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EFFECTS OF SOIL FABRIC ON UNDRAINED BEHAVIOR OF SANDS

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ABSTRACT: The undrained behavior of sands in monotonic triaxial compression and extension tests was simulated using the Distinct Element Method (DEM). Soil specimens were prepared at different initial soil fabrics but at similar void ratios and the effects of soil fabric on the undrained behavior were investigated. The DEM results show that soil fabric and its change have profound effects on the undrained response of sands. They also provide some insights for the interpretation of the published experimental data that show the effects of specimen reconstitution methods and of preshearing on the undrained behavior of sands.

INTRODUCTION

Soil fabric has been recognised as one of the factors affecting the undrained response of sands. The observed effects of specimen reconstitution methods and of preshearing on undrained behavior of sands have been suggested to result from the soil fabric (e.g. Finn et al., 1970; Ishihara and Okada, 1982). Although the physical interpretation of the experimental results as the effects of soil fabric is widely appreciated, its effects have not been explicitly explained from the micromechanics' point of view. This study investigates the effects of soil fabric on the undrained response of sands using the Distinct Element Method (DEM). Direct study of the soil fabric by DEM analysis can yield some insights into how it affects the undrained response of sands.

In this study, isotropically consolidated undrained monotonic triaxial compression and extension tests were simulated by the DEM. Specimens were sheared from almost identical void ratio and isotropic confining stress with different initial soil fabrics, which were created by applying different modes of preshearing process. The DEM analysis results show that the undrained behaviors are different among the specimens with different initial fabric conditions. The numerical analysis results were compared qualitatively to the published experimental data that show the effects of sample reconstitution methods and of preshearing on the undrained behavior of sands. The microscopic interpretation introduced in this study can systematically describe the undrained response of sands observed in the experiments.

SOIL FABRIC

Soil fabric is a term used to represent the arrangement of particles and associated voids in a soil mass. Oda (1972a) suggested two sub-concepts of soil fabric, i.e. (i) orientation of an individual particle and (ii) position of the particle and its mutual relationship to other particles. The orientation of individual particles can be characterised by the spatial distribution of the long axes of the particles, whereas the mutual relationship to other particles can be characterised by the distribution of the contact normals. In this study, only the contact normal distribution represents the soil fabric because spherical particles were used in the DEM analysis. Oda (1972b) also suggested that the contact normal distribution is a more meaningful parameter than the long-axes distribution.

In this study, the fabric tensor is introduced as an index to describe the soil fabric quantitatively. According to Oda and Nakayama (1988), the second-order fabric tensor F_{ij} is defined as;

$$F_{ij} = \int_{\Omega} n_i n_j E(n) d\Omega \qquad (1)$$

or;

$$F_{ij} = \int_0^{2\pi}\int_0^{\pi} n_i n_j E(\gamma,\beta) \sin\gamma d\gamma d\beta \qquad (2)$$

where n_i is the contact normal in i-direction, $E(n)$ is the contact normal distribution function (spatial probability density function of n), Ω is the unit sphere, $d\Omega$ is the elementary solid angle as defined in Fig. 1, and γ and β angles are also defined in Fig.1.

Using the coordinate systems defined in Fig. 1, n_i can be described as;

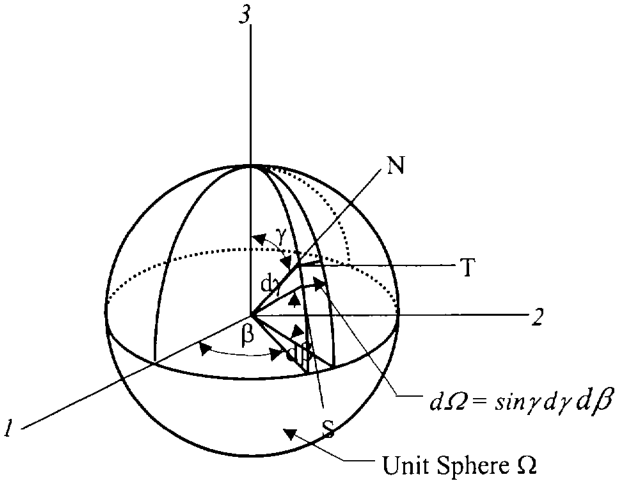

Fig. 1. Elementary Solid Angle and Reference Axes of Global and Local Coordinate Systems

$$n_i = \begin{bmatrix} \sin\gamma\cos\beta \\ \sin\gamma\sin\beta \\ \cos\gamma \end{bmatrix} \tag{3}$$

In the case of a cross-anisotropic fabric with its axis of symmetry along the vertical axis (the 3-axis in Fig. 1), $E(\gamma,\beta)$ can be approximated by the following Fourier series (Chang et al., 1989).

$$E(\gamma,\beta) = \frac{3(1 + a\cos 2\gamma)}{4\pi(3-a)} \tag{4}$$

where a is the degree of fabric anisotropy ($-1 < a < 1$). Eq. (4) has the symmetry $E(\pi+\gamma) = E(\gamma)$ and is independent of β.

The contact normal distribution functions according to Eq. (4) for different a values are shown in Fig. 2. When $a>0$, the contact normals of the particles in the assembly tend to concentrate in the vertical direction (*3*-direction), whereas, when $a<0$, they tend to concentrate in the horizontal directions (*1*- and *2*-directions).

By substituting n_i (Eq. (3)) and $E(\gamma,\beta)$ (Eq. (4)) into Eq. (2) and completing the integration, the fabric tensor F_{ij} is obtained as shown in Eq. (5). It can be seen that the soil fabric in the cross-anisotropic condition is represented by only single parameter a.

$$F_{ij} = \begin{bmatrix} \frac{3a-5}{5(a-3)} & & \\ & \frac{3a-5}{5(a-3)} & \\ & & \frac{-(5+a)}{5(a-3)} \end{bmatrix} \tag{5}$$

In the DEM numerical analysis, the contact normal distribution data can be directly obtained and the fabric tensor can be derived according to the following equation, which is a limited form of Eq. (1).

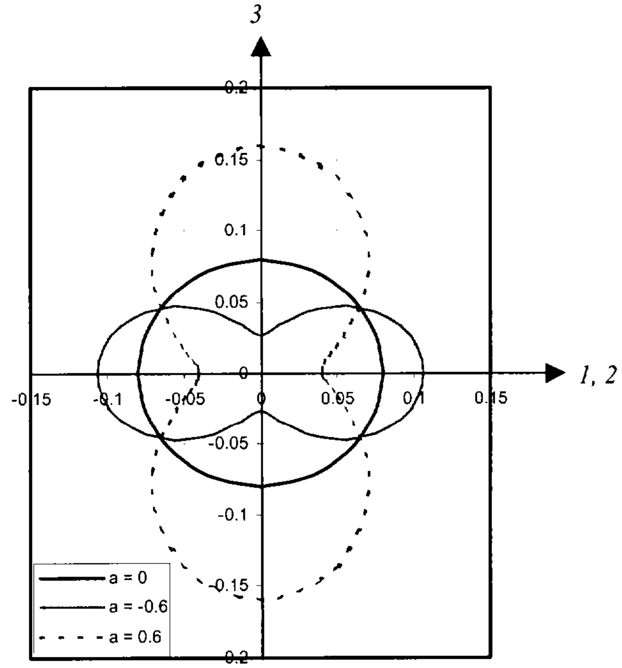

Fig. 2. Contact Normal Distribution Function

$$F_{ij} = \frac{1}{N_c}\sum_{N_c} n_i n_j \tag{6}$$

where N_c is the number of contacts.

By comparing the fabric tensor from the DEM analysis (Eg. (6)) to the analytical form (Eg. (5)), the degree of fabric anisotropy a can be obtained and its evolution during undrained shearing can be examined. It is found that the fabric tensor numerically derived from the DEM analysis by Eq. (6) fits well to the analytical form of fabric tensor in Eg. (5), which is derived from an assumption of cross-anisotropic contact normal distribution function in Eq. (4).

DISTINCT ELEMENT METHOD ANALYSIS

Introduction

The Distinct Element Method (DEM), which was originally introduced by Cundall and Strack (1969), is a numerical analysis that is capable of simulating the interaction of the assembly of particles of any shape (normally discs and spheres) and was first developed for the analysis of rock mechanics problems. In the DEM, the interaction of the particles is view as a transient problem with states of equilibrium developing whenever the internal forces balance. The equilibrium of contact forces and displacements of a stressed assembly of particles are found through a series of calculations tracing the movements of the individual particles. These movements are the result of propagation through the medium of disturbance originating at the boundaries. The important characteristic of the distinct element method is allowing finite displacements and rotations of discrete bodies, including complete detachment and ability to recognise new contact automatically as the calculation progress. The numerical simulation by the DEM can provide the micromechanical information, some of which are cumbersome to derive from the physical modelling, such as particle movement and rotation, contact forces, contact directions, particle velocities, number of contacts, and energy information.

In this study, isotropically consolidated undrained triaxial compression and extension tests are simulated by the DEM software PFC3D by *Itasca* (Itasca, 1995). A cubical assembly of uniform-sized spheres contained within six rigid walls is used to simulate sand specimens in the triaxial testing condition and the boundary effects observed in the actual tests are ignored. The input properties of the simulation are summarised in Table 1. The triaxial tests are simulated by moving the six rigid walls in a specific strain-rate for the strain-controlled condition or by keeping constant stress using servo-controlled for the stress-controlled condition. The undrained condition is achieved by keeping the volume constant during shearing. The constant-volume condition is done by keeping the strains in both of the horizontal directions equal to opposite of half of the strain in the vertical direction (zero volumetric strain). The axial stress σ_a' and radial stress σ_r' calculated from the DEM are in terms of effective stresses, as they are fully transmitted through inter-particle contacts. Under an assumption of fully saturated condition, the excess pore water pressure Δu can be calculated from the DEM as $\Delta u = \sigma_o - \sigma_r'$ (see Fig. 3). Other effective stress parameters are defined as $p'=(\sigma_a'+2\sigma_r')/3$ and $q=\sigma_a-\sigma_r$.

The contact model employed in this analysis is a simple linear elastic contact model. Although, the linear elastic contact model cannot correctly predict the small-strain behavior, it is considered acceptable here since the intermediate and large strain behavior is of interest at which the particle slippage and rotation are more dominant than interaction at the particle contacts.

Table 1 DEM simulation properties

Number of particles	3545
Radius of particles	4.0 cm
Initial specimen size	1.2 m × 1.2 m × 1.2 m
Initial void ratio	0.75~0.76
Particle density	2700 kg/m^3
Inter-particle friction angle	63°
Particle-wall friction angle	0° (smooth wall)
Contact model	Linear elastic
Normal contact stiffness	1.0×10^8 N/m
Shear contact stiffness	1.0×10^8 N/m
Wall normal stiffness	1.0×10^8 N/m
Wall shear stiffness	0 (no wall shear stiffness)

Numerical analysis procedures

The triaxial testing procedures performed in the simulation are described as follows. A specimen is numerically prepared by filling the predetermined number of particles into the required cubical space and then expanding the spheres radially to a specific value so that a predetermined void ratio of the specimen can be obtained. This specimen preparation method has some advantages over wall-moving because it provides a more isotropic and uniform specimen, requires less time to reach equilibrium, and preserves the boundary geometry (Itasca, 1995). The assembly of particles after the specimen set-up is shown in Fig. 4. The specimen is initially isotropically consolidated to p'=1 MPa. Then the specimen is subjected to undrained preshearing before isotropically reconsolidating back to p' = 1 MPa. In order to obtain two

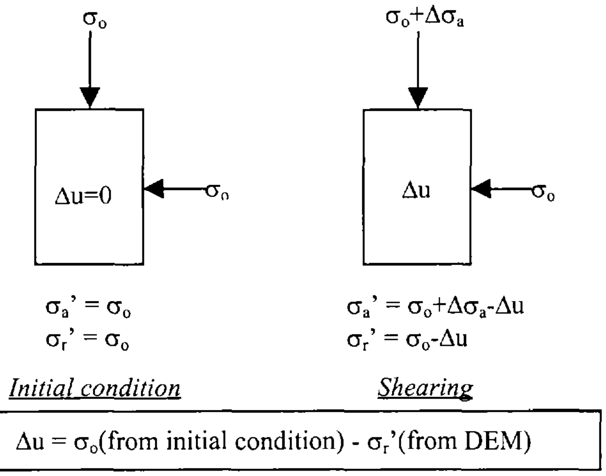

Fig. 3. Calculation of Δu from constant-volume test in DEM

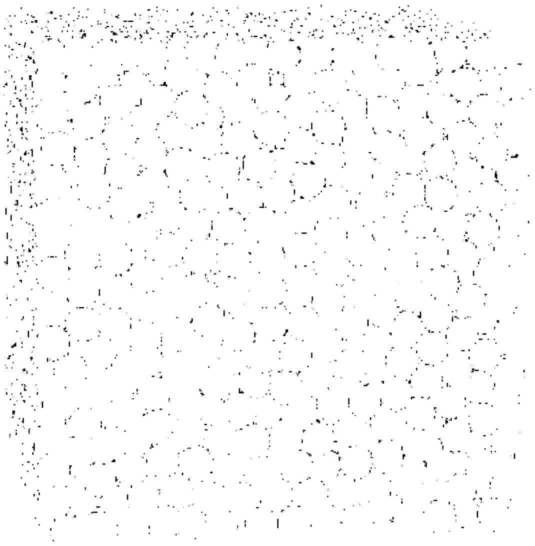

Fig. 4. Assembly of particles after specimen set-up by radius expansion (walls are omitted)

different anisotropic fabric conditions, we employed two types of undrained preshearing, i.e. compression and extension preshearing. Finally, the specimens which are at the same isotropic stress and have similar void ratio (e = 0.75-0.76) but with different fabrics (a varying from –0.12 to 0.09) are monotonically sheared in compression and extension in the constant-volume condition.

During the analysis, the data of contact normal distribution are analysed to obtain the degree of fabric anisotropy a following the procedures described earlier to characterise the fabric condition and its evolution.

Macroscopic stress and strain in the DEM analysis are defined differently from continuum mechanics. Stress is derived from the contact forces between the particles using Eq. (7) (Christoffersen et al., 1981).

$$\sigma_{ij} = \frac{1}{V}\sum_{N_c} x_i f_j \tag{7}$$

where N_c is number of contacts in volume V, x_i is location vector of the contact, and f_j is contact force. Strain is derived from the movement of the six walls. The compressive stress and strain are positive. The gravitational force is neglected.

Numerical analysis results

The conditions of the specimens after undrained preshearing and before undrained shearing are summarized in Table 2. The compression preshearing makes the contact normals concentrate in the vertical direction (ANISO1: a>0), whereas the extension preshearing makes the contact normals concentrate in the horizontal direction (ANISO2: a<0). The results of the undrained compression and extension shearing are shown in Fig. 5 ((a) stress paths, (b) deviatoric stress vs. axial strain, (c) excess pore pressure vs. axial strain, and (d) changes in fabric anisotropy a with axial strain). The numerical results show that the initial soil fabric can have profound effects on the undrained behavior. The specimen, which has been presheared in compression (contact normals concentrate in the vertical direction), is stiffer and more dilative in compression, but weaker and more contractive in extension. On the other hand, the specimen, which has been presheared in extension (contact normals concentrate in the horizontal direction), is stiffer and more dilative in extension, but weaker and more contractive in compression. The evolution of a during undrained shearing reveals that the soil fabric changes itself to best resist the applied stress; the contact normals tend to concentrate in the major principal stress direction (the vertical direction in compression and the horizontal direction in extension shearing). The initial fabric effect diminishes at large strains. The measured change in soil fabric during shearing is consistent with the experimental results by Oda (1972b) and also similar to the DEM analysis by Rothennerg and Batherst (1989).

Table 2 Conditions of the specimens before undrained shearing

Specimen	Initial void ratio, e_0	Initial degree of fabric anisotropy a_o	Initial mean effective stress, p_o' (MPa)	Initial deviatoric stress, q_o (MPa)
ISO	0.757	0.01	1.05	-0.04
ANISO1	0.752	0.09	1.06	-0.01
ANISO2	0.762	-0.12	0.99	-0.09

DISCUSSIONS

The numerical analysis results presented here are consistent with the published experimental data in both microscopic and macroscopic aspects. From the microscopic perspective, the results can be compared with the published data concerning the effect of specimen reconstitution methods on undrained behavior of sands. From the macroscopic perspective, the results can be compared with the published data concerning the effect of preshearing.

The DEM analysis shows that the specimen, which has contact normal distribution concentrating in the vertical direction, has higher stiffness and is more dilative when subjected to subsequent compression shearing. However, it has lower stiffness and is more contractive when subjected to subsequent extension shearing. This is consistent with the published data of the effect of specimen reconstitution methods on the mechanical behavior of sands based on microscopic studies (e.g. Oda, 1972 a,b; Mahmood and Mitchell, 1974; Mahmood et al., 1976; and Mulilis et al., 1977) and on mechanical studies (e.g. Oda, 1972b; Ladd, 1974, 1977; Silver et al., 1976, Mulilis et al., 1977; and Lee, et al., 1999). These studies indicate that the contact normal distribution characteristic has a major influence to the mechanical behavior of sands. In the case of undrained triaxial compression, when the contact normals of a soil are concentrated in the vertical (direction of subsequent loading), the stiffness, strength, and cyclic stress ratio increase and it becomes dilative. These observations are based on the data from triaxial compression tests only. Our DEM study shows that the opposite is true in triaxial extension. However, there is no available data in the literature to confirm this. Nevertheless, Ladd (1977) suggested that a preferred fabric orientation, which yields a higher static strength in compression, does not necessarily yield a higher static strength in extension.

The DEM results show that the specimen, which was presheared in compression, has higher stiffness and is more dilative when subjected to subsequent compression shearing, whereas it has lower stiffness and is more contractive when subjected to subsequent extension shearing. On the other hand, the specimen, which has been presheared in extension, has higher stiffness and is more dilative when subjected to subsequent extension shearing, but it has lower stiffness and is more contractive when subjected to subsequent compression shearing. This finding is consistent with the experimental data on the effect of large strain preshearing on the subsequent undrained behavior of sands reported by several researchers. Ishihara and Okada (1978, 1982) showed that subsequent liquefaction response of sands, which has been liquefied previously, depends not only on the magnitude of preshearing but also more significantly on the direction of the preshearing. Vaid et al. (1989) showed that large prestraining makes the soil become more dilative in reloading without strain reversal but more contractive in reloading with strain reversal. Our DEM results agree with these observations that the specimen subjected to large preshearing on one side of triaxial loading, compression or extension, has higher stiffness on that side but lower stiffness on the opposite side during subsequently shearing.

CONCLUSIONS

In this study, the effects of soil fabric on the undrained behavior of sands are numerically investigated using the DEM. The results show that soil fabric has a profound influence on the undrained response of sand. Soil specimens with the same void ratio and under identical initial confining stress can exhibit different behaviors depending on their initial soil fabrics. The numerical results obtained are qualitatively consistent with the published experimental data on the effect of specimen reconstitution methods and of preshearing on the mechanical behavior of sands especially in the undrained condition. The experimental observations can systematically be explained through the soil fabric and its change during shearing. Perhaps the origin of the effect of specimen reconstitution methods and of the effect of preshearing is actually the same which results from soil fabric condition. This study coupled with the experimental evidence re-emphases the necessity to take into account of the effect of soil fabric when undrained or liquefaction behavior of sands in the field is evaluated from their reconstituted specimens.

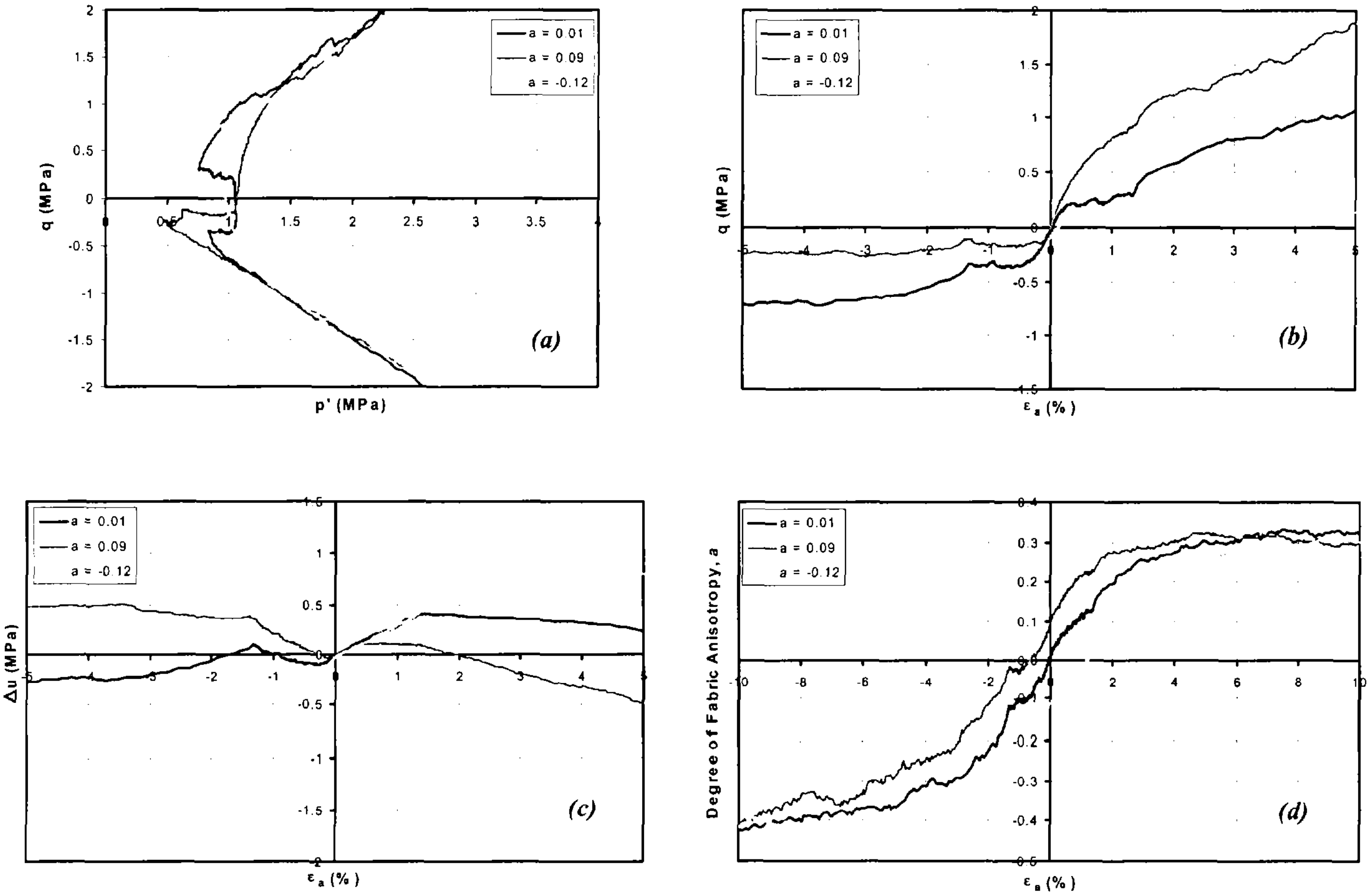

Fig. 5. DEM results of undrained triaxial compression and extension shearing: (a) stress paths, (b) deviatoric stress vs. axial strain, (c) excess pore pressure vs. axial strain, and (d) degree of fabric anisotropy vs. axial strain

REFERENCES

Chang, C. S., Sundaram, S. S., and Misra, A. (1989), "Initial moduli of particulated mass with frictional contacts", *Int. J. for Num. and Anal. Methods in Geo.*, Vol. 13, pp. 629-644

Christoffersen, J., Mehrabadi, M. M., and Nemat-Nasser, S. A. (1981), "A micromechanical description of granular material behavior", *J. of App. Mech.*, ASME, Vol. 48(2), pp. 339-344

Cundall, P. A. and Strack, O. D. L. (1979), "A discrete numerical model for granular assemblies", *Geotechnique* 29(1), pp. 47-65

Finn, W. D. L., Bransby, P. L., and Pickering, D. J. (1970), "Effect of strain history on liquefaction of sand", *J. of Soil Mech. and Found. Div.*, ASCE, Vol. 96(SM6), pp. 1917-1934

Ishihara, K. and Okada, S. (1978), "Effects of stress history on cyclic behavior of sand", *Soils and Found.*, Vol. 18(4), pp. 31-45

Ishihara, K. and Okada, S. (1982), "Effects of large preshearing on cyclic behavior of sand", *Soils and Found.*, Vol. 22(3), pp. 109-125

Itasca Consulting Group (1995), *PFC3D Manual*, Vol. I, II, III

Ladd, R. S. (1974), "Specimen Preparation and Liquefaction of Sands", *J. of Geotech. Eng. Div.*, ASCE, Vol. 100(GT10), pp. 1180-1184

Ladd, R. S. (1977), "Specimen Preparation and Cyclic Stability of Sands", *J. of Geotech. Eng. Div.*, ASCE, Vol. 103(GT6), pp. 535-547

Lee, K. M., Shen, C. K., Leung, D. H. K., and Mitchell, J. K. (1999), "Effects of Placement Method on Geotechnical Behavior of Hydraulic Fill Sands", *J. of Geotech. and Geoenviron. Eng.*, ASCE, Vol. 125(10), pp. 832-946

Mahmood, A. and Mitchell, J. K. (1974), "Fabric-property relations in fine granular materials", *Clays and Clay Minerals*, Vol. 22, pp. 397-408

Mahmood, A., Mitchell, J. K., and Lindblom, U. (1976), "Effect of Specimen Preparation Method on Grain Arrangement and Compressibility in Sand", *Soil Specimen Preparation for Laboratory Testing*, ASTM STP 599, pp. 169-192

Mulilis, J. P., Seed, H. B., Chan, C. K., Mitchell, J. K., and Arulanandan, K. (1977), " Effect of Sample Preparation on Sand Liquefaction", *J. of Geotech. Eng. Div.*, ASCE, Vol. 103(GT2), pp. 91-108

Oda, M. (1972a), "Initial fabrics and their relations to mechanical properties of granular material", *Soils and Found.*, Vol. 12(1), pp. 17-36

Oda, M. (1972b), "The mechanism of fabric changes during compressional deformation of sand", *Soils and Found.*, Vol. 12(2), pp. 1-18

Oda, M. and Nakayama, H. (1988), "Introduction of inherent anisotropy of soils in the yield function", in *Micromech. of Granular Materials*, Eds. Satake&Jenkins, Elsevier, pp. 81-90

Rothenburg, L. and Bathurst, R. J. (1989), "Analytical study of induced anisotropy in idealized granular materials", *Geotechnique* 39(4), pp. 601-614

Silver, M. L., Chan, C. K., Ladd, R. S., Lee, K. L., Tiedemann, D. A., Townsend, F. C., Valera, J. E., and Wilson, J. H. (1976), "Cyclic Triaxial Strength of Standard Test Sand", *J. of Geotech. Eng. Div.*, ASCE, Vol. 102(GT5), pp. 511-523