Effect of confining pressure on the strength behaviour of granular material simulated by the discrete element method

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Abstract: Numerical simulation tests using the Discrete Element Method (DEM) were carried out to investigate the stress-strain-dilatancy response of granular materials, giving special emphasis to the confining pressure. Three randomly generated samples were selected using a computer code and were placed in circular discs in a square loading frame. The assembly was isotropically consolidated, and then strain-controlled biaxial compression tests were carried out. These were undertaken to investigate the effect of confining pressure on the mechanical behaviour of granular materials. The stress-strain and volumetric curves show good agreement with the behaviour of granular materials like sands. With an increase in confining pressure, failure stress increases, while dilatancy is reduced. The maximum dilatancy index occurs at the peak stress level.

Résumé: Des essais numériques de simulation employant la méthode discrète d'élément (DEM) ont été effectués pour étudier la réponse d'soumettre à une contrainte-contrainte-épaississement des matériaux granulaires, donnant la considération particulière à la pression d'emprisonnement. Trois échantillons aléatoirement produits ont été choisis en utilisant un code machine et ont été placés dans les disques circulaires dans une armature carrée de chargement. L'assemblée a été isotropically consolidée, et alors des essais de compressibilité biaxiales contrainte-commandés ont été effectués. Ceux-ci ont été entrepris pour étudier l'effet de confiner la pression sur le comportement mécanique des matériaux granulaires. La contrainte-tension et les courbes volumétriques montrent la bonne concordance avec le comportement des matériaux granulaires comme des sables. Avec une augmentation de pression d'emprisonnement, augmentations d'effort d'échec, alors que l'épaississement est réduit. L'index maximum d'épaississement se produit au niveau maximal d'effort.

Keywords: Numerical models, cohesionless materials, properties, shear stress, strain, biaxial loading.

INTRODUCTION

The Discrete Element Method (DEM) is recognized as a powerful tool for studying a wide range of problems. Amongst these is the mechanical behaviour of granular materials, from macro to micro scales. The method was pioneered by Cundall (1971) for rock mass problems and was later extended to soils (Cundall & Strack 1979). This numerical technique provides an excellent means to investigate the micro-mechanics of granular materials, and has been used to investigate micro-deformation mechanisms of shear bands (Bardet & Proubet 1991; Oda & Iwashita 2000), the effects of particle rotation and the angle of inter-granular friction (Ng 1994), sample preparation methods and stress path (Ng 2004), and coordination number (Rothenburg & Kruyt 2004). However, little work appears to have been carried on the effect of confining pressure on the stress-strain response of granular materials, and this is the focus of the present numerical study.

It is already well known from experimental study (e.g. Sitharam 1999) that confining pressure has some effect on the strength behaviour of granular materials, but experimentation is limited in the extent to which it can investigate micro-mechanical behaviour in samples. Although Sitharam (1999) studied the effect of confining pressure on particulate materials, he did not consider dilative behaviour in detail. DEM is therefore used here to study the effect of confining pressure on the stress-strain-dilative behaviour of granular materials.

BIAXIAL COMPRESSION TEST

Sample Preparation

Sample preparation comprised two phases: initial particle generation and then densification (isotropic consolidation). In the first phase, three assemblies, were randomly generated, each in a square frame of 175 cm x 175 cm size containing 1000 particles, and with radii respectively of 4 mm, 5 mm and 6 mm.

Deformation of the particle assembly was controlled by four boundaries. The upper and lower boundaries moved vertically under strain-controlled conditions. The lateral (left and right) boundaries were 'flexible boundaries', composed of particles with radii of 8 mm that were linked in chains and could stretch or shrink like a membrane. No friction was permitted between the sample particles and the linked (boundary) particles. At their extremities, the linked particles could only move vertically with the upper and lower boundaries, but could move freely in the horizontal direction. The three different assemblies were then consolidated on the four boundaries. Three different uniform pressures, of 100 kPa, 150 kPa and 300 kPa respectively, were applied until stress oscillation was lowered to a negligible level. No gravitational force was applied during the consolidation so the particle arrangement after consolidation could be considered to be isotropic.

DEM Parameter and Material Properties

Discrete element analysis requires various parameters, e.g. normal, shear and rolling stiffness etc, to which the mechanical properties of the assembly are very sensitive. Selection of these parameters is very important, especially when results from numerical simulation tests are to be compared quantitatively with those from the laboratory tests. In this study, however, values for the parameters (constants) were chosen on a purely empirical basis as the study is intended to investigate the mechanical behaviour qualitatively rather than quantitatively. The parameters and materials used are shown in Table 1.

Table 1. DEM parameter and material properties

DEM parameters and material properties	Chosen Value
Number of particles	10,000
Radius of particles	4mm, 5mm, 6mm
Particle density	2600 kg/m^3
Incremental time Step	1.00×10^{-5} s
Frictional coefficient between particles	0.5
Frictional coefficient between particles and wall	0.0
Cohesion between particles	0.0 N
Normal spring constant	1.00×10^{8} N/m
Tangential spring constant	1.00×10^{7} N/m
Damping constant at the contact	0.05

Test Procedure

The three samples, DSFB100, DSFB200 and DSFSB300, were each tested under biaxial compression with flexible boundary conditions under constant consolidation pressures of 100 kPa, 200 kPa, and 300 kPa respectively. Vertical stress was increased incrementally, while the lateral i.e. confining, pressure remained constant. The experiment continued until oscillation was lowered to a negligible level. With each increment, calculations were performed and electronic data for stress, strain, volume, position of the particle, void ratio, coordination number etc. were recorded.

RESULTS AND DISCUSSION

Effect of Confining Pressure on Stress-Strain Response

To study the effect of confining pressure on the stress-strain behaviour of the granular assembly, a relationship between deviatoric stress (q) and equivalent deviatoric strain (e1-e2) was established (Figure 1) from the numerical data for the three samples. This relationship clearly shows an increase in failure stress due to the increase of confining pressure, but the peak stress occurs in all cases at a lesser strain than was observed in laboratory results. The microscopic frictional angles at peak stress were also found to be less than the microscopic frictional angle established in the laboratory (26.6°). However, qualitatively, the stress-strain response is in excellent agreement with the laboratory experimental results.

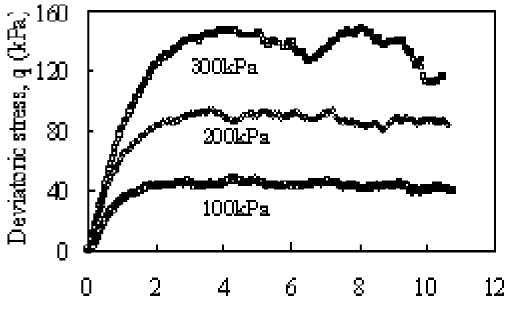

Figure 1. Deviatoric stress versus equivalent deviatoric strain for different confining pressure.

Effect of Confining Pressure on dilatancy of granular materials

To investigate the effect of confining pressure on the dilatancy of the granular materials, two relationships were established (Figures 2 and 3).

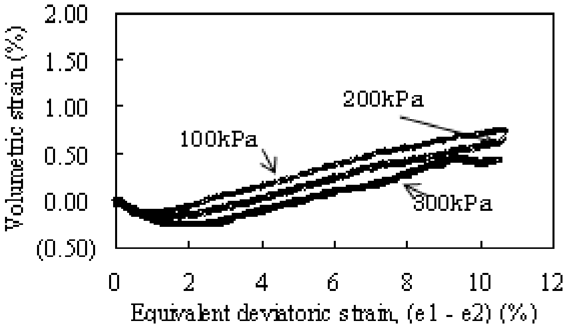

Figure 2. Relationship between volumetric strain and equivalent deviatoric strain

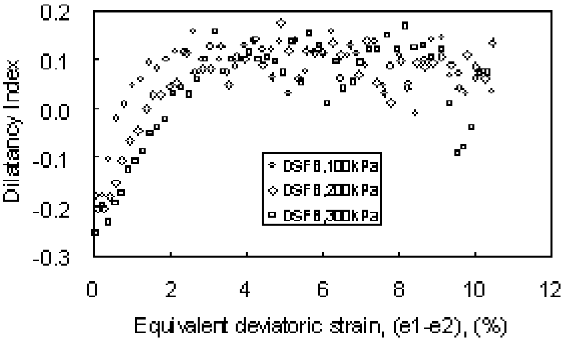

Figure 3. Relationship between dilatancy index and equivalent deviatoric strain

Figure 2 shows that with the increase in confining pressure, the dilatancy of the granular materials is reduced i.e., confining pressure has a significant effect on the reduction in dilatancy of a granular assembly. Figure 3 shows the relationship between dilatancy index and the equivalent deviatoric strain. The dilatancy index is the slope of the curve of volumetric strain versus the equivalent deviatoric strain with a negative sign, i.e.:

$$(-d\varepsilon_{vol} / d\bar{\varepsilon})$$

The dilatancy index is obtained at each equivalent deviatoric strain $\bar{\varepsilon}$ by dividing the volumetric strain increment

$\Delta\varepsilon_{vol}$ between $\bar{\varepsilon}-\frac{1}{2}\Delta\bar{\varepsilon}$ and $\bar{\varepsilon}+\frac{1}{2}\Delta\bar{\varepsilon}$.

From the Figures 1 and 3 there is a good correlation between dilatancy index and deviatoric stress. The dilatancy index reaches its maximum at peak stress level.

Effect of Confining Pressure on coordination numbers

The average number of contacts per particle is called the coordination number of the particle. Clearly, each physical contact contributes two contacts to the assembly. The average coordination number of the assembly is defined as the ratio of the total number of contact points within the assembly volume to the total number of particles in the assembly. With the increase in confining pressure, the initial specimen achieves a higher average coordination number and under shear it decreases with the increase in axial strain (Figure 4). It means that the collapse of the loose part of the specimen is higher than the formation of more inter-particle contacts.

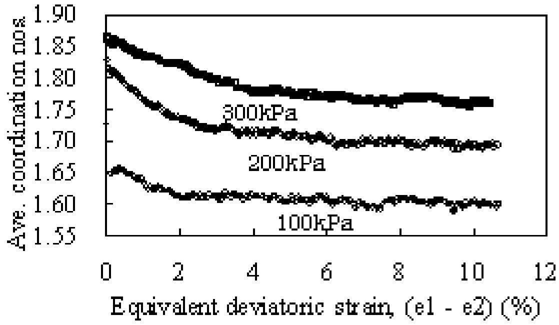

Figure 4. Average coordination numbers versus equivalent deviatoric strain

CONCLUSIONS

The following conclusions were reached:

(i) Confining pressure has a significant effect on the strength behaviour of granular materials. The failure stress increases with the increase in confining pressure. However, the peak stress occurs in all cases at a lesser strain than was observed in laboratory results and the microscopic frictional angles at peak stress were also less than the observed microscopic frictional angle (26.6°).

(ii) Dilatancy is reduced with increased confining pressure. The dilatancy index reaches its maximum at peak stress level.

(iii) With the increase in confining pressure, the initial specimen achieves a higher average coordination number while under shear it decreases with an increase in equivalent deviatoric strain.

Acknowledgements: The authors greatly acknowledged ADB-JSP for financial support of this study.

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