The effect of particle size distribution on soil dilatancy: discrete element approach

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ABSTRACT

A series of numerical direct shear tests was simulated by a three-dimensional discrete element code PFC3D in this study. The size of the shear box was 6 cm long, 3 cm wide and 4 cm high. Depending on the particle size distribution, the number of particles in a test ranged from about 4,000 to 6,000. The analyses clearly demonstrated that the discrete element model captured the pressure-dependent nature of granular particles satisfactorily. Particle assemblages with essentially the same density before shearing showed varying dilatancy according to the overburden stress in a direct shear test. Dilation was suppressed at higher overburden pressure which agreed with experimental findings on granular matters. Three different particle size distributions but with the same mean particle diameter (d_{50}) were studied. Emphasis was placed on their effects on the macroscopically observed soil dilatancy. It was found that a particle assemblage with monosize particles dilated noticeably more than the other assemblages with more well-graded distributions.

1 INTRODUCTION

Granular soils compose natural substances in discrete form. Upon loading, particle rotation, translation or even breakage may occur. Such changes at the particulate level inevitably lead to deformation in a macroscopic sense which is of prime interest. Dilatancy is a crucial parameter to describe the volumetric behaviour of the soil during shear. Obviously, dilatancy is controlled at the particulate level and is governed by the particle characteristics, such as grain size distribution, particle shape and inter-particle friction. The discrete element method offers an insightful explanation at the microscopic level and it has drawn attention from researchers all over the world (Bardet & Proubet 1991; Ng 1994; Ni et al. 2000; Thornton 2000; Powrie et al. 2005; Cui & O'Sullivan 2006 and many others). In this study, a series of direct shear tests was simulated by the discrete element method three dimensionally. Spherical shaped particles were adopted in the analyses. Dilatancy of the particle assemblage with various combinations of particle sizes was monitored during the tests. The aims of this study were (1) to explore the potential of the 3D discrete element method in simulating soil responses and (2) to study the effect of particle size distribution on a soil's macroscopic dilatancy.

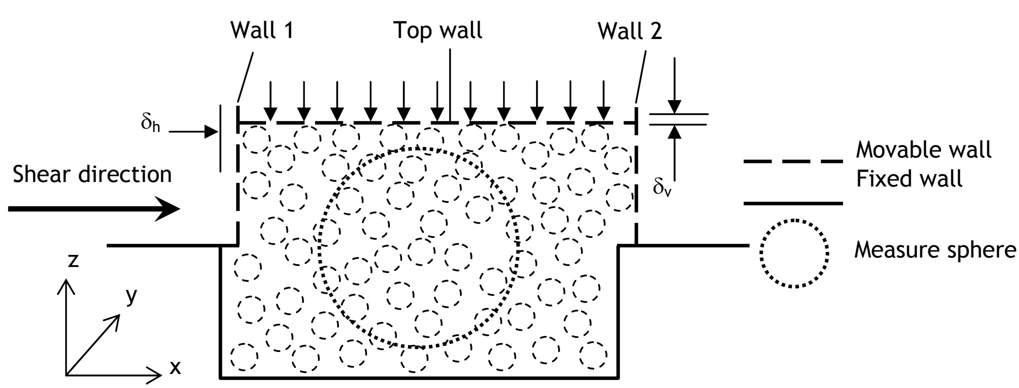

Figure 1. Schematic diagram of the numerical direct shear test

2 NUMERICAL DIRECT SHEAR TEST

The discrete element code PFC3D version 3.1 (Itasca Consulting Group Inc 2000) was adopted in this study. The linear contact model was used to model the contact between sphere to sphere and sphere to wall. The simulated direct shear box consisted of 10 rigid walls, and had internal dimensions 60 mm (length) × 30 mm (width) × 40 mm (depth) as shown in Figure 1 schematically. By considering a plane of symmetry, the width of the simulated box was only half of a typical direct shear box. This idealization also helped to reduce the number of particles in the simulation and thus decreased the time required for iterations. Two additional flanges were added on the sides such that no ball leakage would occur during shearing.

2.1 Specimen preparation and initial stress

Spherical particles were generated randomly inside the shear box to fulfil a target initial density while the friction coefficient was set to zero temporarily. Properties of the spheres and rigid walls as well as the grain size distribution of the assemblage are summarized in Table 1. Three different particle size distributions were simulated as shown in the table. Case I represented an assemblage with monosize particles of diameter (d) = 2.4 mm, while cases II and III showed particles with varying radii. As shown in Figure 2, case III has a wider distribution and the shape of gradation was very similar to a typical soil. On the other hand, case II was simply a uniformly random distribution of particles with various radii. Although their particle size distributions were different, the mean grain diameter (d_{50}) was essentially identical. The numbers of particles adopted in the analyses ranged from around 4,000 to 6,000, depending on the grain size distribution. The assemblage was then stepped to equilibrium. Then, the friction coefficient was changed back to 1.0 (i.e., the adopted value in the current study). A vertical pressure was then applied by moving the top wall downward until the target overburden stress was reached. In the current study, three different overburden pressures were investigated (i.e., 0.1 GPa, 0.5 GPa and 1.0 GPa).

Table 1: Summary of the numerical simulations

Sphere		Wall	
Friction coefficient	1.0	Friction coefficient	0.0
Normal stiffness	1×10^6 kN/m	Normal stiffness	1×10^6 kN/m
Shear stiffness	1×10^6 kN/m	Shear stiffness	1×10^6 kN/m
Grain Size Distribution			
	Diameter, d (cm)	d_{50} (cm)	$C_u = d_{60}/d_{10}$
Case I: Mono-size	0.24	0.24	1.00
Case II: Well-graded 1	0.09 to 0.4	0.242	2.28
Case III: Well-graded 2	0.02 to 0.5	0.238	1.81

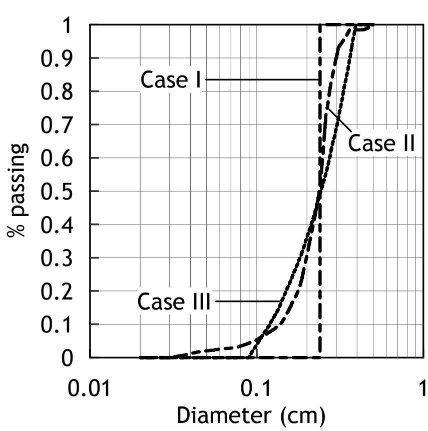

Figure 2. Particle size distribution

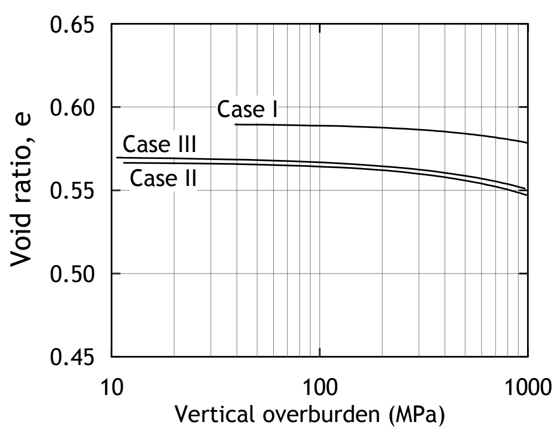

Figure 3. 1D compression results

2.2 Direct shearing

To simulate a direct shearing process, walls 1 and 2 (see Figure 1) were moved simultaneously in the positive-x direction with a constant velocity. At the same time, the position of the top wall was continuously adjusted by a servo-controlled mechanism in which the target overburden pressure was kept unchanged (Cui & O'Sullivan 2006). The positions of the walls were monitored to evaluate the macroscopic deformations (both in the vertical and horizontal directions).

3 RESULTS

The macroscopic vertical pressure (σ_{zz}) and shear stress (τ_{xz}) were evaluated based on the contact forces and areas along the top and vertical movable walls. Global porosity (or void ratio) was evaluated inside the measure sphere, which was located at the centre of the box with a radius of 1.5 cm.

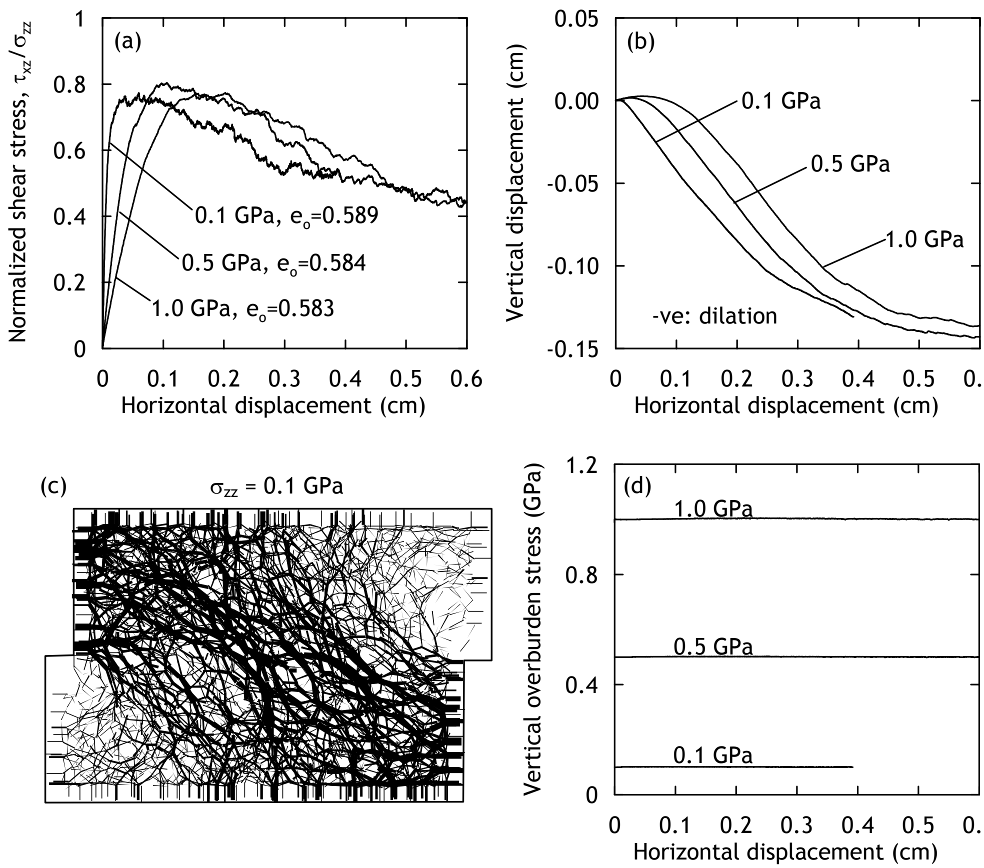

Figure 4. Responses of a particle assemblage with monosize sphere (a) normalized shear stress; (b) dilation; (c) inter-particle contact forces; (d) vertical overburden pressure

3.1 Monosize spheres

The response of the particle assemblages under one-dimensional compression are shown in Figure 3. It can be seen that only negligible deformation was induced under the study range of pressure, which agreed well with experimental findings on granular materials prior to particle crushing. The macroscopic mechanical responses of the monosize assemblage are shown in Figure 4. The shear stress was evaluated at the measure sphere and it should be noted that the values were very close to the values calculated on the basis of the forces acting on the walls. The results agreed well with typical direct shear test results on granular materials. Strain softening behaviour was observed together with dilation which is similar to the results presented by Cui and O'Sullivan (2006). Similar to typical experimental results, dilation was suppressed by increasing the overburden pressure. Contact force vectors at the end of the test shows clearly that the forces transmitted diagonally across the specimen (see Figure 4(c)). Oda et al (2005) attributed the strain-softening behaviour of granular materials to the buckling of stable columnar structures. As shown in Figure 4(d), it can be seen that the servo-controlled algorithm was very effective in keeping a constant overburden pressure during the tests.

3.2 Effect of particle size distribution

The effect of particle size distribution on soil dilation can be revealed in Figure 5. Both cases II and III exhibited less dilative response than case I. This may be due to the reason that smaller size particles migrated into the voids between larger particles during shear. Therefore, less dilation tendency was shown. Case II has the greatest coefficient of uniformity (c_u) among the three cases and it exhibited the least dilation among them under otherwise similar conditions. Case III, though has the widest particle size distribution and contained more smaller-sized particles, showed a greater dilation tendency than case II.

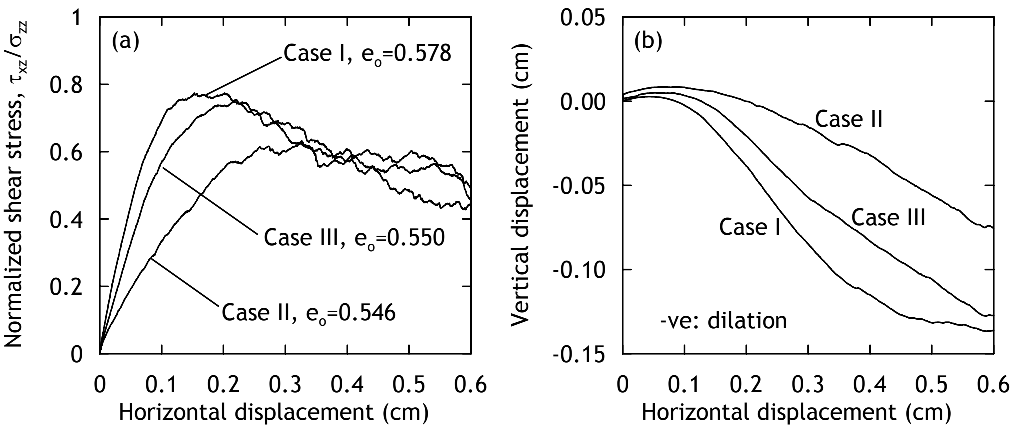

Figure 5. Responses of assemblages with different particle size distributions at σ_{zz} = 1 GPa

4 CONCLUSIONS

A series of numerical direct shear tests was simulated by the three-dimensional discrete element code PFC3D. The main objective of this study was to understand the effect of particle size distribution on a soil's dilatancy. The investigation demonstrated that the discrete element method was able to simulate the pressure dependent nature of soil dilatancy. Dilatancy was suppressed by an increase in overburden pressure. A well-graded particle assemblage exhibited a lower dilative tendency. This may be due to the fact that smaller particles migrated into the voids between larger particles which reduced the dilation. Moreover, based on the current investigation, an assemblage with a higher value of coefficient of uniformity c_u exhibited less dilation.

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