Research Article

Numerical Study of Spherical Particle Breakage Based on Nonlinear Discrete Interface Bonded Model

Lin Li,1 Sifeng Zhang,2 Shicai Yu,3 and Xuanyu Zhang4

1Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China
2School of Transportation Engineering, Shandong Jianzhu University, Jinan, Shandong, 250101, China
3CSC Dongfu Assets Management Co. Ltd., Shanghai 200125, China
4Shandong Hi-speed Infrastructure Construction CO., LTD, Jinan, Shandong, 250101, China

Correspondence should be addressed to Sifeng Zhang; sddxzsf@sdu.edu.cn

Received 19 January 2022; Revised 8 March 2022; Accepted 23 March 2022; Published 30 April 2022

Copyright © 2022 Lin Li et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

To study the contact mechanical characteristics and breakage mechanism of single particle, the particle contact experiment is simulated using the discrete element method. In this paper, to solve the problem that the envelope of the shear strength of the classical model is linear, a nonlinear discrete surface bonded model is introduced by applying nonlinear tangential strength criterion. The new model is compared with the classical model to verify its validity. Then, based on the new model, the particle contact experiment is numerically simulated, and the ball-plane contact breakage mechanism is analysed and discussed from the mesoscopic perspective. The results reveal that the nonlinear discrete interface bonded model can provide shear properties similar to those of actual materials. The numerical result reflects the shear failure of the edge of the conical region and the tensile failure of the whole specimen. Combined with the analysis of the results of stress distribution, velocity field, and force chain distribution, the formation mechanism of the cone core can be obtained.

1. Introduction

Granular materials, such as sand, gravel, ballast, and rockfill, are common in nature and are widely used in civil engineering and geotechnical engineering. The inherent characteristics of natural granular materials, such as brittleness and natural defects, cause the particles to break under external forces, especially in a state of high stress. Particle breakage will create changes in the mechanical properties of particles, which may cause a slew of engineering issues. Therefore, the study on the breakage behavior and mechanism of coarse-grained soil plays a very important role in the engineering application of coarse-grained soil. However, due to the limitations of experimental methods, research on mesoscale particle breakage based on physical experiments is greatly restricted. Numerical simulation analysis provides an effective method for studying the particle breakage characteristics at different scales.

Nowadays, many numerical methods have been introduced for particle breakage studying. Among them, the discrete element method (DEM) can establish specimen of any shape and can simulate the formation of cracks. The DEM method is computationally effective because it does not require the generation of a complex particle grid. After many years of development, the DEM-based particle breakage simulation has been widely used, which provides an effective way to study the mesoscopic mechanism of particle breakage. Many scholars [1–10] have studied particle breakage based on the DEM and have obtained a large number of research results.

At present, research on particle breakage based on the DEM mainly focuses on the influence of particle breakage on the macroscopic mechanical properties of particle groups [11–19]. In the existing discrete-element analysis of single particle breakage, scholars mainly focus on the simulation of macroscopic breakage phenomena [20–24], as well as the selection and calibration of discrete element
meso-parameters [25, 26] and breakage criteria [27, 28] in the simulation. However, there are few studies on the mechanical mechanism of single particle breakage from the meso-point of view of the stress distribution and force chain distribution based on the DEM.

However, the two current particle breakage simulation methods based on the DEM, that is, the particle breakage simulation method based on the fragment replacement method (FRM) [29] and bonded particle model (BPM), also have some limitations. The particle breakage simulation method based on the FRM can reflect the mechanical response of particle aggregates to a certain extent, which provides an effective method for large-scale physical experiments and mesoscale research [30–32]. However, in numerical simulations based on the FRM, the number of replacement fragments, the size of the fragments, and the replacement logic have a substantial impact on the simulation efficiency and results [33, 34]. Moreover, numerical simulations based on the FRM not only require that the particle breakage criterion is obtained in advance, but problems such as the nonconservation of mass after breakage replacement need to be solved [35–39], which makes it difficult to meet the needs of mesoscopic analysis of the particle breakage mechanism. At present, numerical simulations based on the FRM are mainly used to study the influence of particle breakage on the overall characteristics in large particle swarm simulations. The particle breakage simulation method based on the BPM can simulate the particle breakage behaviour to a certain extent and can effectively reproduce the complex mechanical response of breakable particle aggregates [40, 41]. This method can simulate complex particle shapes [42–44]. However, the numerical simulation of particle breakage based on the traditional BPM often has difficulty replicating the macroscopic mechanical properties of actual materials. It can only simulate the experimental phenomena, which makes it difficult to provide the basis for the analysis of the breakage mechanism [45–47].

In this paper, aiming at improving the deficiency of the classical discrete-element bond model, the nonlinear discrete interface bonded model is obtained by improving the tangential bond strength criterion based on the flat-joint contact model. The ball-surface particle contact experiment of a 50 mm spherical gypsum sample is simulated. The simulation results are analysed from the force-displacement curve, breaking morphology, stress distribution, and force chain distribution, and then the meso-mechanism of particle breaking is studied.

2. Nonlinear Discrete Interface Bonded Model

As the classical BPM in PFC, the parallel bonded model is widely used to simulate rock and rock-like materials because it can effectively simulate cement. The macroscopic phenomenon of numerical simulation of particle breakage based on the parallel bonded model is similar to that of laboratory test. However, due to the insufficient anti rotation capability of the contact, the details of meso-phenomenon of particle breakage are partially different from the actual test. Moreover, the shear strength envelope of numerical simulation based on the parallel bonded model is linear, which is inconsistent with the actual mechanical properties of rock. Therefore, there are some limitations in numerical simulation of particle breakage based on the parallel bonded model. It is difficult to explain the meso-mechanism of particle breakage. In view of the aforementioned shortcomings, based on the flat-joint model proposed by Potyondy [48], a nonlinear discrete interface bonded model suitable for simulating brittle rock breakage is established by introducing nonlinear shear line strength criterion.

The logical structure of the model is shown in Figure 1. The model basic particles interact with each other through the contact surface which is a rigid disk, as shown in Figure 1(a). The contact surface is discretized into 16 sectors along the radial and axial directions respectively as shown in Figure 1(b). Each sector adopts the same logical structure. The logical structure of the bonded state and the unbonded state is shown in Figure 1(c). For each discrete sector, the equivalent normal and shear stresses of the contact are as follows:

\[
\begin{align*}
\sigma^{(sec)} &= \frac{F^{(sec)}_n}{A^{(sec)}}, \\
\tau^{(sec)} &= \frac{F^{(sec)}_s}{A^{(sec)}},
\end{align*}
\]

where \(F^{(sec)}_n\) is the normal contact force, \(F^{(sec)}_s\) is the tangential contact force, and \(A^{(sec)}\) is the area of the contact element.

When the normal or tangential bond of the sector is destroyed, it is considered that the bond of the sector has been destroyed.

The normal force acting on the contact of discrete sector is tension or pressure. The normal bonded strength of contact is defined by tensile strength \(\sigma_c\). At the same time, the ultimate compressive strain parameter \(\beta\) is introduced, and the bond failure occurs when the equivalent compressive strain is equal to \(\beta\). Therefore, the arithmetic expression of normal compression bond strength \(\sigma'_c\) in numerical calculation is as follows:

\[
\sigma'_c = \begin{cases} 
0, & \sigma \geq \sigma_c \text{ or } g_s \geq \beta R, \\
\sigma_c, & \text{otherwise},
\end{cases}
\]

where \(R\) is the contact radius and \(\sigma_c\) is the normal bond strength. The default value of \(\beta\) is 1.0, which is equivalent to normal pressure failure without considering bonding.

The contact shear strength of the classical bonded model is defined using the friction coefficient (unbonded state) or Moore–Coulomb criterion (bonded state). The intensity envelopes of both are linear. The triaxial test results based on the classical bonded model are quite different from the actual results. Therefore, the nonlinear strength criterion of rock is introduced in the model.

It is generally believed that the quadratic parabolic Mohr strength criterion can comprehensively reflect the nonlinear strength characteristics of rock. This criterion can be used to
describe both plastic rock and the shear failure of brittle rock. The specific forms of the Mohr strength envelope include linear, quadratic parabolic, hyperbolic forms, and so on. Among them, the strength envelope of rock with weak to subhard lithology, such as sandstone and marl, can often be fitted by a quadratic parabola. In the nonlinear discrete interface bonded model, considering that the properties of the high-strength gypsum selected in the experiment [49] are similar to those of soft rock such as fine sandstone, the quadratic parabolic Mohr strength criterion is chosen as the tangential bond strength criterion of the model. The ultimate equivalent shear stress of the discrete unit can be expressed as follows:

$$\tau_c = \sqrt{n (\sigma_c^{\text{sec}} - \sigma_1^{\text{sec}} + \sigma_2^{\text{sec}})},$$

(3)

where $\sigma_c$ is the normal bond strength. The normal stress on the unit is positive under tension. To avoid a negative value in the root sign on the right side of the equation, tensile failure of the bond is first detected in each operation, and then the shear strength is determined. If the bond of the unit is damaged, the strength criterion shown in equation (3) fails immediately. The element follows the friction limit criterion shown in (4), which provides a certain tangential bearing capacity under compression.

$$\tau_{\text{max}} = -\mu \sigma_c^{\text{sec}},$$

(4)

where $\mu$ is the sliding friction coefficient of the bond. If the equivalent shear stress of the unit is greater than the tangential friction limit, the shear force of the unit maintains the peak value, and tangential relative sliding can occur.

The improved model may form aggregates by bonding a certain number of elementary particles and simulate the formation of cracks by breaking the bonds between elementary particles.

3. Validation of Improved Model

Based on the new nonlinear discrete interface bonded model, a cylinder specimen with a diameter of 50 mm and a height of 100 mm is generated by referring to the material simulation library provided by Itasca. The minimum elementary particle size of the model is 2.5 mm, and the maximum elementary particle size is 5.0 mm. The average size is 3.75 mm. Tests of fundamental mechanics, such as direct tensile tests and triaxial tensile tests, are carried out to calibrate the macroscopic mechanical properties of the specimens. This can be used to verify that the macroscopic mechanical properties of the specimens in the improved model were in accordance with the design.

In the direct tensile test shown in Figure 2(a), the particles on the upper and lower surfaces of the sample move upward and downward at a constant velocity of 0.001 mm/s, respectively, to simulate the loading boundary conditions in the actual test. Figure 2(b) shows the test curve obtained by direct tensile simulation using the nonlinear bonded model and parallel bonded model. The two test curves in the figure are basically linear, and there is no loading platform before the failure of the sample. The failure characteristic is brittle failure.

In the triaxial compression test shown in Figure 3, the radial constraint of the specimen is controlled by the annular wall. The lateral restraint pressure levels are 2.0 MPa, 5.0 MPa, 10.0 MPa, 20.0 MPa, and 40.0 MPa, respectively. The upper and lower walls of the sample are loaded inward at a constant speed of 0.001 mm/s. As shown in Figure 3(b), the peak deviatoric stress of the specimen increases with increasing radial restraint stress in the simulated triaxial compression test. Similar to actual rock or rock-like materials, when the confining pressure of the triaxial test is sufficiently large, the specimen based on the nonlinear
discrete interface bonded model will no longer show the characteristics of brittle failure, and the equivalent deviator stress will show a postpeak platform after reaching the peak value. When the confining pressure level is high, the equivalent deviatoric stress can continue to rise until reaching the peak value after the linear stage of the curve.

Considering that the shear strength of a contact bond is related to its tensile strength in the nonlinear discrete interface bonded model, the results of the triaxial test and direct tensile test are obtained as stress circles, and the strength envelopes of the stress circles are made by the arc tangent fitting method, as shown in Figure 4(a). The results show that the shape of the shear strength envelope of the specimen based on the nonlinear discrete interface bonded model is similar to that of the nonlinear Mohr shear strength envelope, which can be well fitted by the quadratic parabolic strength criterion. In this case, the expression of the shear strength envelope is as follows:

\[
\begin{align*}
\sigma & = \frac{1}{2} \left( \sigma_1 + \sigma_3 \right) + \frac{1}{2} \sqrt{\left( \sigma_1 - \sigma_3 \right)^2 + 4\tau^2} \\
\tau & = \frac{1}{2} \left( \sigma_1 - \sigma_3 \right)
\end{align*}
\]

\[
\tau = \frac{1}{2} \left( \sigma_1 - \sigma_3 \right)
\]

**Figure 2:** Simulation of direct tensile test: (a) the loading diagram and (b) the equivalent stress-equivalent strain curve.

**Figure 3:** Simulation of triaxial test: (a) the loading diagram and (b) the equivalent deviator stress-equivalent axial strain curve.
the theoretical shear strength expression of the bonded state of the grained soil particle breakage. The de/iciency of the parallel bonded model and provides linear discrete interface bonded model effectively improves the quadratic parabolic Mohr strength criterion. The non-linear discrete interface bonded model is suitable for simulating brittle soft rock or other materials suitable for parabolic Mohr shear strength criterion. It is more suitable based on the improved model is close to the quadratic strength envelope shows that the shear strength envelope on the parallel bonded model. The macroscopic shear strength under the same confining pressure than that based on the nonlinear bonded model can provide a relatively higher triaxial compressive strength and shear strength under the same confining pressure than that based on the parallel bonded model. The macroscopic shear strength envelope shows that the shear strength envelope based on the improved model is close to the quadratic parabolic Mohr shear strength criterion. It is more suitable for simulating brittle soft rock or other materials suitable for the quadratic parabolic Mohr shear strength criterion. The nonlinear discrete interface bonded model effectively improves the deficiency of the parallel bonded model and provides abilities for the study of the meso-mechanism of coarse-grained soil particle breakage.

4. Calibration and Verification of Numerical Model Parameters

In order to make the macroscopic mechanical properties of the numerical model well fitted with the test material, it is necessary to calibrate and adjust the numerical meso-parameters. According to the correlation and sensitivity analysis of parameters [49] and referring to the parameter adjustment method in the PFC official manual, the cross-debugging simulation is carried out by interpolation analysis and iterative approximation. Finally, the mesoscopic parameters of the numerical simulation of gypsum particle breakage suitable for the nonlinear discrete interface bonded model are obtained, as shown in Table 1.

5. Simulation of Ball-Plane Contact Experiment

Based on the aforementioned parameters, the numerical models in Figure 5 are established for uniaxial compression test and splitting test. The results show that the numerical simulation matches the test well, as shown in Figure 6. It is worth explaining that the peak loading force of the numerical splitting test is basically consistent with the experiment results, but the secant stiffness in the initial stage is quite different. Through the analysis of the indoor test process, it is considered that the curve stiffness is small because the loading conditions are not strictly met in the initial stage of the Brazilian splitting test. With the progress of loading, the loading force will gradually be uniformly distributed on the contact surface. At this time, the loading boundary condition of the sample is consistent with the experimental hypothesis, and the force-displacement curve is basically linear. The slope of the force-displacement curve of the numerical splitting test is generally consistent with the results of the experiment.

In conclusion, the meso-parameters based on the improved discrete contact surface bonded model are reasonable and can accurately fit the fundamental mechanical properties of high-strength gypsum used in indoor contact tests. The discrete contact surface bonded model can be used to simulate the particle contact breakage process. The basic mechanical properties of the simulated sample material are compared with those of high-strength gypsum, as shown in Table 2.
Table 1: Contact generation parameters and contact mechanics parameters based on the discrete contact surface bonded model.

| Mesoscopic parameter | Parameter description                                      | Value               |
|----------------------|------------------------------------------------------------|---------------------|
| $D_r$                | Number of radial discrete elements                        | 2                   |
| $D_α$                | Number of circumferential discrete elements               | 8                   |
| $C_λ$                | Contact radius amplification control parameters           | 0                   |
| $λ_r$                | Contact radius magnification factor                        | 1.0                 |
| $g_0$                | Contact installation distance                              | $2.0 \times 10^{-4} m$ |
| $g_0$                | Initial distance between contact surfaces                 | 0 m                 |
| $Φ_B$                | Contact bonded ratio                                       | 1.0                 |
| $Φ_C$                | Contact separation ratio                                   | 0                   |
| $E^*$                | Effective modulus of elasticity                            | $8.0 \times 10^9 Pa$ |
| $κ^*$                | Normal-tangential stiffness ratio                          | 2.7                 |
| $μ$                  | Surface friction coefficient                               | 0.577               |
| $σ_c$                | Bond tensile strength                                      | $4.0 \times 10^6 Pa$ |
| $n$                  | Mohr shear strength parameter                              | $3.5 \times 10^7$   |
| $E_{\text{linm}}^*$  | Effective modulus of elasticity (linear stiffness)         | $8.0 \times 10^9 Pa$ |
| $κ_{\text{linm}}$    | Normal-tangential stiffness ratio (linear stiffness)       | 2.7                 |
| $μ_{\text{linm}}$    | Surface friction coefficient (linear stiffness)            | 0.577               |

Figure 5: Numerical model: (a) unconfined compression test and (b) splitting test.

Figure 6: Comparisons between numerical simulations and experiments: (a) axial stress-strain curves of uniaxial compression tests and (b) force-displacement curve of splitting test.
contact experiment are compared with those of the experiment [49], as shown in Figure 8.

The force-displacement curve obtained by the numerical simulation is generally consistent with that of the experiments. The numerical simulation curve also effectively reflects the four loading stages divided according to the curve shape: (1) initial linear stage; (2) nonlinear stage with reduced contact stiffness; (3) contact stiffness linear stage; and (4) overall breakage after the peak. In the second stage, the contact stiffness decreases to a certain extent but then gradually recovers. The shape of the curve indicates that there is a nonlinear process in the contact between the elementary particles in the sample, that is, the failure of bonding or the separation of the contact. According to the loading stage of the experiment and the variation range of the curve slope, it can be confirmed that the change is caused by the local bond failure of the contact point.

5.2. Cracks Evolution. In the discrete-element numerical simulation, the numerical model is formed by bonding the elementary particles based on the improved model. The formation of cracks is simulated by breaking the bond between elementary particles. In the process of numerical simulation, the cracks are stored and visualized by the crack-monitoring algorithm, which are displayed as the disks with certain thickness in the three-dimensional model. The thickness of the disk is proportional to the gap between the elementary particles. Cracks formed by different failures are represented by different colors. The yellow disks indicate tension failures and the red disks indicate shear failures. By observing the distribution and evolution of bonded failures, the formation of cracks throughout the loading process and the final failure form of the numerical model can be observed.

Figures 8(a)–8(c) shows the generation and evolution process of cracks on the semi-longitudinal section of the model passing through the upper and lower contact points in the simulation process. It can be seen from the figure that the bonded fractures are first concentrated at the upper and lower contact points at the initial stage of loading. With the progress of loading, the bonded fractures gradually expand to the middle of the model. The bonded fractures form a penetration on the connecting line of the upper and lower contact points. Then the bonded fractures continue to expand to both sides and finally extend to the whole cross-section. The through crack is formed and the model is broken into two parts. Among them, the bonded fractures are mostly tension failures, and the shear failures occur less, which is mostly concentrated in the conical area below the contact point. Figure 8(d) shows a side view of the final broken shape of the numerical model. As can be seen from the figure, the final breakage pattern of the specimen in the numerical simulation is also similar to that in the experiment, both of which break symmetrically along the section passing through the upper and lower loading points into almost complete parts.

5.3. Stress Distribution. According to the results of the indoor ball-plane contact experiment, the final penetrating fracture surface of the specimen will pass through the central section. Therefore, in the process of numerical simulation, 10 measurement balls are introduced vertically along the geometric centre of the sample (that is, the sphere centre) to record the horizontal stress distribution at the axis of the sample, as shown in Figure 9. The measurement balls are uniformly distributed along the diameter direction of the sample. The diameter of the measurement ball is 5 mm. When the contact force is 6.3137 kN, the recorded horizontal stress values of the measurement balls are used to draw the horizontal stress distribution map at different heights on the axis according to the sample height. The results are shown in Figure 9(a). The compressive stress is positive, and the tensile stress is negative. As the sample approaches overall

Table 2: Basic mechanical properties of numerical simulation materials.

| Material                   | Tensile strength (MPa) | Uniaxial compressive strength (MPa) | Elastic modulus (GPa) | Poisson’s ratio |
|----------------------------|------------------------|-------------------------------------|-----------------------|-----------------|
| Numerical simulation material | 2.87                   | 40.15                               | 7.16                  | 0.29            |
| High strength gypsum       | 2.83                   | 40.42                               | 7.20                  | 0.30            |

Table 3: Formation parameters of spherical numerical sample.

| Model parameter | Parameter description       | Value               |
|-----------------|---------------------------|---------------------|
| g               | Gravity acceleration      | 9.8 N/kg            |
| $\rho_b$        | Material density          | 2650 kg/m$^3$       |
| $r_{\text{min}}$ | Minimum particle size     | $1.0 \times 10^{-3}$ m$^3$ |
| $r_{\text{max}}$ | Maximum particle size     | $1.6 \times 10^{-3}$ m$^3$ |
| r$_{\text{avg}}$ | Average particle size     | $1.3 \times 10^{-3}$ m$^3$ |
| D               | Diameter of spherical sample | $50.0 \times 10^{-3}$ m$^3$ |
| L/R             | Model size ratio          | 38.46               |
| e               | Model void ratio          | 0.35                |
| $\lambda$       | Particle size magnification factor | 1.2                |
breakage in the current state, the maximum equivalent tensile stress is close to the bond tensile strength used for the contact mechanics parameters. The maximum equivalent tensile stress occurs at the bottom third measurement ball with a value of 3.848 MPa.

Hiramatsu and Oka [50] obtained analytical solutions of the internal stress elasticity of spherical specimens under uniaxial loading in 1966 by photo elastic mechanical experiments and analytical methods. The theoretical horizontal stress distribution on the central longitudinal axis according to the theoretical results is shown in Figure 9(b). The equivalent horizontal stress distribution on the central longitudinal axis in the numerical simulation is similar to the theoretical distribution map. The results show that the horizontal stress in the conical core is compressive and that the stress level is high before overall breakage. To some extent, this explains the shear fracture of the bond at the edge of the conical nucleus. The horizontal stress in the middle part of the longitudinal axis of the centre of the sample is mainly tensile stress, which explains why the bond fracture on the fracture surface is mainly tensile fracture when the final overall fracture occurs.

5.4. Velocity Field. Figure 10 is the central longitudinal section of the instantaneous velocity field of particle breakage. The velocity field at the moment of particle breakage shows that the broken block tends to move away from the central longitudinal axis. The elementary particles in the broken block have similar movement rates and the same direction. This indicates that the broken
block is of strong integrity, and the movement trend is consistent with the overall tensile fracture characteristics. The breakage phenomenon is generally the same as the test phenomenon (Figure 8(e)). On the surface of the sample at the edge area of the loading plate, the elementary balls with different movement directions from the whole can be observed. It can be considered that the local breakage occurred at the corresponding position, resulting in the collapse of debris.

5.5. Force Chain Distribution. The contact force chain in the numerical model is analysed to study the transfer and distribution of the loading force in the numerical specimen. The direction of the force chain is consistent with the direction of the maximum principal stress of the external load [51]. The particles near the cross-section perpendicular to the penetrating breakage surface are selected for observation. The distribution of the compression chain and tension chain during the loading process is shown in Figures 11 and 12, respectively. The blue and red line segments are used to represent the force chain transfer path, and the thickness of the line segment is proportional to the magnitude of the contact force. Owing to the different magnitudes of contact forces under tension and compression, different linewidth scale factors are used.

The distribution diagram of the contact compression chain indicates that the contact pressure is primarily concentrated near the contact point at the beginning of loading. With continuing loading, the loading platform is produced. Through the loading platform, the contact pressure is conveyed and diffused into the model, where it is uniformly distributed on the central horizontal section of the sample. The pressure chain in the conical area beneath the loading plate spreads in all directions. The angle formed by the force chain at the conical area’s edge and the vertical direction is roughly 45°. This demonstrates that the balls in the corresponding position of the conical region are in a state of multidirectional compression. The equivalent horizontal stress is compressive stress, which is consistent with the results of stress distribution analysis.

The distribution diagram of the tension chain shows that the maximum tension chain in the numerical sample is mainly concentrated near the central longitudinal axis. The direction of the tension chain is basically perpendicular to that of the compression chain except for a small area near the contact point. The number of force chains in the conical area below the contact point is significantly less than that in the surrounding area. The area with the highest force chain density appears at the bottom of the conical area before the overall breakage of the numerical model, as shown in Figure 12(b). At the instant of overall breakage, a large number of tension chains on the central longitudinal axis disappear, that is, the corresponding contact undergoes tensile failure and loses the tensile capacity. The distribution of tension chains at the moment of overall breakage reflects the arching effect, and a tension chain with an approximately uniform distribution appears on the outer surface of the sample. At the instant of overall breakage of the numerical sample, the contact force of the corresponding basic particles at the interruption of the force chain on the central axis is extremely unbalanced, and the disintegration will be accelerated under the combined external force. This reflects the brittle failure characteristics.

6. Discussion

Previous investigations have revealed that after the sample has been broken, there is a cone core beneath the contact location, as shown in Figure 13. During the experiment, the cone core penetrates into the ball particle, which results in the final breakage of the particle [49]. According to the aforementioned analysis, it can be seen that the final broken phenomenon of the model in the numerical simulation is consistent with the laboratory experiment, and the result well reflects the important feature of the cone core. The results of the numerical simulation show that a significant degree of shear failure occurs at the edge of the cone core. Combined with the aforementioned stress distribution, velocity field, and force chain distribution, the formation mechanism of the cone core can be obtained. Figure 14 shows the distribution of force chain during loading and the
bonded fracture and velocity field at the moment of breakage in the cone core region. As shown in the figure, under the action of the loading force, a certain area below the loading plate is in the stress state of triaxial compression (see Figure 14(a)). When the contact force reaches the critical value, the shear stress on the oblique section in the region reaches the shear strength of the material and causes shear failure. The bonded failure is shown in Figure 14(c), where the yellow discs represent the bonded failures caused by tension, and the red discs represent the bond failures caused

Figure 11: Distribution diagram of the compression chain: (a) 0.662 kN, (b) 4.089 kN, and (c) breaking moment.

Figure 12: Distribution diagram of the tension chain: (a) 0.662 kN, (b) 4.089 kN, and (c) breaking moment.

Figure 13: Morphologies after breakage: (a) contact point, (b) broken surface, and (c) cone core.
by shear. The shear failure angle is perpendicular to the
direction of the compression chain at the edge of the conical
zone, and the angle between the shear failure angle and the
vertical direction is approximately 45°. With the accumu-
lation of local shear failure, the cone core is gradually
formed. At the moment of particle breakage, the instantan-
eous movement direction of the balls in the cone core is
mainly downward, while the outer particles move to both
sides (see Figure 14(d)). The whole ball is broken into two
halves.

7. Conclusion

In this paper, the discrete interface bond model is obtained
by introducing the nonlinear shear bond strength criterion.
The improved model solves the intrinsic problem of classical
bonded particle model (BPM) in PFC. Based on this new
model for simulating the high-strength gypsum material,
numerical analysis of the ball-surface contact breakage ex-
periment of the spherical sample with a diameter of 50 mm
was carried out. This provides a basis for the analysis of ball-
to-surface contact breakage from a mesoscopic point of view
and further verifies the validity and reliability of the model.
The main conclusions are summarized as follows:

(1) The tensile strength and shear strength of the
specimens based on the nonlinear discrete interface
bonded model are significantly higher than those of
the classical bonded model, and this makes up for the
deficiency that the shear strength envelope of the
classical bonded model is linear. This can provide
shear properties similar to those of actual materials.
The mechanical properties of high-strength gypsum
used in experiments can be accurately simulated by
selecting model samples with reasonable meso-
parameters.

(2) The macro-breakage morphology of numerical
simulation reveals the generation of local breakage
and the formation process of cone core from the
mesoscale. The sample is finally broken into almost
equal two parts. The numerical phenomenon is
similar to the indoor test results.

(3) The force chain distribution results show that the
contact in the conical area below the loading plate is
subjected to a large compressive load. The angle
between the force chain direction at the edge of the
conical region and the vertical direction is approx-
imately 45°. The maximum value of the tension chain
is mainly distributed horizontally near the central
longitudinal axis, and the distribution of the tension
chain in the conical region is sparse.

(4) Combined with the stress distribution and force
chain distribution, the formation mechanism of cone
core can be obtained. Under the action of the loading
force, the conical area under the loading plate is
under triaxial compression. When the contact force
reaches the critical value, the shear stress on the
inclined section reaches the shear strength of the
material and causes shear failure. With the accu-
cumulation of local shear failure, the cone core is
formed gradually.

Data Availability

All data used to support the findings of this study are in-
cluded within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest
regarding the publication of this article.

Acknowledgments

This work was supported by the National Natural Science
Foundation of China (grant no. 51479138) and the Scientific
Research Project of Shandong Hi-Speed Infrastructure Construction Co., Ltd (grant no. SDGS-2021-0491).

References

[1] N. Cho, C. D. Martin, and D. C. Sego, "A clumped particle model for rock," *International Journal of Rock Mechanics and Mining Sciences*, vol. 44, no. 7, pp. 997–1010, 2007.

[2] C. Thornton, K. K. Yin, and M. J. Adams, "Numerical simulation of the impact fracture and fragmentation of agglomerates," *Journal of Physics D: Applied Physics*, vol. 29, no. 2, pp. 424–435, 1996.

[3] E. E. Alonso, M. Tapias, and J. Gili, "Scale effects in rockfill behaviour," *Géotechnique Letters*, vol. 2, no. 3, pp. 155–160, 2012.

[4] M. Tapias, E. E. Alonso, and J. Gili, "A particle model for rockfill behaviour," *Géotechnique*, vol. 65, no. 12, pp. 975–994, 2015.

[5] P. Wang and C. Arson, "Discrete element modeling of shielding and size effects during single particle crushing," *Computers and Geotechnics*, vol. 78, pp. 227–236, 2016.

[6] D. Shi, L. Zheng, J. Xue, and J. Sun, "DEM modeling of particle breakage in silica sands under one-dimensional compression," *Acta Mechanica Solida Sinica*, vol. 29, no. 1, pp. 78–94, 2016.

[7] Y. Liu, H. Liu, and H. Mao, "DEM investigation of the effect of intermediate principle stress on particle breakage of granular materials," *Computers and Geotechnics*, vol. 84, pp. 58–67, 2017.

[8] J. Manso, J. Marcelino, and L. Caldeira, "Crushing and odometer compression of rockfill using DEM," *Computers and Geotechnics*, vol. 101, pp. 11–22, 2018.

[9] A. B. Shemirani, H. Haeri, V. Sarfarazi, and A. Hedayat, "A review paper about experimental investigations on failure behaviour of non-persistent joint," *Geomechanics and Engineering*, vol. 13, no. 4, pp. 535–570, 2017.

[10] V. Sarfarazi and H. Haeri, "Three-dimensional numerical modeling of effect of bedding layer on the tensile failure behavior in hollow disc models using Particle Flow Code (PFC3D)," *Structural Engineering & Mechanics*, vol. 68, pp. 537–547, 2018.

[11] J. Liu, F. Liu, and X. Kong, "Particle flow code numerical simulation of particle breakage of rockfill," *Rock and Soil Mechanics*, vol. 29, pp. 107–112, 2008.

[12] G. R. McDowell and O. Harireche, "Discrete element modelling of soil particle fracture," *Géotechnique*, vol. 52, no. 2, pp. 131–135, 2002.

[13] G. R. McDowell and O. Harireche, "Discrete element modelling of yielding and normal compression of sand," *Géotechnique*, vol. 52, no. 4, pp. 299–304, 2002.

[14] M. D. Bolton, Y. Nakata, and Y. P. Cheng, "Micro- and macro-mechanical behaviour of DEM crushable materials," *Géotechnique*, vol. 58, no. 6, pp. 471–480, 2008.

[15] W. Zhou, L. Yang, G. Ma, X. Chang, Z. Lai, and K. Xu, "DEM analysis of the size effects on the behavior of crushable granular materials," *Granular Matter*, vol. 18, no. 3, pp. 64, 2016.

[16] J. P. De Bono and G. R. McDowell, "Investigating the effects of particle shape on normal compression and overconsolidation using DEM," *Granular Matter*, vol. 18, no. 3, pp. 55, 2016.

[17] H. Haeri, V. Sarfarazi, and Z. Zhu, "Effect of normal load on the crack propagation from pre-existing joints using Particle Flow Code (PFC)," *Computers and Concrete*, vol. 19, no. 1, pp. 99–110, 2017.

[18] V. Sarfarazi, H. Haeri, and A. B. Shemirani, "Direct and indirect methods for determination of mode I fracture toughness using PFC2D," *Computers and Concrete*, vol. 20, pp. 39–47, 2017.

[19] M. Xu, J. Hong, and E. Song, "DEM study on the effect of particle breakage on the macro- and micro-behavior of rockfill sheared along different stress paths," *Computers and Geotechnics*, vol. 89, pp. 113–127, 2017.

[20] X. Wang, L. Lim, and G. R. McDowell, "Discrete element modelling of railway ballast," *Granular Matter*, vol. 7, no. 1, pp. 19–29, 2005.

[21] D. Shi, J. Zhou, and M. Jia, "Numerical simulations of particle breakage property of sand under high pressure 1D compression condition by use of particle flow code," *Chinese Journal of Geotechnical Engineering*, vol. 29, pp. 736–742, 2007.

[22] J. Zhou, S. Yu, and J. Zhang, "The process and mechanism for the contact breakage of marble particles," *Journal of Harbin Institute of Technology*, vol. 50, pp. 110–119, 2018.

[23] H. Haeri, "Experimental crack analyses of concrete-like CSCBD specimens using a higher order DDM," *Computers and Concrete*, vol. 16, no. 6, pp. 881–896, 2015.

[24] V. Sarfarazi, H. Haeri, A. B. Shemirani, and Z. Zhu, "Shear behavior of non-persistent joint under high normal load," *Strength of Materials*, vol. 49, no. 2, pp. 320–334, 2017.

[25] J. Zhou, J. Zhang, and Q. Wang, "Experimental study on contact of gypsum particles," *Journal of Tongji University*, vol. 44, pp. 67–72, 2016.

[26] U. artin and S. Rapp, "Discrete element modeling of the single-particle crushing test for ballast stones," *Computers and Geotechnics*, vol. 88, pp. 61–73, 2017.

[27] G. R. McDowell and J. P. de Bono, "On the micro mechanics of one-dimensional normal compression," *Géotechnique*, vol. 63, no. 11, pp. 895–908, 2013.

[28] W. Zheng and D. D. Tannant, "Grain breakage criteria for discrete element models of sand crushing under one-dimensional compression," *Computers and Geotechnics*, vol. 95, pp. 231–239, 2018.

[29] J. A. Åström and H. J. Herrmann, "Fragmentation of grains in a two-dimensional packing," *The European Physical Journal B-Condensed Matter and Complex Systems*, vol. 5, pp. 551–554, 1998.

[30] S. Lobo-Guerrero and L. E. Vallejo, "Discrete element method analysis of railtrack ballast degradation during cyclic loading," *Granular Matter*, vol. 8, no. 3–4, pp. 195–204, 2006.

[31] G. Marketos and M. D. Bolton, "Compaction bands simulated in discrete element models," *Journal of Structural Geology*, vol. 31, no. 5, pp. 479–490, 2009.

[32] M. B. Gi and G. Buscarrera, "DEM assessment of scaling laws capturing the grain size dependence of yielding in granular soils," *Granular Matter*, vol. 18, no. 3, pp. 36, 2016.

[33] M. O. Ciantia, M. Arroyo, F. Calvetti, and A. Gens, "An approach to enhance efficiency of DEM modelling of soils with crushable grains," *Géotechnique*, vol. 65, no. 2, pp. 91–110, 2015.

[34] M. Takei, O. Kusakabe, and T. Hayashi, "Time-dependent behavior of crushable materials in one-dimensional compression tests," *Soils and Foundations*, vol. 41, no. 1, pp. 97–121, 2001.

[35] O. Ben-Nun and M. Einav, "The role of self-organization during confined comminution of granular materials," *Philosophical Transactions of the Royal Society A: Mathematical, Physical & Engineering Sciences*, vol. 368, no. 1910, pp. 231–247, 2010.
T. Brosh, H. Kalman, and A. Levy, "Fragments spawning and interaction models for DEM breakage simulation," Granular Matter, vol. 13, no. 6, pp. 765–776, 2011.

O. Tsoungui, D. Vallet, and J.-C. Charmet, "Numerical model of crushing of grains inside two-dimensional granular materials," Powder Technology, vol. 105, no. 1–3, pp. 190–198, 1999.

W. Zhou, L. Yang, G. Ma, X. Chang, Y. Cheng, and D. Li, "Macro-micro responses of crushable granular materials in simulated true triaxial tests," Granular Matter, vol. 17, no. 4, pp. 497–509, 2015.

G. Yang, J. Xu, and K. Liu, "Numerical simulation of particle breakage of coarse aggregates," Rock and Soil Mechanics, vol. 36, pp. 3301–3306, 2015.

J. Wang and H. Yan, "On the role of particle breakage in the shear failure behavior of granular soils by DEM," International Journal for Numerical and Analytical Methods in Geomechanics, vol. 37, no. 8, pp. 832–854, 2013.

M. B. Cil and K. A. Alshibli, "3D assessment of fracture of sand particles using discrete element method," Geotechnique Letters, vol. 2, no. 3, pp. 161–166, 2012.

M. Lu and G. R. McDowell, "Discrete element modelling of ballast abrasion," Geotechnique, vol. 56, no. 9, pp. 651–655, 2006.

M. Lu and G. R. McDowell, "Discrete element modelling of railway ballast under triaxial conditions," Geomechanics and Geoengineering, vol. 3, no. 4, pp. 257–270, 2008.

L. Shao, S. Chi, Y. Zhang, and J. Tao, "Study of triaxial shear tests for rockfill based on particle flow code," Rock and Soil Mechanics, vol. 34, pp. 711–720, 2013.

Y. Cheng, M. Bolton, and Y. Nakata, "Grain crushing and critical states observed in DEM simulations," Powders and Grains, vol. 2, pp. 1393–1397, 2005.

H. Jiang and M. Xu, "Study of stress-path-dependent behavior of rockfills using discrete element method," Engineering Mechanics, vol. 10, pp. 151–157, 2014.

J.-g. Qian, J.-b. Gu, X.-q. Gu, and M.-s. Huang, "Discrete numerical modeling of granular materials considering crushability," Journal of Mountain Science, vol. 14, no. 4, pp. 758–770, 2017.

D. O. Potyondy, "A flat-jointed bonded-particle material for hard rock," in Proceedings of the 46th US Rock mechanics/geomechanics symposium, Chicago, Illinois, June 2012.

S. Yu, M. Jia, J. Zhou, C. Zhao, and L. Li, "Micro-mechanism of spherical gypsum particle breakage under ball-plane contact condition," Applied Sciences, vol. 9, no. 22, p. 4795, 2019.

Y. Hiramatsu and Y. Oka, "Determination of the tensile strength of rock by a compression test of an irregular test piece," International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, vol. 3, no. 2, pp. 89–90, 1966.

M. Otto, J. P. Bouchaud, P. Claudin, and J. E. Socolar, "Anisotropy in granular media: classical elasticity and directed-force chain network," Physical Review. E, Statistical, Nonlinear, and Soft Matter Physics, vol. 67, Article ID 031302, 2003.