Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Distinct element analysis of sand under cyclic loading using oval elements

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ABSTRACT: The mechanism of the liquefaction and cyclic mobility phenomena of sand subjected to cyclic loadings has been investigated by Distinct Element Method (DEM). The element size is reduced nearly to the real particle size in order to approach the phenomena reasonably. In order to examine the effect of shapes of elements on the behavior of granular materials, circular elements and oval elements have been used. Simulations are performed for an assembly of particles under constant volume and subjected to either monotonic or cyclic shear stress. It was found that (a) DEM can be a useful tool for the investigation of liquefaction phenomena and (b) shape of particles affect the stress- strain behavior and liquefaction potential of the assembly.

1 INTRODUCTION

Finite Element Method (FEM) based on continuum mechanics theory has mostly been used for the analysis of soil behavior. However, FEM can hardly be extended for the analysis of large deformations. Yatomi et. al., (1989) has recently proposed a finite element numerical method for the simulation of shear band formation using non-coaxial Camclay model. In order to deal with large deformation problems, numerical models like Rigid Body Spring Model (RBSM) by Kawai (1980), Distinct Element Method (DEM) by Cundall et.al., (1971, 1979) have been proposed based on discontinuous body. Iwashita et. al., (1990) has proposed Modified DEM (MDEM) for the simulation of cliff collapse. Hakuno et. al., (1991) has also proposed Extended DEM (EDEM) to analyze a series of behavior of tunnel collapse and large movement of buried pipe. Sawada et. al., (1991) has also shown that DEM is a powerful tool for analyzing the intrinsic behavior (stress- strain- dilatancy behavior) of granular materials.

In almost all DEM analyses, circular elements has been used. Since most of the geo-materials are not rounded, it is necessary to know the effect of element shapes on the overall behavior. A microscopic view of a standard sand (Toyoura sand) is shown in Fig.1. The flatness ratio was measured considering the sand particles as oval elements and is shown in Fig.2. The average flatness ratio for this typical sand was 0.63.

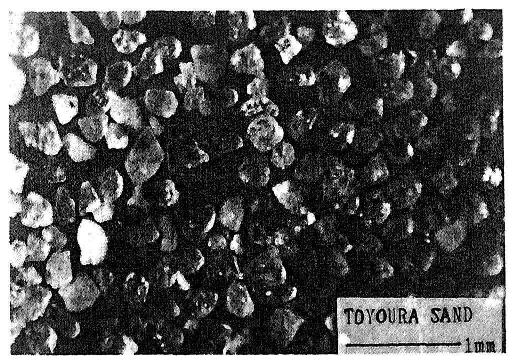


Fig.1 Microscopic view of Toyoura sand

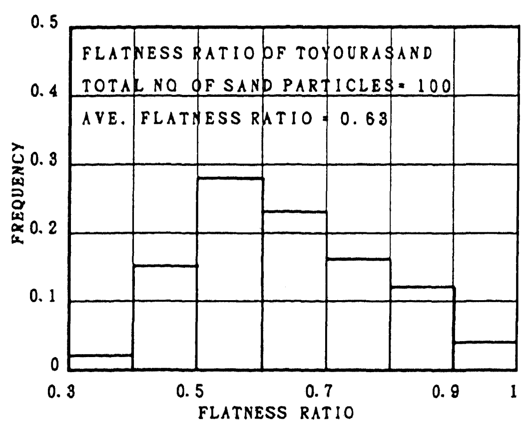


Fig.2 Flatness ratio of Toyoura sand

In this paper oval elements has been used in DEM analysis for the simulations of liquefaction and cyclic mobility phenomena and also to investigate on the effect of element shapes.

2 ANALYTICAL MODEL

DEM was originally developed by Cundall. The basic principle of this method lie on the numerical integration on time domain of the Newton's equation of motion with considering the equilibrium contact forces between each individual elements in an assembly of particles. Fig.3 shows the systematic diagram of the mechanical model for two particles in contact. Two Voigt's models are used in normal and tangential directions. The slider is governed by the Coulomb's friction law as shown in Fig.3, where c and ϕ_μ are the cohesion and the angle of inter-particle friction between two particles. The correlation between the stiffness (k), coefficient of viscosity (η), size of the element and the time increment has been discussed in Sawada et. al., (1991).

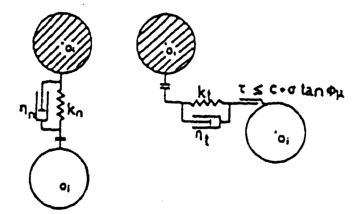


Fig.3 Systematic diagram of model

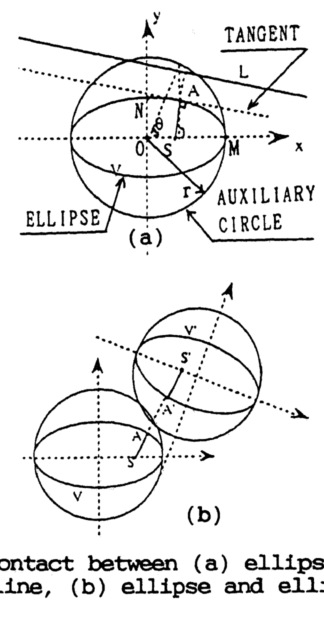


Fig.4 Contact between (a) ellipse and line, (b) ellipse and ellipse

The CPU time required for the analysis using the element shape other than circular one is comparatively very large. Most part of the CPU time is covered by the judgement of the contacts between individual particles. In this model a simple method has been used to judge the contact between two oval elements. As shown in Fig.4(a), consider an arbitrary point A($r\cos\theta, r\alpha\sin\theta$) on an ellipse V with flatness ratio α (=OM/ON; r=OM). A point S $\{r(1-\alpha^2)\cos\theta, 0\}$ on x-axis can be fixed from a normal line to the tangent at point A. Hence the slope $\delta(=\sin\theta/\alpha\cos\theta)$ and length $\{r\alpha\sqrt{(\sin^2\theta+\alpha^2\cos^2\theta)}\}$ of the line AS is determined. From the slope of a given boundary line L, slope δ of line AS can be determined and hence points A and S can be fixed. The judgement of contact between line L and ellipse V is done by comparing the length AS and the distance of the line L from the point S. In a similar way, the judgement of contact between ellipse V and ellipse V' (Fig.4(b)) is done by determining a fixed value of δ when AS and A'S' lie in the same line. In the calculation this judgement is done in two steps to save the time. First, the judgement of contacts between the two auxiliary circles is done. Next, the judgement of contact between two ellipses is done only for those whose auxiliary circles are in contact. By this way, the CPU time required for oval elements can be diminished to only four times compared with that for the circular ones.

In the simulations, 1000 elements (either oval or circular) are used with different sizes and having a mean diameter of 3mm. In order to have the same area, the long and short diameter of an oval element is multiplied and divided by $\sqrt{2}$ to the diameter of an equivalent circular element. The flatness ratio for all the oval elements is fixed to 0.5.

3 MODEL CONDITIONS AND PARAMETERS

A model specimen of width 8cm and height 12cm is formed by the free fall of particles under 1g. It is then one-dimensionally compressed by a specified initial vertical pressure. In this method, the boundary effect has been eliminated by combining the analytical regions in left and right boundaries.

The parameters $\{\Delta t, k_n, k_t, \eta_n, \eta_t, \phi_\mu\}$ used in the simulation is shown in Table 1. Cohesion c is zero.

4 SIMULATIONS

Simulations under constant volume simple shear conditions are performed for an assembly of particles (either oval or circular elements) subjected to either

Table 1 Model Parameters

Stiffness (N/m)	*10^7
Normal Direction k_n	6.6
Tangential Direction k_t	6.6
Coefficient of Viscosity (N·sec/m)	
Normal Direction η_n	200
Tangential Direction η_t	0.8
Angle of Inter-particle Friction $\phi\mu$ (deg)	27
Time Increment (sec)	$2*10^{-6}$
Total No. of Elements	1000

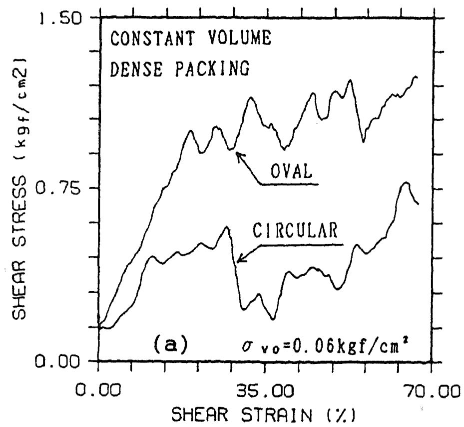
monotonic or cyclic loading conditions. According to Dyvik et. al., (1987) the change in applied vertical stress in a constant volume test is equal to the pore pressure which would be developed in an undrained simple shear test. Hence, the liquefaction or cyclic mobility process has been simulated by the change in the vertical stress during constant volume simulation.

4.1 Monotonic simple shear simulation

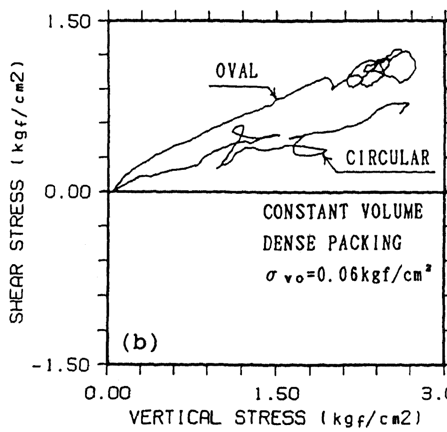
A dense packing of particles (either circular or oval) is compressed one dimensionally with an initial vertical stress of 0.06 kgf/cm^2 and sheared horizontally under a constant volume and constant rate of deformation conditions. Since the same way of packing has been adapted, model specimen of oval elements is somewhat looser than that of circular elements. Shear stress (τ), shear strain (γ) and vertical stress (σ_v) relations are shown in Figs 5(a), 5(b). Positive dilatancy (increase in σ_v) can be seen (Fig. 5(b)) from the beginning for both cases since the initial σ_v is quite small. The maximum angle of internal friction ϕ mobilized is about 30° and 20° for oval and circular elements respectively. ϕ for assembly of angular particles is greater than that for round particles was reported by Yoshimura et. al., (1991a) from experimental data.

Stick-slip behavior is more pronounced in case of circular elements as can be seen in Fig. 5(a). This tendency was also reported from experimental data.

The movements of particles for circular and oval elements at a shear strain of 30% are shown in Figs 6(a), (b). In both cases, the development of a clear shear zone (shear band) in the horizontal direction and the localization of strain can be seen. This tendency of generation of shear band in horizontal direction was also observed in torsional simple shear tests as reported by Pradhan et. al., (1988a). It can also be observed that in case of circular elements a wider range (zone) has been sheared as compared with that in case of oval elements. The ratio of width of shear zone to the mean diameter was found to be about 7.5 and 4.5 for the assembly of circular and oval elements respectively. Miura et. al., (1991) from experimental data has reported that the ratio is 20 for the assembly of round glass beads and 10 for Toyoura sand. The value of the ratio is different, however similar tendency could be observed from the simulation.

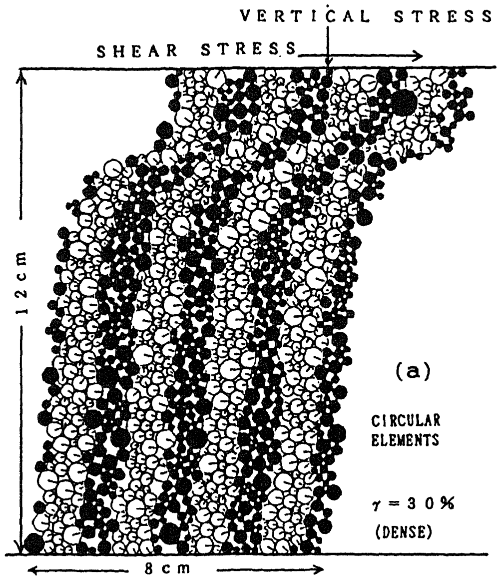


(a) stress- strain,

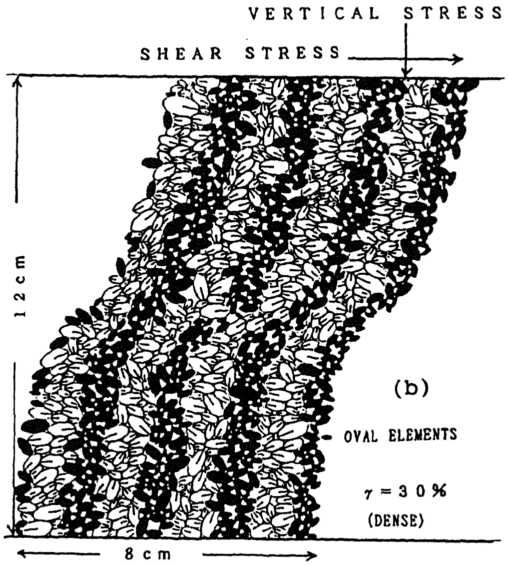


(b) stress-path,

Fig.5 Monotonic simple shear simulations



(a) circular,



(b) oval

Fig.6 Movements of particles during simple shear

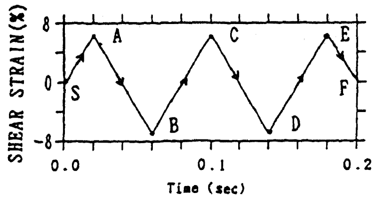


Fig.7 Strain history in cyclic shear

4.2 Cyclic simple shear simulations

Cyclic simple shear simulations under the condition of constant volume were performed for densely and loosely packed assembly of particles with either circular or oval elements. Cyclic shear stress at the top of the model specimen was applied with constant shear strain (γ) amplitude of about 6% as shown in Fig.7. Stress strain relationship and stress path (shear stress and vertical stress) are shown in

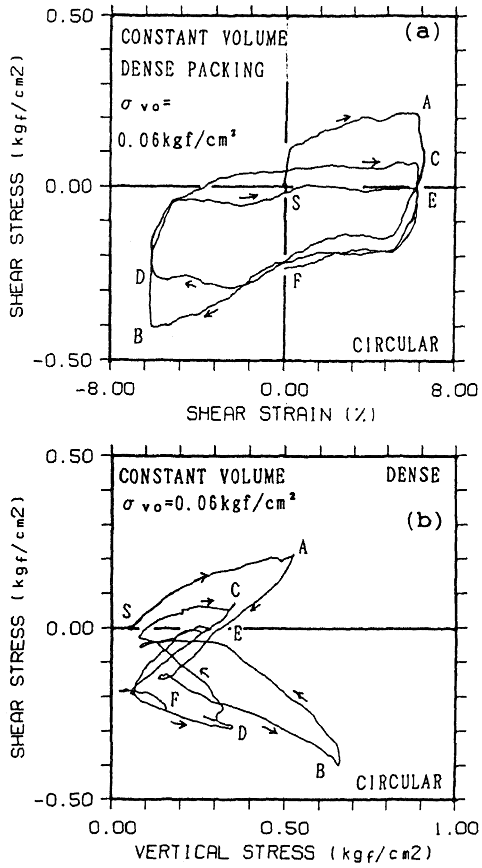


Fig.8 Cyclic simple shear simulations (Circular, Dense)

Figs 8(a) and 8(b) for densely packed circular elements and in Figs 9(a) and 9(b) for densely packed oval elements respectively. The initial vertical stress σ_{vo} is 0.06 kgf/cm². Since the strain amplitude is kept constant, the peak stresses decreases in each cycle in both cases (see points A B C D E in the figures). This implies the decrease in stiffness during cyclic loading in undrained condition. This kind of behavior is also observed in the experiments as reported by many researchers. Concerning the effect of the element shapes, it can be observed that the degree of stiffness reduction in case of oval elements is smaller than that in case of circular elements. This can be interpreted as that the liquefaction potential of oval granular assembly is higher than the round granular assembly. Yoshimura et. al., (1991b) has performed liquefaction tests using round glass beads and Toyoura sand. They found that liquefaction potential of Toyoura sand is higher for the same relative density and this tendency is more pronounced in the denser region.

The cyclic mobility phenomena is well simulated in both cases.

Stress strain relationship and stress path are shown in Figs 10(a) and 10(b) for loosely packed circular elements and in Figs 11(a) and 11(b) for loosely packed oval elements respectively. The initial vertical stress σ_{vo} is 1.0 kgf/cm^2. The decrease in the vertical stress during cyclic loading can be observed in both cases. This is quite similar to the accumulation of excess pore water pressure during liquefaction tests. In loose cases also cyclic mobility phenomena can be observed. These tendencies are quite similar to the experimental data as reported by Pradhan et. al., (1988b).

By comparing Fig.10(b) and Fig.11(b), it can be noticed that liquefaction potential for oval elements seems lower than that for circular elements. The reason may be that the oval element assembly is very loosely packed as compared to the circular ones since the same way of packing has been used. Further study is needed to specify the density of the assembly and the method of packing to obtain the same density for elements with different shapes.

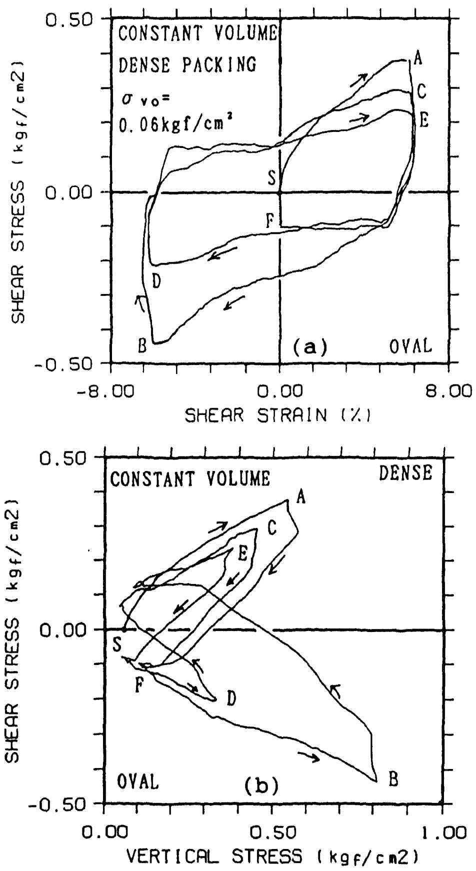


Fig.9 Cyclic simple shear simulations (Oval, Dense)

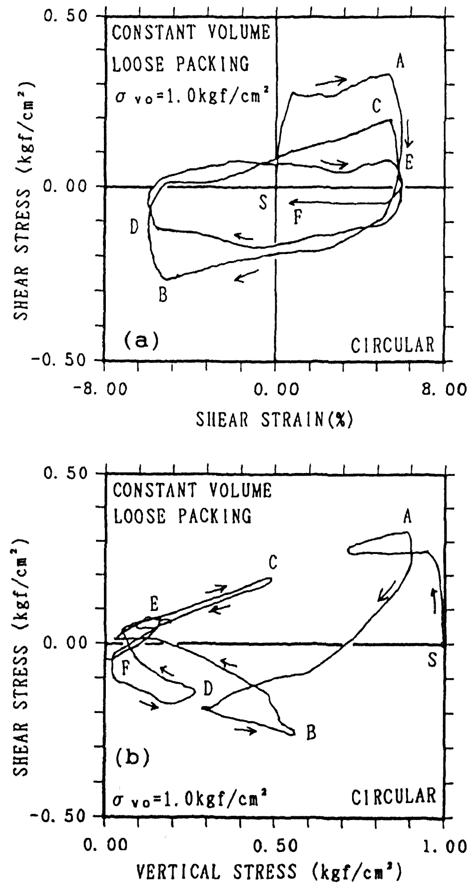


Fig.10 Cyclic simple shear simulations (Circular, Loose)

5 CONCLUSIONS

Distinct Element Analysis has been performed to simulate the behavior of granular assembly when subjected to undrained cyclic loading by using circular

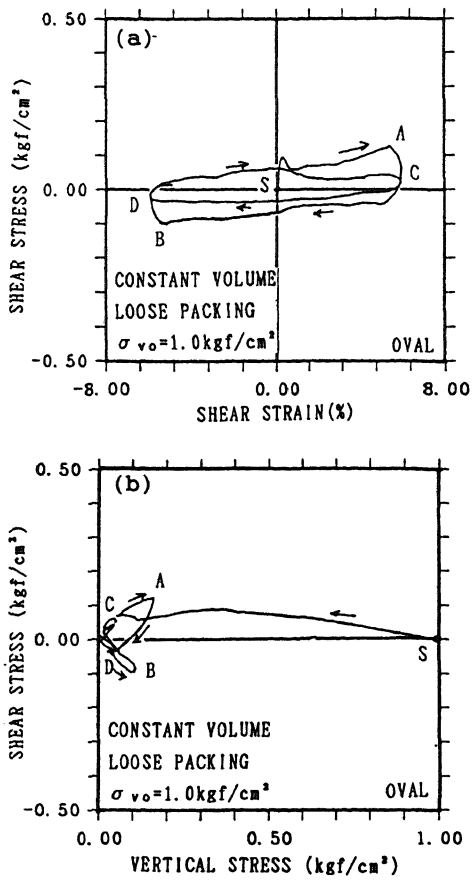


Fig.11 Cyclic simple shear simulations (Oval, Loose)

and oval elements. It was found that this numerical method is quite reasonable to simulate (a) effect of particle shape, (b) the liquefaction and cyclic mobility process.

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