete element model are basically consistent with the laboratory test results (note that the experimental curve exhibits a nonlinear increase due to the presence of microfractures in the granite specimens at the compaction stage, whereas the simulation curve shows a linear increase because of the relatively uniform contact between particles in the PFC3D model), indicating that the overall mechanical properties of the rock can be captured by using the PBM model and calibrated microparameters in the PFC.

2.2. Test Procedure. Due to the influence of excavation unloading effect, the surrounding rock is in the state of tangential stress concentration and radial stress reduction. Therefore, in order to study the unloading characteristics of deep rock under different stress levels and H/W (height/

width ratio) and simulate the stress state of surrounding rock of deep tunnel, the specific steps are as follows: (1) the simulation adopts the force loading mode. Firstly, load σ_1 , σ_2 , and σ_3 to the set stress level, as shown in Table 3; (2) keep the other five stresses unchanged and remove the unloading surface stress and stabilize for 2000 steps; (3) keep the σ_2 and σ_3 unchanged and load σ_1 with 0.1 MPa/step until the specimen fails.

The H/W of the specimen is set in three groups, and the specific size is shown in Figure 2, in which the normal direction along the negative direction of the X-axis is the unloading surface.

3. Simulation Results

3.1. Stress-Strain Relationship. Figure 3 shows the relationship between the complete stress-strain curve and AE under different H/W and initial stress level. In the figure, the black curve corresponds to the axial stress, the red curve corresponds to the number of AE events, and the blue curve corresponds to the total number of microfractures (F_a). It can be seen from the figure that the stress-strain curve obtained by simulation experienced an elastic stage, a plastic stage, and a postpeak failure stage (due to the influence of the PFC loading mechanism, there is no compaction stage in the curves obtained from numerical simulation). It can be found that the nonlinear stage of the curve is short. After reaching the peak value, the fractures in the specimen rapidly expand and penetrate, and the stress-strain curve drops rapidly. The deformation and failure of the sample showed obvious brittleness.

Combined with Table 4, the results indicate that when H/W is constant, the peak stress and peak strain (the corresponding ϵ_1 at the peak stress) increase with increasing initial stress level. Under the three H/W conditions, the peak stress increases by 16% to 19%, and the peak strain increases by 12% to 14%. The results show that the strength of rock will

(a) $L/H = 0.5$, S1 (b) $L/H = 0.5$, S2 (c) $L/H = 0.5$, S3

FIGURE 3: Continued.

(d) $L/H = 1$, S1

(e) $L/H = 1$, S2

(f) $L/H = 1$, S3

FIGURE 3: Continued.

(g) $L/H = 2$, S1 (h) $L/H = 2$, S2 (i) $L/H = 2$, S3

FIGURE 3: Relationship between complete stress-strain curve and AE.

TABLE 4: Simulation results.

Stress level	Peak stress σ_1 (MPa)			Peak strain $\varepsilon_1/10^{-3}$		
	$L/H = 0.5$	$L/H = 1$	$L/H = 2$	$L/H = 0.5$	$L/H = 1$	$L/H = 2$
S1	251.71	237.42	212.09	8.01	7.11	6.11
S2	278.13	259.26	236.84	8.79	7.54	6.72
S3	290.79	272.21	251.38	8.97	7.74	6.97

TABLE 5: AE simulation results.

Stress level	Peak value of AE events			Total number of microfractures		
	$L/H = 0.5$	$L/H = 1$	$L/H = 2$	$L/H = 0.5$	$L/H = 1$	$L/H = 2$
1	2485	3971	6518	38227	50884	76435
2	2431	3743	6332	41963	55549	98766
3	2449	3648	6084	45991	61937	114869

be improved with increasing lateral stress, and the ductility of rock will be more obvious with increasing lateral stress, which shows the transformation trend from brittleness to ductility. Under the same initial stress level, the peak stress and peak strain decrease with increasing H/W. The peak stress and peak strain decrease by 14% to 16% and 22% to 24%, respectively. This shows that the strength of rock will be reduced with increasing H/W, and the brittleness of rock will be more pronounced with increasing H/W.

3.2. Acoustic Emission (AE) Simulation Results. Through the monitoring of information such as time, space, and the fracture intensity generated by AE signals during the rock fracture process, the process of rock crack initiation, development, and coalescence can be derived. In the PFC program, particles are used to construct a computational model, where the bonds between particles are broken under external force and microfractures are generated. Therefore, the rupture initiation and evolution in the model can be simulated to effectively reproduce the AE mechanism of the rock [36–38]. PFC is used in this study to simulate the AE characteristics of the rock unloading failure under different H/W and different initial stress level. Figure 3 shows that before reaching the peak value, the number of microfractures in the sample and the number of AE events increase only slightly, but when the stress reaches the peak value, both start to increase rapidly, and the curve of total number of microfractures exhibits a steep rise. This phenomenon is consistent with the characteristics of brittle failure of granite under unloading conditions.

Combined with Table 5, it can be found that under the same stress level, the peak value of AE event number and the total number of microfractures increase with increasing H/W. Under the three stress levels, the peak AE event number increases by 1.48 to 1.62 times, the total number of microfractures increases by 64.4% to 90.9%, and the failure progress of the rock is the most severe under the condition of H/W = 2. Under the same H/W conditions, the total number of microfractures increases with increasing initial stress level, while the peak value of AE events decreases with increasing initial stress level. Under the three H/W condi-

tions, the peak value of AE events decreases by 2.2% to 8.1%, which indicates that the AE activity is more severe in the progress of rock failure when the initial stress level is low, and the increase of lateral stress will limit the coalescence of microfractures.

3.3. Rock Failure Mode. Table 6 shows schematic diagrams of the typical macrofailure of specimens obtained by simulation under different conditions; the red and yellow parts represent the tensile and shear failure of bond between particles, respectively. It can be seen from the figure that under different conditions, the bonds in the specimen mainly fail under tension, and the splitting fracture and inclined shear fracture extending from unloading surface the interior of the rock can be observed; the failure mode is tensile-shear failure.

As shown in Table 6, under the same H/W condition, with the increase of initial stress level, the overall fragmentation degree of the specimen increases. The specimen macrofailure mode gradually changes from shear failure to tensile-shear failure, and the number of splitting fractures in the specimen increases significantly. Under the condition of H/W = 1, 2, it can be found that under the condition of initial stress level of S1, the interior of the specimen is penetrated by oblique shear fractures, and there are a few splitting fractures. When the initial stress levels are S2 and S3, the rock plate formed by splitting appears near the unloading surface of the specimen. Under the same initial stress level, the overall fragmentation degree of the specimen decreases with increasing H/W. The overall fragmentation of the specimen was relatively high under the condition of H/W = 0.5, and the splitting failure is the main failure mode when H/W is low.

4. Discussion

4.1. Analysis of Micromechanism of Rock Failure. Figure 4 shows the proportion of shear fractures in rock microfractures under different conditions. It can be found that the bond between rock particles mainly fail under tension. With increasing stress level, the proportion of microfractures formed by shear failure increases gradually, and the tension

TABLE 6: Macrofailure mode of specimen.

Failure mode	
(a) S1
(b) S2
(c) S3
(a) S1
(b) S2
(c) S3

TABLE 6: Continued.

Failure mode

(a) S1

(b) S2

(c) S3

FIGURE 4: Proportion of shear fractures in rock microfractures.

effect between rock particles gradually weakens. When the stress level is S1 and S2, the proportion of shear fracture decreases with increasing H/W, while the proportion of shear fracture decreases first and then increases with increasing H/W at stress level of S3. It can be found that when H/W = 2 and the initial stress level is S1, the tension effect is more pronounced between particles.

To further explain the micromechanism of rock failure under different conditions, the particle motion of typical samples is analyzed. The velocity distribution in the specimen is shown in Table 7.

It can be seen from the table that particles in the rock mainly move along the unloading direction, and the closer the particles are to the unloading surface, the higher their velocities are. Combined with Table 4, it can be seen that the rock specimen first fails near the unloading surface and gradually expands to the interior. The fragmentation degree of the specimen near the unloading surface is relatively high; this is consistent with the true-triaxial unloading test, which shows that the deformation of the specimen exhibits strong expansion along the unloading direction. According to the velocity and movement direction of rock particles in the table, the formation of fractures in rock is mainly attributed to the following: (1) local particles move in the same direction but at different velocities. The particle velocity at the unloading surface is larger than that in the inner part of the specimen, the velocity of particles in front being higher than that of particles in the rear, which eventually form the splitting fractures; (2) local particles move relative to each other at a certain angle ($<180^\circ$) and velocities are different, forming tensile-shear fractures, i.e., under the combined tensile-shear action.

It can be found that the velocity of rock particles increases with increasing H/W and initial stress level. According to Table 7, when the initial stress level is constant, under the condition of higher H/W, the velocity of rock particles is higher, the deformation and failure progress and AE

activity of rock are more intense, but the overall fragmentation degree of rock is low. Under constant H/W, the increase of initial stress level will make the rock accumulate more energy and improve the velocity of particles in the rock, the fractures in the rock developed and propagated relatively fully, and the overall fragmentation degree of rock will be higher. But the increase of lateral stress will limit the coalescence and connection of microfractures in the rock and weaken AE activity in the process of rock failure.

As shown in Figure 5, taking the distribution of the angles of microfractures in rock under the condition of H/W = 1 and initial stress level of S3 as an example (Dip is the dip angle of the microfracture plane, and dip-direction is the angle between the inclination of the microfracture plane and the Y-axis), it can be found that dip of the microfracture plane is mostly concentrated at 90° , and dip-direction of the microfracture plane is mostly concentrated between -90° and 90° . Indicating that due to the unloading effect, the bonds in the rock under unloading conditions generally crack along the unloading direction. Combined with Table 7, it can be found that the specimen is under tension along the unloading direction, and the tensile force exerted on the bonds in the specimen exceeds its normal strength, leading to the tensile failure of the bonds.

4.2. Energy Evolution of Rock. Figures 6 and 7 show the strain energy and kinetic energy evolution curves under different conditions. From an energy perspective, rock failure is the result of the combined effect of the accumulation and transformation of energy, including internal strain energy and dissipative energy. Taking the patterns of strain energy and kinetic energy evolution as an example, it can be found that the strain energy in the rock increases continuously during the test process. When it is close to failure, the strain energy is rapidly released and converted into dissipative energy and kinetic energy acting on the development and expansion of fractures. The kinetic energy is basically zero in the prepeak stage (the kinetic energy increases slightly due to the unloading effect when unloading the unloading surface stress, then decreases rapidly and tends to zero), and the kinetic energy of particles increases rapidly when it is close to failure, which results in the rapid development and coalescence of microfractures in the rock and leads to the failure of the rock.

It can be found from Figures 6 and 7 that under constant H/W, the strain energy of the specimen increases with increasing initial stress level, which indicates that the increase of the lateral stress improves the strength of the rock and makes the rock accumulate more energy during the test. When H/W = 0.5, the kinetic energy changes little with increasing initial stress level but increases with increasing initial stress level under the conditions of H/W = 1 and 2, which indicates that the increase of the initial stress level has little effect on the evolution of kinetic energy of rock particles. Under constant initial stress level, the strain energy and kinetic energy of the specimen increase with increasing H/W, and the energy release is more rapid with increasing H/W, which indicates that the increase of H/W will make the rock accumulate more energy and accelerate the process

TABLE 7: The velocity distribution in the specimen.

	Velocity field		Failure mode	
			(A) Tension failure	(B) Tension-shear failure
S1, $H/W = 0.5$
S3, $H/W = 0.5$
S3, $H/W = 1$

TABLE 7: Continued.

Velocity field			Failure mode
<div><p>Ball arrow velocity Maximum: 53.8527 Minimum: 2.3900E-02 Arrows: (60825)</p><p>5.3853E+01 5.0000E+01 4.5000E+01 4.0000E+01 3.5000E+01 3.0000E+01 2.5000E+01 2.0000E+01 1.5000E+01 1.0000E+01 5.0000E+00 2.3900E-02</p></div>			(A) Tension failure
			(B) Tension-shear failure

S3, H/W = 2

FIGURE 5: Distribution of the angles of the microfractures.

FIGURE 6: Curves of the strain energy evolution.

FIGURE 7: Curves of the kinetic energy evolution.

of energy transformation, which makes the rock more likely to be damaged.

5. Conclusion

The effects of different H/W and initial stress levels on unloading characteristics of deep rock were investigated based on PFC3D true-triaxial unloading simulation. The conclusions drawn are as follows:

- (1) The increase of H/W will increase the velocity of rock particles. During the test process, the deformation and failure of rock and the activity of AE are more intense, and the failure of the rock showed obvious brittleness. When the H/W is low, the splitting failure is the main failure mode of rock, and with increasing H/W, the failure mode of rock gradually changes into tensile-shear failure
- (2) With increasing initial stress level, the particle velocity and overall fragmentation degree of rock increase. However, the increase of lateral stress will limit the coalescence of microfractures and weaken AE activity in the rock
- (3) Under unloading condition, the main failure mode of bond is tensile failure, and the bonds between particles generally crack along the unloading direction, and the tensile effect is more pronounced under the condition of low initial stress level and high H/W
- (4) Under unloading condition, the variable energy of rock increases with increasing H/W and initial stress level, and the kinetic energy of rock particles increases with increasing H/W. When H/W is low, the change of initial stress level has little effect on kinetic energy, while the increase of initial stress level will increase the kinetic energy of rock particles when H/W is high

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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