Particle breakage characteristics of coarse-grained soil under point-point contact

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Abstract. As an excellent building material, the coarse-grained soil is widely used in various construction engineering. The breakage of coarse-grained soils has a great influence on the overall quality of the engineering. Therefore, it is very important to study the breakage characteristics of coarse-grained soils. In this study, limestone was used to simulate coarse-grained soil. Point-point contact experiments of different particle sizes and loading conditions were carried out to study the breakage characteristics of soil particles. The effect of particle size and loading conditions on breakage characteristics was investigated through analyzing the breakage processes, failure modes, force-displacement curves and cone core sizes. The results indicated that the spherical limestone particles break locally at the contact point with the increase of normal force in the normal loading experiments. And with the contact area expanding, the particles finally split into several fragments. The diameter and the depth of the cone core are proportional to the particle size. Whether particles broke completely depended on the loading lever of normal force under complex load conditions. The critical loading level of normal force of limestone with a diameter of 5cm was 70%. The horizontal angles of crack are proportional to the loading lever of the normal force. The diameter of the cone core is affected by both normal force and tangential force, and its depth is mainly affected by the magnitude of the normal force.

Keywords. coarse-grained soil; breakage modes; cone core; force-displacement curve

1. Introduction

As an engineering building material, coarse soil has the characteristics of high strength, small deformation and good permeability, which is widely used in engineering applications such as earth rock dams, highways, railways, bridges, artificial islands, and foundation treatment. However, coarse-grained soil is easy to be broken. Particle breaking can cause the change of soil gradation and the structure of the soil itself, which will have an important effect on the strength of the soil, internal friction angle, permeability coefficient and so on. In recent years, the construction of super-high earth-rockfill dams in China has developed rapidly, of which most of the dam height above 150 m is the rockfill dam. Due to the significant increase in dam height, the stress conditions of the dam will also be more complex. Therefore, it is urgent to study the meso-mechanical properties and particle breakage characteristics of coarse soil under high stress.

The study of mechanical properties of particle contact is one of the bases for the study of mechanical properties of coarse-grained soil. The experimental research on the particle contact problem of coarse-
grained soil is mainly carried out from the characteristics of strength and deformation and particle crushing characteristics. Charles and Watts [1] carried out large-scale drained triaxial compression tests on heavily compacted samples of different types of rockfill under different surrounding pressure conditions. Guo [2] studied the effects of lateral pressure, particle density and other factors on the stress-strain relationship of large particles by drainage triaxial test. Lee and Coop [3] investigated the intrinsic mechanics of the granite soil by triaxial tests to summarize the behavior in its different states. Cavarretta et al.[4] studied the effects of mechanical and geometric properties of particles such as particle roughness, inter-particle friction and particle shape on the overall properties of cohesionless granular materials by simulating particles with glass ball, and found that the influence of particle shape was more significant. Pan et al. [5] carried out the true triaxial compression tests and plane strain experiments by using the large-scale true triaxial apparatus to study the influence of the medium principal stress on the stress-strain characteristic of coarse-grained soil. Zhou et al. [6] conducted uniaxial compressive tests and particle contact tests to investigate mechanical properties of gypsum test specimens by using rock rheological testing system.

The breaking problem of coarse-grained soil is studied by a large number of experiments and numerical simulation. Hardin [7] carried out experiments on rockfill materials of different materials and defined new crushing parameters. Liu et al. [8] analyzed the particle crushing of coarse-grained material by using indoor large triaxial tests. W. Wang and M. R. Coop [9] carried out a series of single-particle uniaxial compression tests on different kinds of sand particles by using a high-speed microscope camera to capture the processes of breakage and explored the relationship between the particle strength and the breakage mode. Taplas et al. [10] introduced into particle crushing a discrete model for rockfill aggregates by a novel approach and simulated two breakage modes. Zhao et al. [11] gained new insights into the mechanism of breakage of individual sand particles under single-particle compression by combining mechanical tests with three-dimensional X-ray micro-computed tomography during loading. Liu et al. [12] carried out numerical true triaxial tests to investigate the influence of the intermediate principal stress on the particle breakage of granular materials. Zhou et al. [13–15] analyzed the breakage process and morphology of particles, cone core and force-displacement curve by carrying out the particle contact experiments and the numerical simulation with parameters for strength reduction. Yu et al. [16] carried out the particle contact tests and the corresponding numerical simulations to investigate the process and mechanism of spherical particle breakage under the ball–plane contact conditions. At present, a lot of progress has been made in the study of coarse soil, and its mechanical properties and crushing laws have been deeply understood. However, most of the previous studies are carried out from a macro point of view, and the research on particle mesostructure is still in its infancy.

The present study investigated breakage characteristics between real particles through the point-point contact experiments. Breakage modes, force-displacement curve and cone core were occupied to study the breakage characteristics of coarse-grained soil. The effects of particle size and force form on particle breakage were also discussed.

2. Experimental study
In this study, particle contact of coarse-grained soil in practical engineering was simulated with a real particle contact experiment. Contact between actual particles was simplified as point-point contact and simulated by ball particle-ball particle contact.

2.1. Experimental material
In order to study the breakage characteristics of coarse-grained soil, it is better to use the coarse-grained soil which can be collected in nature for contact test. As an important part of natural coarse-grained soil, limestone was selected as experimental material to perform normal contact experiments and normal with tangential contact experiments. However, because naturally collected limestone are heterogeneous and disorganized, they can not be directly used to carry out highly repetitive and persuasive experiments. Therefore, the collected limestone blocks in this experiment are processed and ground into spherical particles. In order to compare different particle sizes, 1 cm, 2.5 cm and 5 cm spherical particles were
produced. In order to discuss the effect of force form, normal contact and normal with tangential contact were designed. The physical and mechanical properties of the standard specimens for limestone obtained from basic mechanical tests are shown in Table 1.

Table 1. Physical and mechanical properties of experimental materials.

| Material   | Compressive strength (MPa) | Tensile strength (MPa) | Elastic modulus (GPa) | Possion ratio |
|------------|-----------------------------|------------------------|-----------------------|---------------|
| Limestone  | 85.9                        | 5.7                    | 53.8                  | 0.28          |

2.2. Experimental instrument

The instrument used in the experiment was the rock rheological testing system shown in Figure 1. Special devices were designed to fix particles, as shown in Figure 2, and the curvature of the fixture is the inverse of the particle size. The ball-ball contact was shown in Figure 2. According to the static loading, all the normal force was applied at a displacement rate of 0.002 mm/s until the normal displacement reached the predetermined value - 0.5 mm for 1 cm limestone, 1.2 mm for 2.5 mm limestone, and 2 mm for 5 cm limestone for normal contact. All the tangential force was applied at a loading rate of 5 N/s until the particles crushed or the relative tangential displacement reached 2 mm for normal with tangential contact. The measurement and control precision for specimen force and deformation were 5 N and 0.001 mm, respectively. The data acquisition frequency was approximately 1 Hz.

Figure 1. Rock rheological testing system

Figure 2. Experimental devices and Experimental conditions

2.3. Experiment scheme

In this study, the breakage characteristics between non-cohesive particles were investigated, based on the basic contact model. Considering various factors, the main content of this experiment included the following:

1. Normal contact experiment

   In this experiment, the normal contact properties of limestone ball particles were investigated, and the effects of different particle sizes on particle breakage characteristics were compared.

2. Normal with tangential contact experiment

   In this experiment, the normal with tangential contact properties of limestone were investigated. The experimental results were then compared to the normal contact and the effect of force forms was discussed. The groups used in the experiment are shown in Table 2.
Table 2. Particle groups used in the experiments.

| Number | Material   | Particle size (cm) | Contact form | Force form          | Normal force percentage |
|--------|------------|--------------------|--------------|--------------------|-------------------------|
| 1      | Limestone  | 1                  | Point-point  | Normal force       |                         |
| 2      |            | 2.5                | Point-point  | Normal force       |                         |
| 3      |            | 5                  | Point-point  | Normal force       |                         |
| 4      |            | 5                  | Point-point  | Normal with tangential force | 60%                  |
| 5      |            | 5                  | Point-point  | Normal with tangential force | 70%                  |
| 6      |            | 5                  | Point-point  | Normal with tangential force | 80%                  |
| 7      |            | 5                  | Point-point  | Normal with tangential force | 90%                  |

3. Analysis of experimental results

In this study, it was assumed that (1) the normal force and tangential force in the experiments all acted on the contact points, (2) the deformation of particle is much smaller than any relevant dimension of the body that could be neglected, and (3) the influence of fissure inside particles was not discussed in this paper.

3.1. Breakage properties of normal contact

3.1.1. Breakage modes. The results of the normal contact experiment are shown in figure 3. The experimental results show that limestone crushed at the contact point and the contact area progressively increased with the increasing normal force. Then, the vertical cracks produced near the contact area and propagated until the particle broke completely into several pieces, as shown in figure 3. Some debris was scattered around the pieces after failure.

The failures of 1 cm, 2.5 cm and 5 cm limestone are shown in figure 4. It can be seen that 1 cm, 2.5 cm and 5 cm limestone particles broke into 3 pieces, 3 pieces and 2 pieces, respectively. According to the current experiments, it is found that the smaller the particle size of limestone is, the more pieces it tends to break into. Mass ratio of broken pieces for 1 cm, 2.5 cm and 5 cm limestone are 2:1:1, 2:1:1, 1:1, respectively.
Figure 3. Breaking process of limestone particles with different particle sizes.  
(a) Particle size 1 cm; (b) Particle size 2.5 cm; (c) Particle size 5 cm.

Figure 4. Breakage modes of limestone particles with different particle sizes.  
(a) Particle size 1 cm; (b) Particle size 2.5 cm; (c) Particle size 5 cm.

3.1.2. Normal force-displacement curve. The normal force-displacement curves of 1 cm, 2.5 cm and 5 cm limestone particles are virtually the same. It can be seen that the curves contain two stages. In the initial stage, the normal force increases with the increasing displacement dramatically corresponding to contact point crushing and the cracks propagation. The crushing load to the first peak during compression is called the critical normal force $N_c$. The critical normal forces of 1 cm, 2.5 cm and 5 cm limestone are 0.870 kN, 3.446 kN and 5.914 kN, respectively. The critical normal force increases linearly with the increasing particle size, as shown in figure 6. It represents that the critical normal force for the limestone spherical particles broke completely depends significantly on the particle size.

In the second stage, the normal force drops from the first peak value to nearly zero while crack propagated and the particle crushed into two or three pieces. Several peaks $N_f$ are reached at this stage, which is consistent with the work of Antonyuk et al. [17]. It seems that the peak value $N_f$ tend to be larger than the critical normal force $N_c$ for larger particles.
3.1.3. Cone core analysis. Inverted triangle cone was found under the contact area of limestone after particle failure, as shown in figure 7. We call it Cone core because it is similar to the active region proposed by Prandtl in the bearing capacity theory of foundation. Cone core analysis can contribute to the investigation of the particle breakage mechanism. Due to the small size, cone core size of 1 cm limestone was not discussed here. The diameters of cone core for 2.5 cm, 5 cm limestone are 5.87 mm, 11.45 mm, respectively, which are 0.23 times of the particle size approximately. Similarly, cone core depths for 2.5 cm, 5 cm limestone are 3.35 mm, 7.10 mm, which are 0.13 ~ 0.14 times of the particle size approximately. Therefore, cone core size of particles can be predicted by particle size under normal contact.

![Cone core analysis](image)

**Figure 7.** Cone core size. (a) The diameter; (b) The depth.

3.2. Breakage properties of normal with tangential contact

In the normal with tangential contact experiment, 60%, 70%, 80% and 90% of the critical normal force were selected to investigate the effect of force form on breakage characteristics.
3.2.1. Breakage modes. The results of normal with tangential contact are shown in figure 8. Similar to the normal contact experiment, limestone particles crushed at the contact point and the contact area increased with the increasing normal force. Then, the particles broke into two pieces under the normal force equal to or larger than 70% of the critical normal force. It illustrates that whether 5 cm limestone particle breaks completely largely depends on the normal force under normal with tangential contact. However, although the limestone broke into two pieces in both normal contact experiment and normal with tangential experiment, the breakage modes of particles are different. The mass ratio of pieces for 5 cm limestone after failure under normal contact is close to 1. Whereas, the mass ratio of pieces under 70%, 80% and 90% of the critical normal force are 1:3.3, 1:1.8 and 1, respectively. It illustrates that the mass ratio of pieces after particle failure is closely related to the force form, and mass ratio tends to be closer to 1 under larger normal force.

![Figure 8](image)

**Figure 8.** Breakage process of limestone (under 70% of the critical normal force).

![Figure 9](image)

**Figure 9.** Breakage modes of limestone under normal with tangential force.

The crack angles of particles after failure can also reflect the influence of force form on breakage modes. The crack after particle breakage is closely related to the force form. Actually, we can see that the cracks are parallel to the external force direction. The horizontal angle is the crack angle from the plan view and the vertical angle is the crack angle from the front view, as shown in figure 10. The angels were measured by auto CAD. The horizontal angles are approximately 123, 144 and 164 degrees for particles under 70%, 80% and 90% of the critical normal force, respectively. It can be seen that the horizontal angle increases with increasing normal force. For each 10 percent increase in normal force, the horizontal angle increases by approximately 20~21 degrees. On the contrary, a larger normal force caused a smaller vertical angle. Under 70%, 80% and 90% of the critical normal force, the vertical angles are about 34, 16 and 6 degrees. For each 10 percent increase in normal force, the vertical angle decreases by 10~18 degrees.
Tangential force-displacement curve. The tangential force-displacement curves are shown in figure 11. It can be seen that a typical tangential force-displacement curve includes three stages. The tangential force increases dramatically with the increasing displacement in the initial stage. The static friction produces at the contact area between particles at this stage. In the second stage, the tangential force increases with the increasing displacement while the slope is smaller than that in the first stage. It is because the contact area increased with the contact point eroding under normal with tangential force. The tangential force maintains unchanged with the increasing displacement in the third stage and the sliding friction produced at the contact area. When the normal force percentage is 60%, the tangential force-displacement curve includes all three stages and the particle did not break completely. However, when the normal force percentage is equal to or larger than 70%, particles broke into two pieces in the second stage, and the larger the normal force is, the smaller the tangential force and displacement when the particles broke completely is.

Figure 11. Tangential force-displacement curves of limestone.

3.2.3. Cone core analysis. Cone core was also found when the particle broke completely under normal with tangential contact. The diameter of the cone core of particles under 70% 80% and 90% of the normal force are 9.72 mm, 11.04 mm and 12.14 mm, respectively. It represents that the diameter of cone core linearizes with the normal force percentage, as shown in figure 12(a). Furthermore, cone core depth of particles under normal force percentage 70%, 80% and 90% are 6.04 mm, 6.38 mm and 6.54 mm, respectively. Similarly, cone core depth is positively proportional to the normal force percentage, as shown in figure 12(b).
4. Comparison of breakage characteristics between normal contact and normal with tangential contact

4.1. Breakage modes

The normal contact can be considered as the normal with tangential contact when the normal force percentage is 100%. By comparing two kinds of experiments, it is found that breakage modes for limestone particles depend significantly on the force form. Mass ratio of pieces under 70%, 80%, 90% and 100% of the critical normal force are 1:3.3, 1:1.8, 1:1 and 1:1, respectively. The horizontal angle is positively proportional to the normal force percentage, as shown in figure 13(a). On the contrary, the vertical angle negatively correlated with the normal force percentage, as shown in figure 13(b). In fact, it was found that the cracks are parallel to the external force direction. One possible explanation of the difference of breakage modes in two contact experiments is that the external force leads to the principal stress rotation.

Figure 12. The relationship between cone core size and the normal force percentage.

Figure 13. The relationship between crack angle and the normal force percentage.
4.2. Cone core analysis
The effects of force form on cone core depth and the diameter of cone core are different. Cone core depth is linearly proportional to the normal force, and reaches the maximum value under normal contact, as shown in figure 14. However, the diameter of the cone core under normal contact is between that under 80% and 90% of the normal force. It illustrates that cone core depth is related to normal force only, on the contrary, the diameter of the cone core is related to both normal force and tangential force.

![Figure 14. The relationship between cone core depth and the normal force percentage.](image)

5. Conclusions
In this study, breakage properties of coarse-grained soils were investigated with particle contact experiments. The influence of particle size and force form on particle breakage was discussed. The conclusions are as follows.

(1) Through normal contact experiment, it was discovered that the spherical limestone particles crushed at the contact point and the contact area increased with the increasing normal force. Then particles broke into several pieces. The diameter and the depth of cone core are proportional to the particle size.

(2) Through normal with tangential contact experiment, it was found that the critical normal force percentage is 70% for 5 cm limestone. The larger the normal force, the closer to 1 the mass ratio is. For each 10 percent increase in normal force, the horizontal angle increases by approximately 20 degrees. On the contrary, the vertical angle decreases with the increasing normal force. The cracks are parallel to the force direction. The diameter and the depth of cone core are linearly proportional to the normal force.

(3) By comparing the results of normal contact and normal with tangential contact, it is discovered that particle breakage mode is mainly affected by force form. Cone core depth is correlated significantly with the normal force. However, the diameter of the cone core is affected by both the normal force and the tangential force. The differences between normal contact and normal with tangential contact are due to the principal stress rotation caused by the external force.

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