The 2014 World Congress on
Advances in Civil, Environmental, and Materials Research (ACEM14)
Busan, Korea, August 24-28, 2014

Evaluation of size and boundary effects in simple shear tests with distinct element method

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ABSTRACT

Rainfall induced slope failures in colluvium have been frequently reported in mountainous areas in Taiwan. To perform slope stability analysis in colluvium strata, soil strength parameters are essential. Since the simple shear mode has been recognized as the most representative failure condition along a curved sliding surface, a simple shear testing system capable of testing colluvium material with large soil particles is being developing. In simple shear tests, the size and boundary effects are two crucial factors affecting the consistency of the test results. To evaluate the size and boundary effects in simple shear conditions, numerical experiments using the distinct element method (DEM) have been done to investigate the influences on strength parameters and stress uniformity from the specimen diameter (D), specimen height (H), and maximum particle size (d_{max}). The size effect is evaluated with the variations of strength parameters among the specimen dimensions and particle size. The boundary effect is assessed with the spatial distribution of the particle displacement and contact force field. The results show that: (1) the boundary effect can be reduced effectively when H/D decreases, (2) the difference in boundary effect is insignificant between the Cambridge and NGI types of simple shear, (3) relatively consistent strength is available when the ratio of specimen height to the maximum particle size (H/ d_{max}) is no less than 7.

Keyword: Simple shear test, Size effect, Boundary effect, Distinct element method

1. INTRODUCTION

Slope failures in colluvium strata triggered by rainfall have been reported frequently in mountainous areas. The strength parameters and stress-strain relationships are essential to evaluate the slope stability of colluvium. Limited by the available testing apparatus and rational sample reconstitution procedure, representative strength parameters and stress-strain relationships are difficult to evaluate due to the existence of large particles and highly complexity of the grain size distribution in colluvium. An ongoing research is conducted to tackle these issues with hybrid numerical and

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physical element tests. Distinct element method (DEM) is utilized to study the micromechanical responses of idealized granular system with different grain size distribution. A new simple shear apparatus is developing to perform large specimen tests for validation of DEM results and evaluate the effects of large particles on the macro responses of real soils. Preliminary results on idealized granular system are presented here.

1.1 Boundary and size effects in DSS

Over a few decades, direct simple shear (DSS) tests have been extensively used by researchers to evaluate soil properties and stress-strain responses of soils under simple shear straining conditions, such as slope stability analyses, foundation and embankment designs, and cyclic behavior on foundations. The DSS soil specimen is consolidated under K_0 condition with zero horizontal deformation. Ladd and Foott (1974) described that the strength anisotropy from rotation of principle stresses during shearing can be mitigated with direct simple shear strength parameters. Airey and Wood (1987) stated that the strength parameters from simple shear tests are close to the ones from vane shear and back analyses.

Three types of the DSS devices have been developed: SGI, NGI and Cambridge types. The SGI type was first proposed by Kjellman (1951) and this type was modified by Norwegian Geotechnical Institute (NGI) with a cylindrical sample of soil surrounded by a wire-reinforced rubber membrane (Bjerrum and Landva 1966). The Cambridge type that accepts a cuboidal sample mounted on the rigid steel plate and rotation by two hinged end flaps (Roscoe 1953). Due to the lack of complimentary shear stress on the vertical side, the nonuniformity of stress field within the specimen had been one of the major concerns in promoting the application of DSS in geotechnical society. Significant experimental (e.g., Weight et al. 1978, Budhu 1984, Airey and Wood 1987) and analytical works (e.g., Lucks et al. 1972, Prevost and Hoeg 1976, Budhu and Britto 1987) have been performed to assess the effects of nonuniform stresses in the DSS specimen. The conclusions for all studies accept that the stress conditions in the specimen are non-uniform due to all DSS devices not fully applying shear forces to the side wall of specimens. However, Roscoe (1953) stated that the stress distributions within core of a specimen were uniform and testing results by Airey and Wood (1987) on clay with a NGI type DSS system confirmed the finding. Lucks et al. (1972) performed 3D finite element analysis on NGI type DSS configuration and showed that the stress concentration only occurred within the proximity of the specimen boundaries and 70% of the specimen was subjected to uniform stress field.

The nonuniformity of stress near the specimen boundaries is called boundary effects in this study. In simple shear conditions, the boundary effects are mainly affected by the height to diameter ratio of specimen (H/D). Based on 3D finite element analysis results, Shen et al. (1978) concluded that the deviation of induced shear strains near the specimen boundaries reduced as the H/D decreased. Amer et al. (1987) revealed that the difference of shear stress near the boundaries is 30% of the value in the core zone. In summary, the boundary effects in DSS configuration are closely related to the H/D ratio.

For laboratory element tests, the specimen dimension must satisfy certain criteria in order to get representative and consistent results. The variation of shear strength due to specimen size is called size effects. For shear strength tests, the dimensional criteria are related to the factors affecting the shear strength of soils. The major factors affecting the shear strength of soils are the largest particle size, particle shape, grain size distribution, stress state, and shearing mode. For simple shear tests on colluvium soils, the size effects control the specimen size, which will be crucial to design the DSS apparatus. In the current study, the idealized granular system is analyzed under DSS conditions using the distinct element method. The boundaries and specimen size effects on DSS conditions with idealized round grains are studied to assist the specimen configurations for testing real colluvium.

1.2 Distinct element method

The distinct element method code used in this study is the Particle Flow Code in Two Dimensions (PFC^{2D}) based on prior research proposed by Cundall (1971) and Cundall and Strack (1979). This program modelled two dimensional assemblies of rigid discs. An explicit numerical scheme is employed in the PFC^{2D} to solve the Newton's second law on the particle assembly with a force-displacement law at the contact to update the contact forces arising from the relative motion at each contact.

There have been few attempts to simulate the direct simple shear test by DEM. Dabeet et al. (2011) performed drained direct simple shear tests on air-pluviated glass beads and compared with the three dimensional DEM simulations. The simulation results had shown good agreement with laboratory testing. Dabeet et al. (2012) compared the DEM result with laboratory cyclic direct simple shear. Wijewickreme et al. (2013) conducted the drained and constant volume DSS simulation by three dimensional DEM to illustrate the mobilized friction angle during DSS shearing. These studies showed the potential of using discrete element simulation to evaluate the soil behaviors under DSS shearing process. However, these studies do not pay attention on the micro scale behavior between particles, stress distributions, effects from specimen size and boundary conditions.

The objective of this study is to present the responses of idealized particle systems from both laboratory experiments and DEM simulations. Modeling details, parametric studies, and distributions of particle responses in the DSS samples are presented in this paper. Quantitative dimensional criteria for DSS specimens are proposed.

2. DIRECT SIMPLE SHEAR TESTING

2.1 Testing apparatus and sample preparation

A modified NGI type direct simple shear apparatus is used to perform laboratory experiments of idealized particle assemblies. The apparatus was developed at the National Cheng Kung University (NCKU-DSS) and capable of applying monotonic and dynamic loadings for both stress- and strain-controlled conditions on vertical and horizontal directions. The device is controlled by two direct drive motors in vertical and horizontal directions. A soil container that uses a conventional latex membrane reinforced with low-friction stack rings is used in the NCKU-DSS system to maintain the K_0 condition throughout the testing. Details of stack-ring-reinforced membrane can be found in Chang et al. (2014). The NCKU-DSS apparatus and specimen setup are shown in Fig.1.

Fig. 1 Details of NCKU-DSS system and soil container

In this study, the specimen diameter is 100 mm with height between 20 to 40 mm. To provide verification data for DEM, dry steel balls with diameter of 1.5 mm and density of 7,850 kg/m^3 were filled in the soil container and sheared under a constant vertical stress and constant shear strain rate of 0.1 mm/hr. To reduce the variation of packing during sample preparation, steel balls were placed in the DSS container in ten equal layers (137 g per layer) and controlled void ratio to the densest condition. To arrange the steel balls in the densest condition, shaking at the bottom part of DSS specimen is necessary. The prepared specimen is shown in Fig. 2.

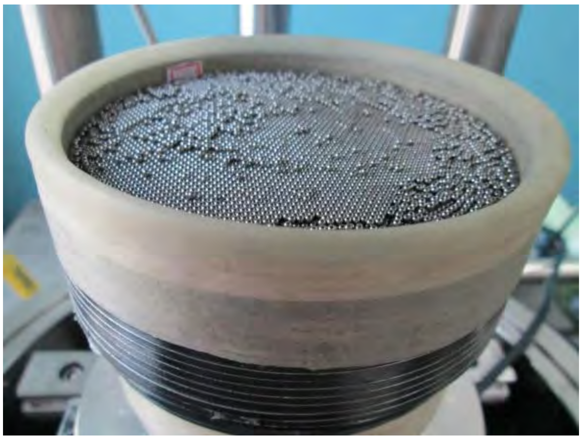
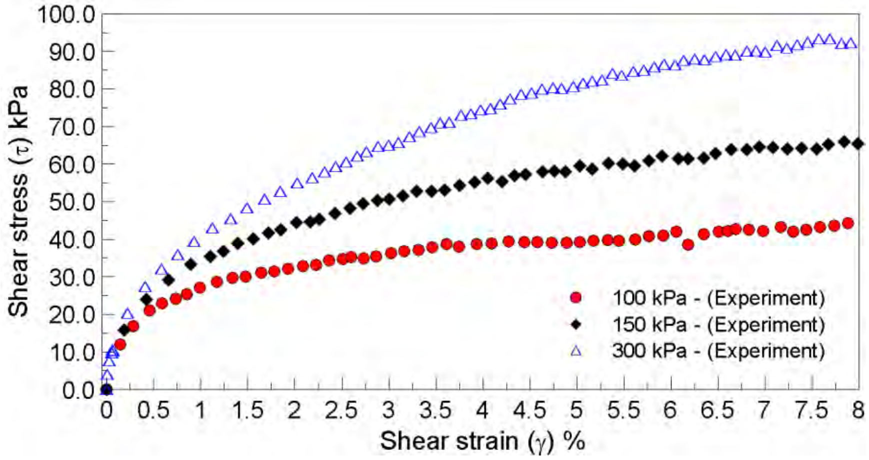


Fig. 2 Uniform steel ball specimen for DSS testing

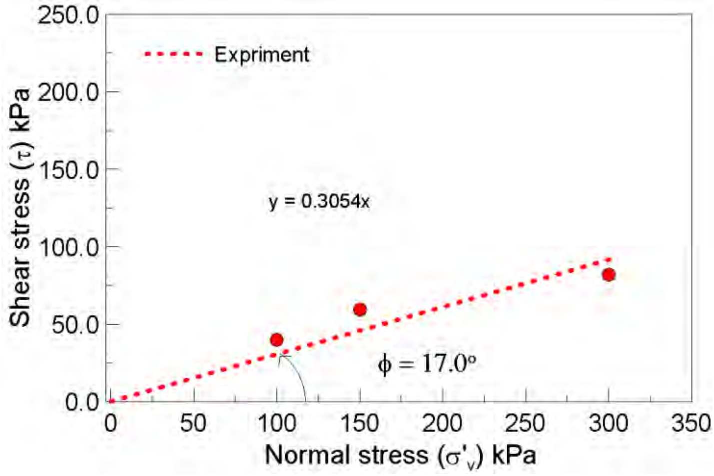
2.2 Testing results

Three specimens with diameter of 100 mm and height of 30 mm were sheared under vertical stresses of 100, 150, and 300 kPa, respectively. The test results are illustrated in Fig. 3 that represented the shearing responses of an idealized granular assembly subjected to K_0 simple shear conditions under three vertical effective stresses. Fig. 3 (a) shows that the peak shear stresses occurred at 5-8 % of shear strains. The shear stresses at 5% of shear strain are 35, 60, and 82 kPa for vertical stresses of 100, 150, and 300 kPa, respectively. The results show that the induced shear stress increases as the vertical effective stress increases.

Fig. 3 (b) shows the Mohr-Coulomb failure envelope of steel ball specimens under 3 vertical stresses with frictional angle of 17.0 degree, which is much smaller than the value of real granular soils due to the smooth surface of round steel balls. This value will be used in the DEM simulations.



(a) Shear stress versus strain



(b) Failure envelope

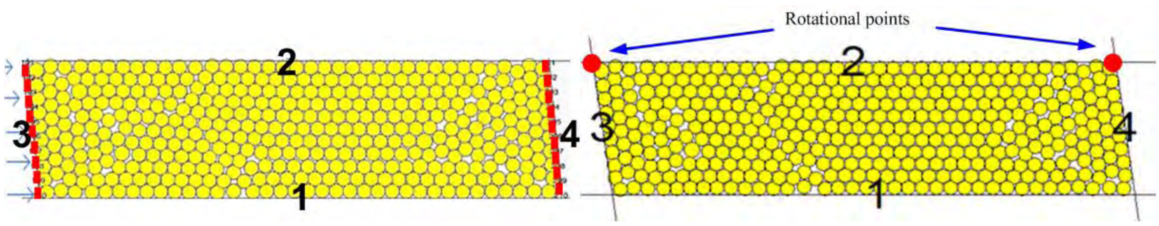
Fig. 3 Direct simple shear experiment results

3. DEM SIMULATION

3.1 Model details

The PFC^{2D} code modelled the particles as rigid circular discs. To verify the simulation with the experimental results, 1544 balls with diameter of 1.5 mm were generate to model a specimen with 100 mm in diameter, 30 mm in height, and porosity of 0.09. The boundaries of the DSS model consisted of one top and bottom wall and two side walls. The top, bottom, and side walls were assigned the same normal and shear stiffness parameters for all contacts between balls to walls.

To investigate the boundary effects in different DSS designs, the modified NGI and Cambridge type boundaries were applied, as shown in Fig. 4. For the NGI type model, ten rigid, stacked rings are employed to form the side walls for lateral support. Assuming no friction between stacked rings and the rings can move independently from each other, linearly varied horizontal velocities were applied to each stacked rings to shear the specimen as illustrated in Fig 4(a). For Cambridge type (CAM) model, rigid side walls with rotational joints with the top and bottom walls are used to provide lateral support of the particle assembly. During the shearing phase, a constant spin rate is applied on the two rotation joints on the top wall, as shown in Fig. 4(b). To simulate the consolidation and constant vertical stress conditions during shearing, the top wall was moved downward. To impose constant vertical stress on the top wall, the vertical velocities of the top wall were controlled by a close-loop servo-mechanism. To monitor distributions of stresses and strains, 40 measurement circles with radius of 3 mm were employed to calculate the local stresses and strains.



(a) NGI DSS model (b) CAM DSS model

Fig. 4 Direct simple shear DEM models

3.2 Verification with experiment result

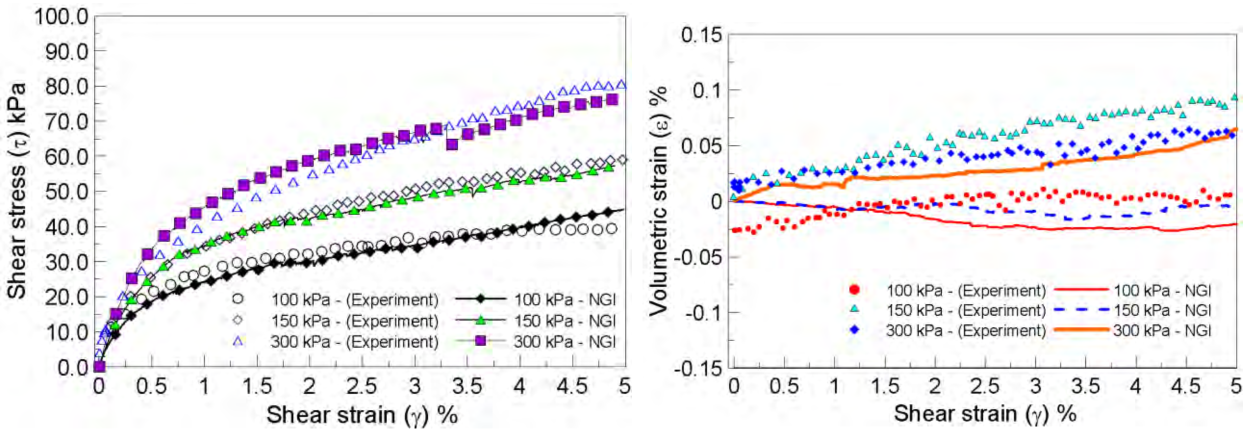
In this study, a linear contact model was employed to model the contact conditions between ball to ball and ball to wall. The input parameters include geometric, material, contact, and numerical parameters. The geometric and material parameters can be directly assigned for round steel balls. The contact parameters, including the normal and shear stiffness, elastic modulus of particles, and coefficient of friction, are major parameters to affect the macro-mechanical responses. The coefficient of friction is referred from the DSS failure envelope in Fig. 3(b). However, the contact normal and shear stiffness are difficult to determine. Consequently, parametric studies were performed to investigate the effects of contact parameters on the stress-strain relationships and a set of contact parameters that best fit the physical test results are obtained. The model input parameters are summarized in Table 1.

Using the models shown in Fig. 4 and the input parameters listed in Table 1, the DEM results of NGI and CAM DSS models along with the experimental results are presented in Fig. 5(a) and 5(b), respectively. Comparisons between the DEM and experimental results reveal that the DEM can well simulate the stress-strain curves at different vertical stresses for both NGI and CAM models. The difference between the NGI and CAM models is insignificant in current setting. Although the volumetric strain-

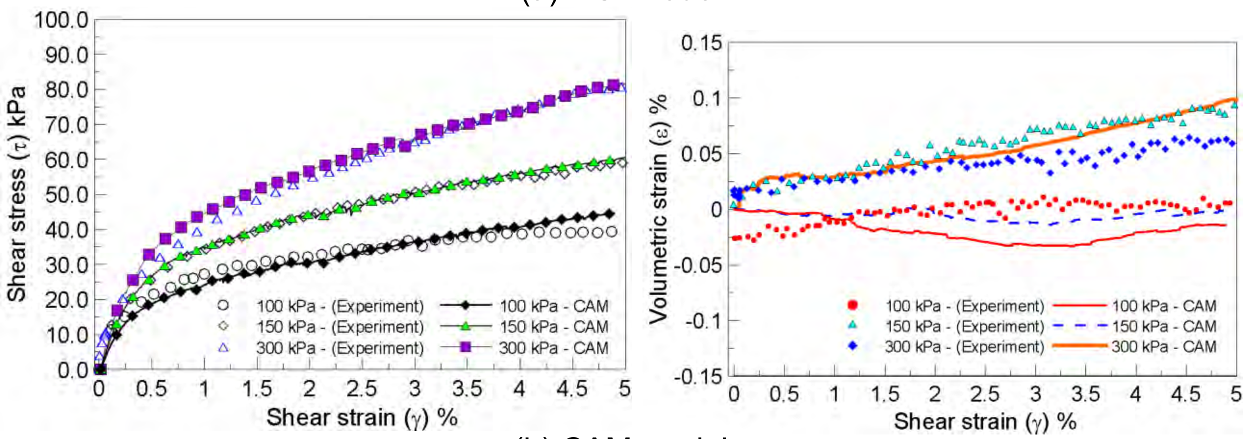
Table 1- DEM input parameters

Parameters	Balls	Rigid wall
Radius of ball r, [mm]	0.75	-
Density, ρ [mg/m^3]	7.85	-
Porosity	0.09	-
Elastic modulus [N/m^2]	2.5×10^7	-
Normal stiffness k_n,	5.0×10^7	2.0×10^6
Shear stiffness k_s,	2.5×10^7	2.0×10^6
Damping ratio	0.7	-
Coefficient of friction, μ	0.31	-

shear strain curves do not fit as well as the stress-strain curves, the trend that the granular system transforms from contract to dilative responses as the vertical stress increases is observed.



(a) NGI model



(b) CAM model

Fig. 5 Comparisons of DEM and experimental results

Continuous rotation of principle stresses during shearing is an important characteristic for DSS testing. The local principle stresses can be approximated with stress calculation inside a measure circle. The principle stress variation near the core of the NGI model is shown in Fig. 6. The results clearly show that the principle axis in stress space rotates as the shear strain increases. Because the stress and strain fields are the major concerns in boundary and size effects and the model results agree well with the laboratory DSS data, the DEM models are convinced to properly represent the mechanical responses of idealized granular specimen subjected to DSS conditions.

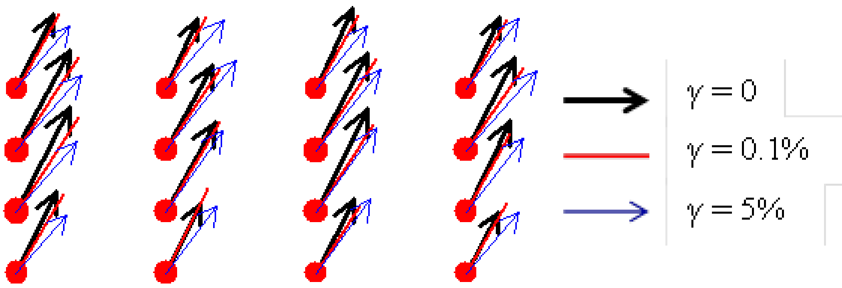


Fig. 6 Rotation of principle stresses in the core of NGI model

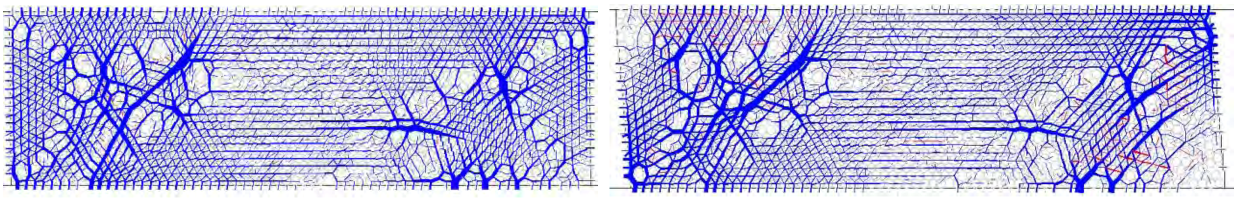
4. EVALUATION OF BOUNDARY AND SIZE EFFECTS IN DSS

4.1 Boundary effects in DSS

The non-uniform distributions of stresses near specimen boundaries or boundary effects have been the major concern in DSS testing. The boundary effects had been evaluated using finite element method based on continuum mechanics (e.g., Lucks et al. 1972, Wright et al. 1978, and Airey and Wood 1987). The results of these studies are significantly affected by selections of constitutive law to represent the stress-strain relationship of soils and interface behavior to describe the interactions between the soil and boundaries. The DEM simulation might be an alternative because no specific constitutive law and interface model are required.

The calibrated DEM models described in the previous section are used to quantitatively evaluate the boundary effects. Lucks et al. (1972) showed that the stress concentration only occurred within the proximity of the specimen boundaries and 70% of the specimen was subjected to uniform stress field. In DEM simulation, the stress distribution in a continuum can be approximated as force chains patterns, which representing the distribution of contact forces among particles. The force chains of NGI model at different strain levels are shown in Fig. 7, in which the thickness of connected lines represents force magnitude.

The distribution of force chains shows that the majority of the particles are subjected to relatively uniform contact forces while non-uniform force chains exist near the four corners. The area with uniform force chains are around 60 to 70% of the model and the value agrees with the findings by Lucks et al. (1972). In addition, the spatial variation of force chains is insensitive to shear strain level although the magnitude of force chains varies during shearing.

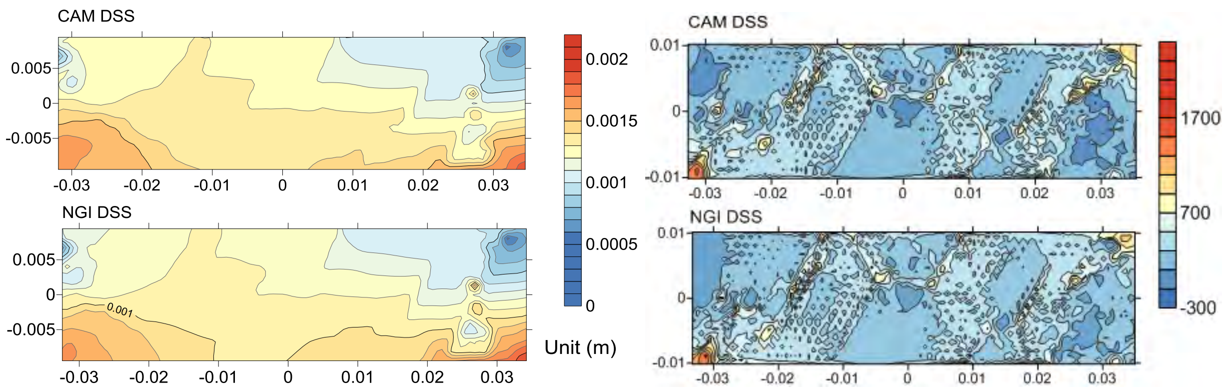


(a) = 1%　　　(b) γ = 8%

Fig. 7 Force chains at two shear strain levels

The boundary effects for NGI and CAM models are shown in Fig. 8 in terms of spatial variations of particle horizontal displacement and normal contact force. Comparisons of particle responses between the two models reveal that the differences between the two models are small. In an idealized continuum, the horizontal displacement should vary linearly along the vertical direction for strain-controlled testing with a fixed top cap. However, this trend only observes in the narrow zone near the two vertical boundaries (Fig. 8(a)). In the core zone of the model, a relatively uniform distribution of particle horizontal displacements was shown and disagreed with the continuum mechanics framework. Nevertheless, a uniform shear strain distribution will be expected.

The contact forces in particulate mechanics are related to the local stress distribution in a continuum analysis. The distributions of normal contact force are shown in Fig. 8(b). Concentrations of normal force occurred at the lower-left and upper-right corners. Unlike the distribution of horizontal particle displacement, approximately parallel bands of uniform force were observed within the specimen. In general, a consistent force transferring pattern was observed within the majority portions of the specimen. This trend reflects that the DEM is better in stress/force simulation than the deformation/ displacement due to the assumptions behind the contact conditions.



(a) Horizontal displacement　　　(b) Normal contact force

Fig. 8 Comparison of particle responses between NGI and CAM DSS models

4.2 DSS specimen size effect

Previous studies had shown that the deviation of induced shear strain near the specimen boundaries reduced as the H/D decreased (e.g. Shen et al. 1978, Vucetic and Lacasse 1982). To investigate the specimen size effect on idealized granular assemblies, simulations of different specimen diameters with a constant height are conducted. Three numerical models with height to diameter ratios (H/D) of 0.2, 0.3 and 0.4 were sheared to 8% of shear strain under a vertical stress of 300 kPa.

The distributions of particle horizontal displacement, normal contact force, and shear contact force for the three H/D ratios at 8% of shear strain are shown in Fig. 9. The displacement gradients near the two side walls are much higher than the ones in the core of the specimen and the displacement gradient in the core zone reduces significantly as the H/D ratio decreases. The deviation in displacement gradient indicates that a different shear strain field in the specimen. Comparisons of the horizontal displacement distribution reveal that the percentage of consistent shear strain area increases as the H/D ratio decreases.

The contact force distributions in a particle system are related to the magnitude of stress field in a continuum system. A uniform distribution of contact forces generally represents a relatively uniform stress field. However, the stresses in a continuum is different from the contact forces due to the directions of normal and shear stresses in a continua element is different from the normal and shear directions at a contact point. Fig. 9(b) shows that the distribution of normal contact force is very similar to the distribution of horizontal displacement with higher gradients near the four corners than the ones in the core zone. Consequently, volumetric percentage of uniform contact forces increases as the H/D ratio decreases. The difference in distribution of contact shear force for different H/D ratios is insignificant. Since the shear contact shear force will cause rotation of the particle, a uniform distribution of the contact shear force indicates that the particles in the specimen rotate uniformly. The DEM simulations for different H/D ratios agrees with previous experimental findings by Vucetic and Lacasse (1982) and Amer et al. (1987), showing that uniformity of stress distribution increases as the H/D ratio decreases.

4.3 Effects of maximum diameter of particle size for DSS

Experimental studies show that the frictional angle of granular soils decreases as the maximum particle size (d_{max}) increases (e.g., Kirkpatrick 1965, Marachi et al. 1972). For simple shear testing, the d_{max} will affect the width of shear band. To reduce the inconsistency of testing result in direct simple shear from d_{max}, the height of specimen must be at least 10 times of the maximum particle size (ASTM 2007). The effects of specimen size are more important for testing colluvium materials due to the existence of large particles.

To systematic study the effects of d_{max} on simple shear results, series of DEM simulations with different values of d_{max} were conducted. A Gaussian distribution of particle size is generated by assigning the minimum radius of 0.075 mm and the radius ratio defined as the maximum to minimum diameter ratio. The results for specimens with a height of 30 mm and H/D ratios of 0.20, 0.30 and 0.40 are presented in Fig. 10. The results show that the d_{max} affects both the initial modulus and the shear strength when the value of H/d_{max} below certain value. For a constant H/D ratio, the stress-strain curves with different d_{max} merged to a curve as the d_{max} decrease. The relationships among H/D ratio, shear stress at 8% of shear strain, and H/ d_{max} are shown in Fig. 11. The results reveal that a consistent shear resistance is available as the H/ d_{max} value

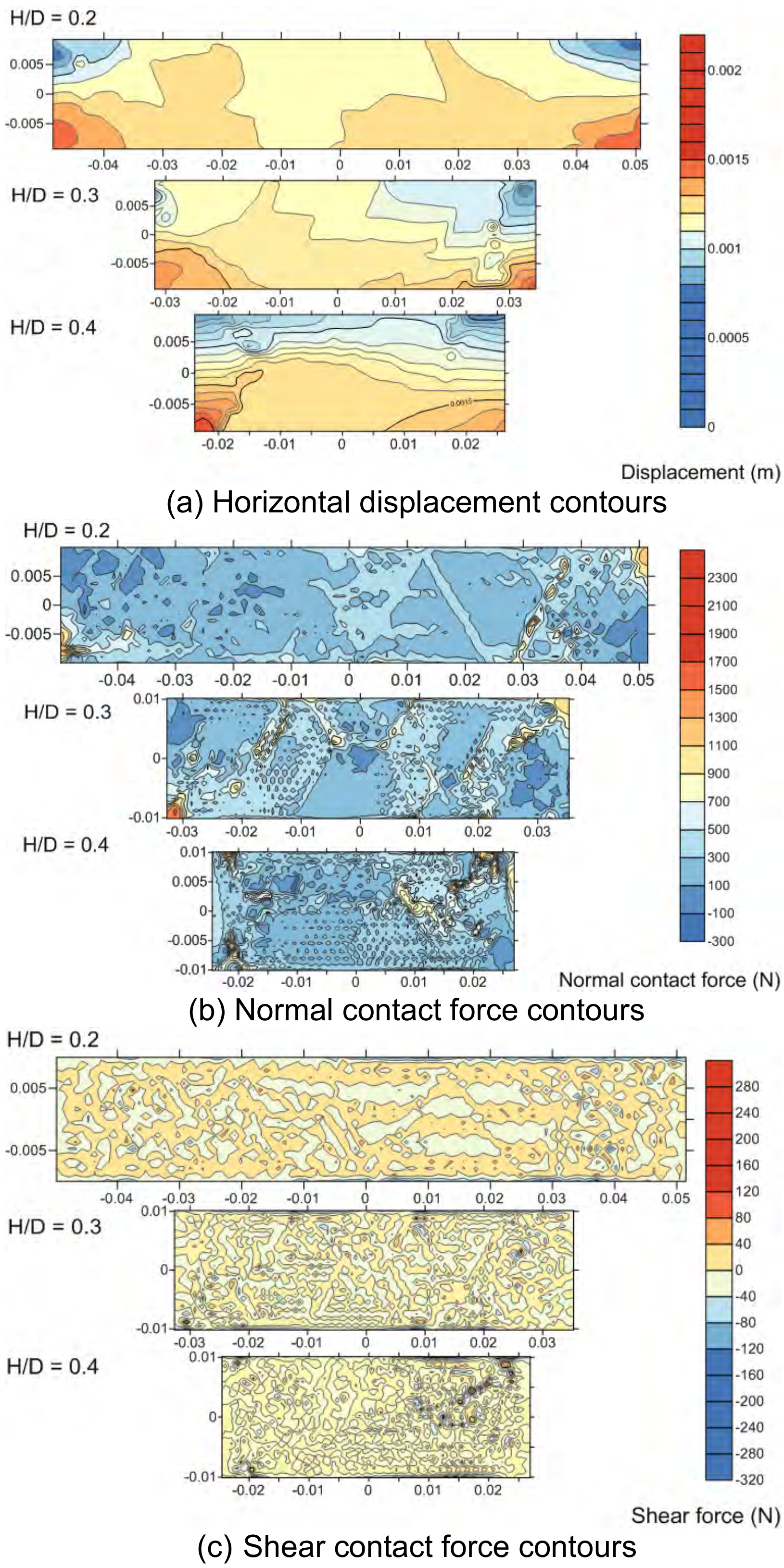


Fig. 9 DEM results for different height to diameter ratios

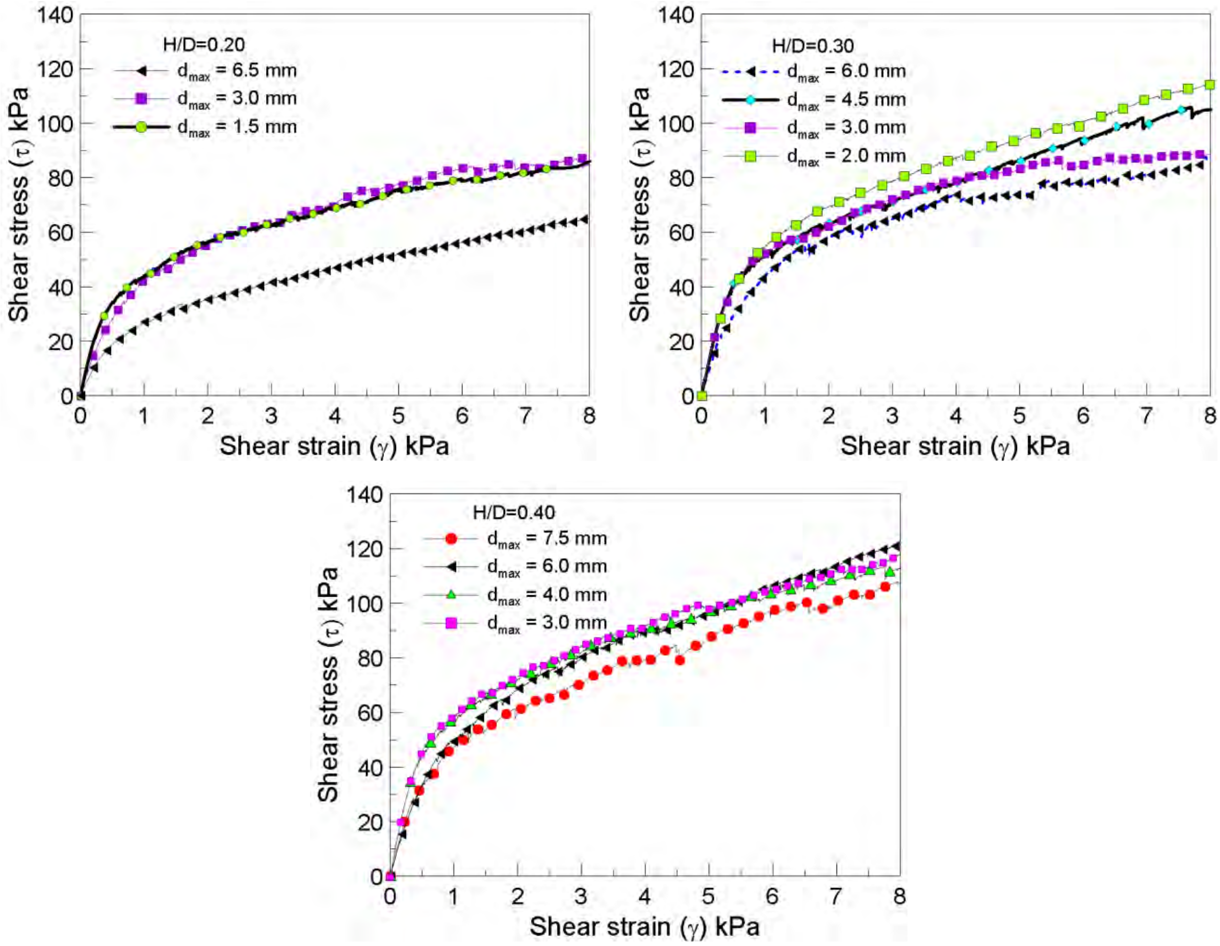


Fig. 10 DEM simulation results for different maximum particle sizes and H/D ratio

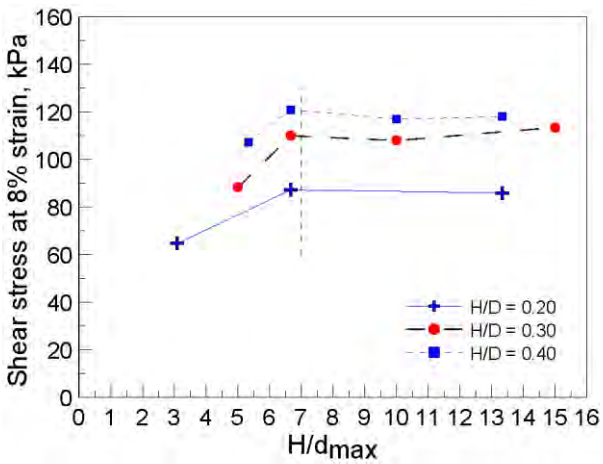


Fig. 11 Shear stress at 8% versus H/d_{max}

no less than 7, regardless of the H/D ratio. For specimen with H/d_{max} value less than 7, the shear stress is underestimated. In addition, the difference of shear resistance for different H/D reduces as the H/D value decreases. These results provide the criteria to determine the specimen size of granular soils for consistent DSS results.

5. CONCLUSIONS

To determine the specimne size of direct simple shear testing for colluvium soils, seies of DEM simulations were conducted to investigate the boundary and size effects for NGI and Cambridge type DSS configurations. The DEM models are calibrated using DSS data on steel ball. Findings are summarized as followings:

(1) The boundary effects can be reduced effectively by reducing the H/D value.
(2) The difference in boundary effect is insignificant between the Cambridge and NGI types of direct simple shear.
(3) A consistent shear resistance is available when the ratio of specimen height to the maximum particle size (H/d_{max}) is no less than 7, regardless of the H/D value.

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