Particle Crushing and Anisotropy of Calcareous Sand During Triaxial Shearing

Ketian Sun[1], Yan Gao[1,2*]

[1]School of Earth Sciences and Engineering, Sun Yat-sen University, Zhuhai, Guangdong, 519000, China
[2]Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, Guangdong, 519000, China

*Corresponding author's e-mail: gaoyan25@mail.sysu.edu.cn

Abstract. This paper studies particle crushing and the related anisotropy of the micro-behavior of calcareous sand during shearing by numerical simulation based on the discrete element method. By analyzing the macroscopic and microscopic responses of calcareous sand under different particle crushing rates, such as the direction of particle crushing and the strong contact force chain, the results show that with the increase of the particle crushing rate, the peak and residual deviatoric stress and the dilatancy decrease, while the concentration degree of particle crushing direction and strong contact force chain reduces, and the degree of anisotropy weakens.

Keywords: Calcareous sand; particle crushing; anisotropy; discrete element method

1 Introduction

Calcareous sand is the main carrier of the development of the South China Sea in China, different from the traditional land-source quartz sand, it is composed of insoluble carbonate (mostly calcium carbonate) and is characterized by irregular particle shape, high internal porosity, easy to break, large internal friction angle [1–5]. The properties of calcareous sand, such as strength [6], permeability, and microstructure [7], can be directly changed by particle breakage under conventional stress. At present, the research on particle breakage is mainly based on laboratory and field tests, which have obtained sufficient data and provided insights into particle breakage. For example, Xiao et al. [8] pointed out that the relationship between strength and particle size of calcareous sand conforms to Webull distribution; Liu et al. [9] proposed that particle breakage is related to particle hardness and stress state; Yu [10] found that higher confining pressure can lead to more particle breakage. However, this research still has many shortcomings, such as high cost, discrete results, and poor process repeatability. More importantly, due to the inherent dispersion and heterogeneity, calcareous sand is very complex, resulting in insufficient micro-understanding of particle breakage.

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In recent years, the discrete element method [11] (DEM) has been proven to be a powerful tool for exploring the behavior of brittle granular materials, such as shear strength, volume expansion, fracture evolution, force chain transmission, and energy distribution. Using various DEM algorithms, extensive numerical simulations of particle breakage have been carried out to supplement the experimental phenomena microscopically. The stress path (such as confining pressure [12] and cyclic load [13]), particle shape (such as aspect ratio [14], particle size [15]), etc., were considered. In this study, based on Yade's open-source 3D discrete element platform [16], a series of triaxial shear numerical simulations are carried out to explore the influence of different particle breakage of calcareous sand on shear strength, micro-behavior, and anisotropy.

2 Establishment of numerical mode

The post-replacement method is adopted to simulate the particle breakage of calcareous sand in the DEM numerical simulation in the study. The strength criterion is the modified Mohr-Coulomb-Webull joint strength criterion by Alaei [17]. The replacement criterion is modified from Brzeziński's algorithm [18], in which it is assumed that each particle is replaced by 9 small particles with equal radii and mass equality is achieved by expanding the range around the broken particle that can be filled with small particles. The process of numerical simulation is shown in Figure 1, and the parameters of simulations are shown in Table 1. The simulation groups and the parameters are shown in Table 2.

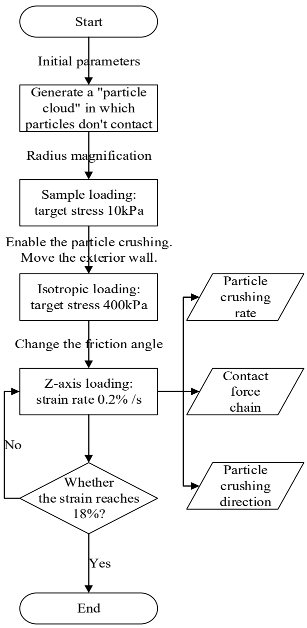


Fig. 1. Numerical simulation flow.

Table 1. Parameters in numerical simulation.

Parameter	Values
Model size	10×10×10 mm
Number of particles	3,000
Contact model	Hertz-Mindlin
Target strain	Z axis, up to 18%
Particle radius	Initial: 0.29±33% mm After particle radius magnification：0.36±33% mm
Particle properties	
Young's modulus	800 MPa
Poisson's ratio	0.05
Particle density	2,810 kg/m^3
Friction angle	Sample preparation and isotropic Loading: 0° Anisotropic loading: 5.7° Shearing: 30°
Wall Properties	
Young's modulus	800 MPa
Poisson's ratio	0.05
Friction angle	Sample preparation and isotropic Loading: 0° Anisotropic Loading: 14° Shearing: 30°

Table 2. Particle strength parameters corresponding to the degree of particle fragmentation.

Degree of particle crushing	Uniaxial tensile strength (MPa)	Uniaxial compressive strength (MPa)
None	∞	∞
Low	4	6
Mid	2	6
High	1	3

3 Shear characteristics of calcareous sand with different particle crushing

3.1 Stress-Strain and Bulk-Strain response

Figure 2 shows the deviatoric stress-axial strain and volumetric strain-axial strain curves of calcareous sand particles with four-particle crushing rates. It can be seen that the deviatoric stress-axial strain response of calcareous sand is similar for all of the samples and increases rapidly in the initial stage (axial strain less than 3%) because, during this stage, the shear deformation is mainly due to the rotation and slip between particles, large inter-particle pores are compressed, and the particle breakage is insignificant as shown in Figure 3. Then, as the shearing stress continues to increase, the stress-strain relationship of calcareous sand with different particle breakage rates shows differences. That is, the deviatoric stress of samples with higher particle breakage slows down with the increase of axial strain, gradually reaching the peak deviatoric stress, while the deviatoric stress of samples with lower particle breakage continues to increase until a higher peak deviatoric stress. With the increase in particle breakage rate, more stress drops occur in the shear process, which is caused by the stress release induced by particle breakage, and both the peak stress and residual stress decrease.

The volumetric strain-axial strain curves of calcareous sand with different particle breakage rates are also basically coincident when the axial strain is less than 6%. At this time, the particle breakage rate (Figure 3) is overall at a low level and changes little. The volume in the shear process is contractive first and then dilative. With the development of axial strain, the particle breakage rate increases, and the breakage rate growth point advances and grows faster. With the continuous occurrence of particle breakage, the dilatancy of samples with a high breakage rate decreasing.

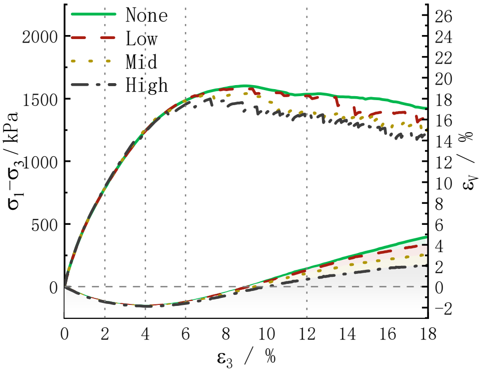


Fig. 2. Deviatoric stress-axial strain and volumetric strain-axial strain curves with different particle crushing rates.

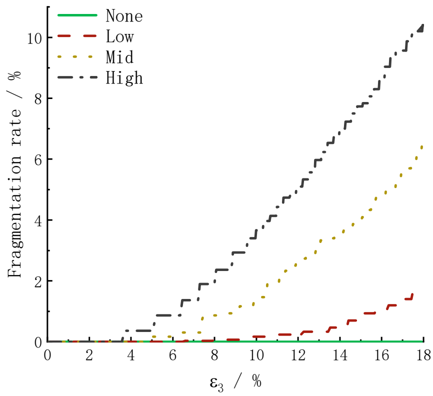
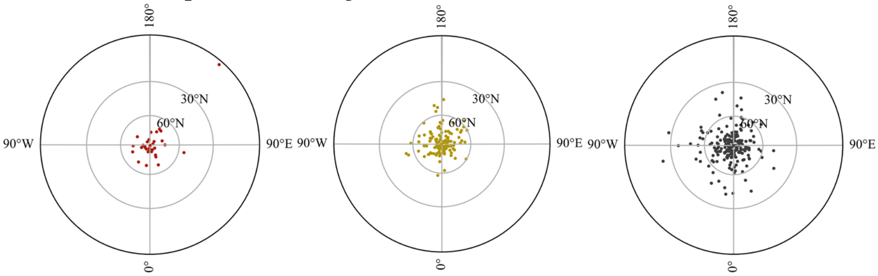


Fig. 3. Particle crushing rate-axial strain curves with different particle crushing rates.

Figure 4 shows the direction of particle breakage in the whole shear process. The maximum contact force direction at the time of particle breakage is used as the particle breakage direction. It is obvious that the main direction of particle breakage is the Z-axis direction (vertical direction), and with the decrease of particle breakage rate, the concentration degree increases, and the anisotropy degree increases. This is because in the shear process, the maximum principal stress direction is the Z-axis direction, so when the particles are broken, the contact force acting on the particles is more likely to be the maximum contact force and the contact force is larger when the contact is parallel to the Z-axis. Therefore, at a low particle breakage rate, almost only contacts parallel to the Z-axis can reach the target breakage stress; and with the decrease of particle strength, the particle breakage rate increases, and contacts with larger angles to the Z-axis can also cause particle breakage.

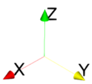
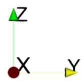
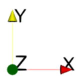
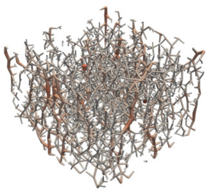
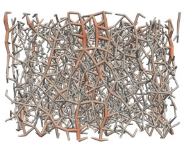
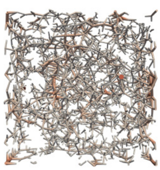


(a) (b) (c)

Fig. 4. Distribution of particle crushing direction with different crushing rates: (a) for low particle crushing; (b) for middle particle crushing; and (c) for high particle crushing.

3.2 Indirect contact chain of microscopic particles

The strong force chains for samples with no particle breakage and the highest particle breakage rate at the end of the shear are analyzed, as shown in Figure 5. The force chains inside the sample are dense, while the force chains at the boundary are sparse, and the obvious force-bearing chains are the main part of the stress transmission in the whole sample. With the increase of particle breakage degree, the concentration degree of the strong force chain in the Z-axis direction decreases, which is reflected in the figure as the reduction of the blank part, and the anisotropy of the strong force chain is weakened. It can be considered that particle breakage mainly destroys the strong force chain framework, causing stress redistribution.

View				
(a)				

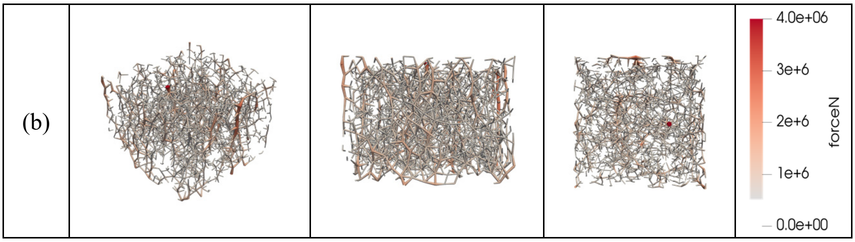


Fig. 5. Distribution of contact force chain: (a) for the sample with no particle breakage; (b) for the sample with high particle fragmentation rate.

4 Conclusions

The discrete element method numerical simulation is used to study the effect of particle breakage rates on the shear characteristics and micro-behavior of calcareous sand. The particle breakage is simulated by using the post-replacement method and the delayed replacement mechanism. The main conclusions are as follows. The higher the particle breakage rate, the lower the peak and residual deviatoric stress in the shear process, and the smaller the dilatancy of the volumetric strain. Particle breakage mainly occurs in the approximate Z-axis direction, which has directional anisotropy, and with the increase of particle breakage rate, the concentration degree decreases, and the anisotropy degree is weakened. Particle breakage can destroy the strong contact force chain of particles, resulting in the decrease of concentration degree of the strong force chain in the Z-axis direction and the weakening of anisotropy.

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Reference

1. Chen H Y, Wang R, Li J G and Zhang J M 2005 Grain shape analysis of calcareous soil *Rock and Soil Mechanics* 1389–92
2. Ma C H, Zhu C Q, Liu H F, Cui X, Wang T M, Jiang K F and Yi M X 2021 State-of-the-art review of research on the particle shape of soil *Rock and Soil Mechanics* **42** 2041–58
3. Wang X Z, Wang X, Liu H F, Meng Q S and Zhu C Q 2017 Field test study of engineering behaviors of coral reef foundation *Rock and Soil Mechanics* **38** 2065-2070+2079
4. Qing Y, Yao T, Wang R, Zhu C Q and Meng Q S 2014 Particle breakage-based analysis of deformation law of calcareous sediments under high-pressure consolidation *Rock and Soil Mechanics* **35** 3123–8
5. Wang X Z, Wang X, Weng Y L, Lv S Z, Yan K and Zhu C Q 2016 Characteristics of dry density of calcareous sand and its testing methods *Rock and Soil Mechanics* **37** 316–22

6. Lade P V, Yamamuro J A, and Bopp P A 1996 Significance of particle crushing in granular materials *Journal of Geotechnical Engineering* **122** 309–16
7. Wang Y, Santosh M, Luo Z H and Hao J H 2015 Large igneous provinces linked to supercontinent assembly *Journal of Geodynamics* **85** 1–10
8. Xiao Y, Liu H L, Ding X M, Chen Y M, Jiang J S and Zhang W G 2016 Influence of Particle Breakage on Critical State Line of Rockfill Material *International Journal of Geomechanics* **16** 04015031
9. Liu S H, Mao H Y, Wang Y S and Weng L P 2018 Experimental study on crushable coarse granular materials during monotonic simple shear tests *Geomechanics and Engineering* **15** 687–94
10. Yu F W 2017 Characteristics of particle breakage of sand in triaxial shear *Powder Technology* **320** 656–67
11. Cundall P A and Strack O D L 1979 A discrete numerical model for granular assemblies *Géotechnique* **29** 47–65
12. Zhang T and Wu J 2019 Discriminative frequency filter banks learning with neural networks *Eurasip Journal on Audio, Speech, and Music Processing* **2019**
13. Dahal B and Mishra D 2020 Discrete Element Modeling of Permanent Deformation Accumulation in Railroad Ballast Considering Particle Breakage *Frontiers in Built Environment* **5**
14. Ueda T, Matsushima T, and Yamada Y 2013 DEM simulation on the one-dimensional compression behavior of various-shaped crushable granular materials *Granular Matter* **15** 675–84
15. McDowell G R and Harireche O 2002 Discrete element modeling of soil particle fracture *Geotechnique* **52** 131–5
16. Smilauer V, Angelidakis V, Catalano E, Caulk R, Chareyre B, Chevremont W, Dorofeenko S, Duriez J, Dyck N, Elias J, Er B, Eulitz A, Gladky A, Guo N, Jakob C, Kneib F, Kozicki J, Marzougui D, Maurin R, Modenese C, Pekmezi G, Scholtes L, Sibille L, Stransky J, Sweijen T, Thoeni K and Yuan C 2023 Yade Documentation
17. Alaei E and Mahboubi A 2012 A discrete model for simulating shear strength and deformation behavior of rockfill material, considering the particle breakage phenomenon *Granular Matter* **14** 707–17
18. Brzeziński K and Gladky A 2022 Clump breakage algorithm for DEM simulation of crushable aggregates *Tribology International* **173** 107661