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A Study on the Effect of Particle Shape and Fragmentation on the Mechanical Behavior of Granular Materials Using Discrete Element Method

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Abstract. Particle crushing can result in changes in the mechanical properties of granular materials. By using Discrete Element Method (DEM), a model is established to simulate the breakage of two-dimensional particles for three different shapes (triangle, square and hexagon). In the simulations, each particle consists of two sub-particles bonded with each other. Particle crushing will occur during the numerical analysis if the bond between these sub-particles breaks. With this model, the effect of particle breakage on macro mechanical behavior of granular materials can be studied for three particle shapes which have the same equivalent radius. For each of these shapes, two series of biaxial tests, with and without breakable particles, are simulated and the results are compared in terms of shear strength and volume change, then the effect of fragmentation on the global behavior is evaluated for discrepant particle shapes. It is observed that particle breakage has a significant influence on mechanical behavior of granular materials such as a decrease in shear strength as well as volume change; moreover, the particle shape does not have so much effect on the final breakage percentage for this kind of failure.

Keywords: DEM, Breakage, Granular material, Simulation, Particle shape
PACS: 91.60.Ba

INTRODUCTION

The stability of soil structures such as foundations, retaining walls and dams is in association with the behavior of their granular materials which is dependent on a lot of factors like mineralogical composition, stress condition, shape and size of fragments, grading and particle crushing. Fragmentation of particles in the lower layers is a probable phenomenon in such high structures since they bear appreciable pressure caused by upper layers.

In this study, the influence of fracture on mechanical behavior of particulate media is investigated for three particle shapes with the same equivalent radii; then, the outcomes are presented and discussed in terms of stress-strain curve and breakage amount for different shapes.

A BRIEF REVIEW

The influence of particle shape and fracture on mechanical properties of granular assemblies, such as bearing capacity and deformational characteristic, has been the topic of several experimental researches in laboratories. Among them, Marsal [1] by carrying out triaxial compression tests on coarse granular materials, showed that particles breakage is a key factor affecting mechanical behavior of a particulate body undergoing breakage. As another example, Varadarajan et al. [2] by performing triaxial compression tests on two dam site rock materials, one of them consisted of rounded particles and the other was angular, observed that angular particles are more susceptible to be fractured than rounded grains. Large size of specimen is required in experimental tests; thus, the use of numerical discrete element method (DEM) has aroused increasing attention. Several investigations about particle breakage have been done by using DEM [3–5].

PARTICLE CRUSHING SIMULATION

The procedure of crushing phenomenon by using DEM is described below briefly.

Methodology

The program POLY [6], a modified version of DISC [7], is utilized to simulate two-dimensional irregular polygon-shaped grains; It has been developed to model breakable particles [5,8].

In this methodology, it is presumed that each particle can break through predetermined straight lines that are two probable failure modes: breaking into half and breaking into several fragments. As demonstrated in Fig. 1.a., particle P is considered breakable through

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the lines d_1, d_2 and d_3; hence, either of failure modes is definite since the beginning of the modeling. It is assumed that each intact particle like P, called Base Particle, comprises smaller bonded particles, called Sub-Particles, like P_1, P_2 … P_n. Both base particles and sub-particles are not deformable. Unlike base particles, sub-particles are not crushable. When two connected sup-particles are separated, the breakage occurs (Fig. 1.b.). This simulation method is presented in details by Seyedi Hosseininia [9].

Test Simulations

Using personal computer, the simulation of two series of biaxial tests, with and without breakable particles, is conducted on three different shapes which have the same equivalent radius (R=1mm). Each assembly consists of only one particular shape (triangle, square and hexagon) and is circumscribed by a circle 40mm in radius.

The parameters utilized in tests A and B are summed up in Tables 1 and 2 respectively.

TABLE 1. Parameters used in test A (with no breakage)

Parameter	Unit	Amount
Normal and tangential stiffness	N/m	2.0×10^8
Unit weight of particles	kg/m^3	2.5×10^3
Transitional damping coefficient	1/sec	1.0×10^4
Rotational damping coefficient	1/sec	2.0×10^4
Time step increment	sec	4.5e-5
Strain rate		5.0×10^{-3}
Cohesion between grains	kPa	0.0

Fig. 2 shows different steps of the simulations in an assembly including breakable square-shaped particles. Both series of tests have three steps. The first step is to compact the primitive computer generated soil assembly (Fig. 2.a.); then, a 0.5MPa confining pressure is applied (Fig. 2.b.). Afterwards, the specimen is subjected to a biaxial shear strain at a constant rate (Fig. 2.c.).

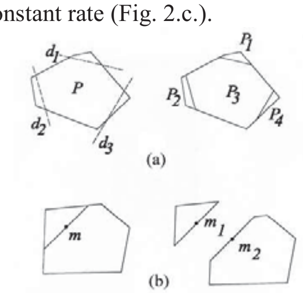

FIGURE 1. Crushing modeling
a. Base particle P and its sub-particles
b. The bond points of two adjacent sub-particles

(a)

(b)

(c)

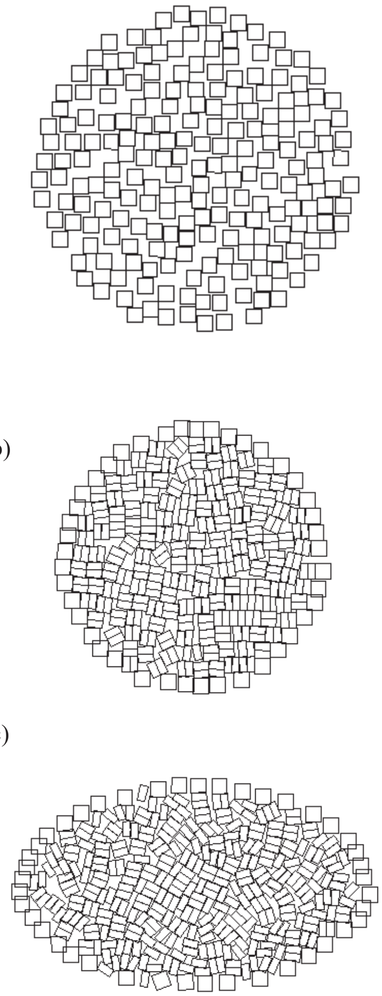

FIGURE 2. Simulation steps for a breakable assembly. (a) Generation of particles assembly; (b) Isotropically compacted specimen; (c) Sheared assembly.

TABLE 2. Parameters used in test B (with breakage)

Parameter	Unit	Amount
Normal and tangential stiffness	N/m	2.0×10^8
Unit weight of particles	kg/m^3	2.5×10^3
Transitional damping coefficient	1/sec	1.0×10^4
Rotational damping coefficient	1/sec	2.0×10^4
Time step increment	sec	1.3e-5
Strain rate		1.0×10^{-2}
Cohesion between grains	kPa	0.0
Module of elasticity (E)	MN/m^2	4.0×10^6
Sand strength		
Compressive strength	MN/m^2	200
Tensile strength	MN/m^2	20
Cohesion	MN/m^2	75
Coefficient of Static Friction		1.60

RESULTS

The simulation results of biaxial tests with breakable and unbreakable particles for three specific shapes under 0.5MPa confining pressure are presented in the form of curves of shear stress and volumetric strain versus axial strain in the following paragraphs. In addition, variation of breakage percentage versus axial strain is shown for three different shapes.

Variation of mobilized shear stress and compressibility is illustrated in Fig. 3. The evolution of mobilized deviator stress of assemblies with axial strain for triangle-shaped particles is depicted in Fig. 3.a For unbreakable particles, from the onset of loading, the mobilized shear stress rises until it reaches a peak value and then it continues to be almost constant until the end of the test. In case of breakable particles, the shear strength goes up to a maximum value and then declines gradually, although the sample with unbreakable particles has a higher peak value. The variation of volumetric strain versus axial strain for both specimens is illustrated in Fig 3.b. Both breakable and unbreakable particles show contractive and dilative behavior during the tests. By comparing the graphs, it is observed that the unbreakable sample shows more contractive behavior at the first steps of loading and higher dilative behavior at larger axial strain levels.

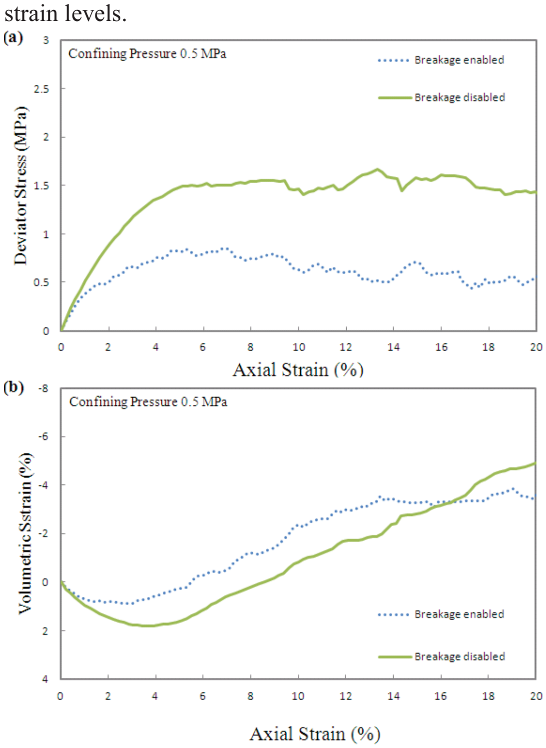

FIGURE 3. Variation of deviator stress and volumetric strain with axial strain for triangle-shaped particles

The evolution of mobilized deviator stress and volumetric strain during axial strain for square-shaped particles is illustrated in Fig. 4. It can be observed that both breakable and unbreakable particles reach a maximum value, and then they decrease to a nearly constant value; however, the unbreakable specimen shows more shear strength compared to breakable sample (Fig 4.a). As presented in Fig 4.b, when the breakage is enabled, the sample shows less contractive behavior and also less dilative behavior. Furthermore, the unbreakable particles have a sudden rise at the middle strain range during volumetric changes.

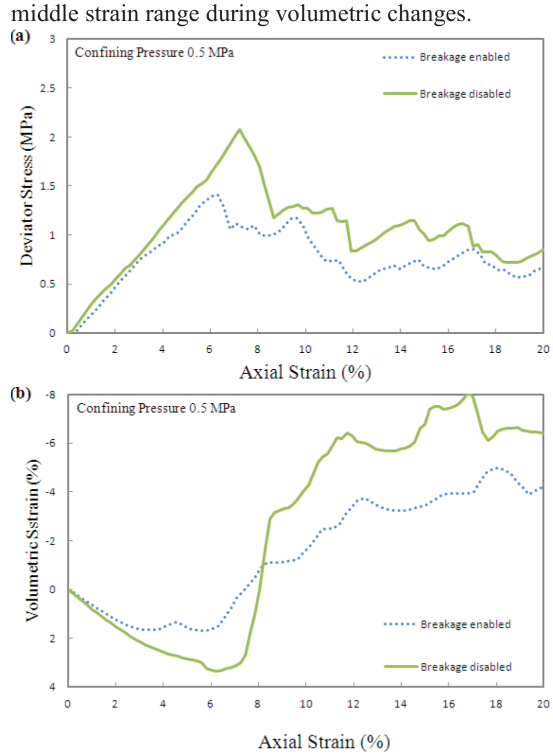

FIGURE 4. Variation of deviator stress and volumetric strain with axial strain for square-shaped particles

As presented in Fig. 5, the influence of particle crushing on mechanical behavior of hexagon-shaped particles is akin to that of the square-shaped particles, though different in several respects: the peak value of mobilized shear stress is widely extended; moreover, the dilation rate in middle strain range decreases.

Fig. 6 illustrates the amount of breakage in percentage during axial strain for samples comprised of triangular, square and hexagonal particles. It is clear that the final breakage percentage has not changed dramatically for three different shapes; although, the most and the least breakage amount are observed for square-particles and triangular-particles respectively. Moreover, the crushing rate is faster at the beginning of the test and then slows down because the larger unbroken sub-particles are surrounded by smaller fractured sub-particles becoming more resistive to fragmentation called cushioning effect [10].

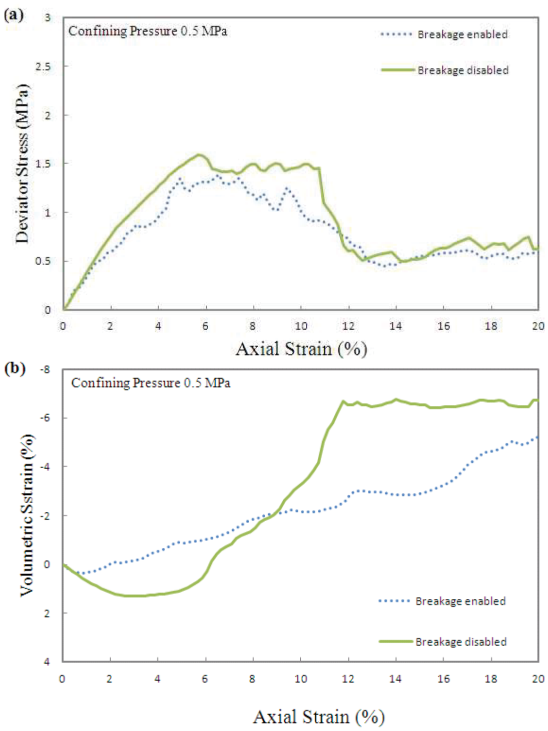

FIGURE 5. Variation of deviator stress and volumetric strain with axial strain for hexagon-shaped particles

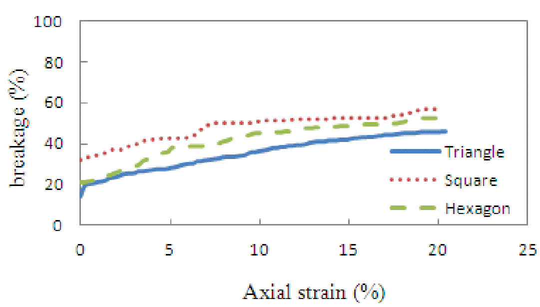

FIGURE 6. Variation of breakage amount for different particle shapes

5. COCLUSION

By using discrete element method (DEM), a series of numerical biaxial compression tests were performed to investigate the influence of particle breakage on the mechanical behavior of granular materials. To reach this goal, biaxial tests were carried out on three different particle shapes with the same equivalent radius for breakable and unbreakable particles. The simulations indicate that the breakable sample has less shear strength and more compressibility, which is consistent with experiment [2,11].

By comparing the simulation results, one can observe that both breakage phenomenon and particle shape have a great influence on the mechanical behavior of granular materials. On the other hand, the breakage amount for different particle shapes does not change dramatically so it may be inferred that the mechanical behavior is strongly influenced by particle shape rather than breakage for this kind of fracture.

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