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NRCC-45386

A version of this paper is published in / Une version de ce document se trouve dans:
Canadian Society for Civil Engineering Annual Conference, Victoria, May 30-June 2, 2001, pp. 1-5

EFFECT OF PARTICLE SHAPES ON THE RESILIENT BEHAVIOUR OF AGGREGATE MATERIALS

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ABSTRACT: This paper presents the results of numerical simulations of the resilient modulus test using the discrete element method. The simulations were performed on 2 assemblies made of individual circular particles and clusters composed of three circular particles linked together (prescribing one big triangular element), respectively. Similar to laboratory testing, the assemblies were subjected to a hydrostatic confining pressure and then to repetitive loading. Results of preliminary numerical simulations conducted on the two assemblies suggest that particle shapes have an effect on the resilient behaviour of aggregate materials. This effect influences the performance of roads and a special attention should be paid to the shape of particles used in road foundation.

1. INTRODUCTION

The degradation of road surfaces such as cracking and deflection can be related to deformations of underlying layers (base, subbase and subgrade). Consequently, the characterisation of these layers received much of the attention during the last 15 years. In 1986, the American Association of State Highways and Transportation (AASHTO, 1986) introduced the resilient modulus in the design of pavement structures. This new mechanical property came to replace the California Bearing Ratio and has been going through many improvements (AASHTO, 1993). Since the resilient modulus is the best measure, available today, to characterise elastic deformations of soils under repeated loading (similar to traffic), it has been the subject of many investigations assessing the effect of various parameters (confining pressure, deviator stress and water content) on this parameter. Lately and due to the lack of consistency of resilient modulus values reported by different investigators, more elaborate work has been undertaken to delineate the effect of other factors overlooked by previous investigations. Factors such as the percent of fines and gradation have been investigated for their influence on the resilient behaviour of granular materials. However, other elements such as particle shapes received little attention. Particle shapes affect the degree of compaction of samples and stress distribution (inside them) in response to loading. Since laboratory testing do not allow looking at grain orientation and packing and do not permit investigating the way loads are distributed and transferred between grains, numerical techniques were used. Since the discrete element method is the only method that is capable of replicating the nature of granular materials, it was adopted for this work. Moreover, using an association of particles (clusters) enhanced the circular shape idealisation. A description of the DEM method and the clustering technique is given in the following sections.

2. DISCRETE ELEMENT MODELLING

The discrete element method (DEM) is a special numerical technique for investigating the mechanical behaviour of granular materials. It has been gaining popularity during the last two decades mainly because it allows simulating the discontinuous and discrete paths of load transfer behaviour directly linked to the material microstructure. Moreover, it permits monitoring particle movement in terms of displacements and rotations through the simulation process. In fact, DEM treats materials as an assemblage of discrete, distinct, particles behaving independently while interacting with each other at contacts. The relative displacements of two particles in contact can be used along with a force-displacement law to determine the interparticle forces. It is through tracking the interparticle forces and application of Newton's law that particle accelerations can be calculated for any time step. The velocities and then displacements of each particle can then be obtained by successive integration of the accelerations.

The flexibility of the DEM enables adoption of different loading configurations, particle sizes, size distributions, and physical properties of the particles. The technique provides a wealth of information that no other methods can offer which made it a very attractive and powerful tool for studying granular materials assemblies.

This method was first applied by Cundall (1974) to investigate the behaviour of rock masses and then adapted by Cundall and strack (1978 and 1979) for studying the behaviour of granular materials. They analysed the response of soil by idealising grains by 2-D circular elements (discs). As computer computational capabilities evolved, the method became very attractive and has been used in a variety of fields such as fluid mechanics and earthquake engineering and was applied to study many practical engineering problems (slope stability and wave propagation for example).

Since its introduction by Cundall to the field of geomechanics, the technique has been evolving, with refinement of constitutive laws governing the behaviour at the contact and improvement of particle shapes being the main areas of enhancement. Many individuals proposed more complex shapes than the circular idealisation, used by the first generation of DEM codes, in order to replicate more closely those find in real materials.

Many researchers focused on the particles shape and its effect on the behaviour of assemblage under various loading conditions. First, polygon-shaped elements were used to more realistically model particles. Though this approach is very attractive and can better replicate experimental results, it was faced with high computational requirements resulting from the relative large number of facets (compared to circular elements) that need to be stored and monitored. In fact Ting et al. (1989) working with polygon idealisation reported an increase of one order of magnitude in computation time compared to circular elements. At a second stage, particles shape enhancement shifted to the elliptic idealisation since it is less demanding than polygon-shape when it comes to detection and monitoring of contacts. Lately, faced with the computational time problem, researchers have been leaning towards improving particles shape through association of circular elements to form one big element (clustering). This association technique is described below.

3. DEM ALGORITHM

In DEM, each particle is defined by two sets of properties. The first set defines particle radius, mass and moment of inertia and the second includes its contact properties. The contact consists of a combination of spring-dashpot in the normal direction and spring-dashpot-slider in the tangential direction (see Figure 1). Tangential forces are bound by a maximum (Coulomb friction):

$$F_s(\max) = \mu F_n$$

Where F_s and F_n are the normal and tangential forces respectively and μ is the coefficient of friction between the particles in contact.

The stiffnesses of the particles and their velocities at the time of collision determine the overlap between them. The change in overlap can be used along with a force-displacement law to determine interparticle forces. The contact forces can be used to determine the motion of particles by using Newton's second law of motion to first calculate accelerations and then by integration to determine velocities and displacements.

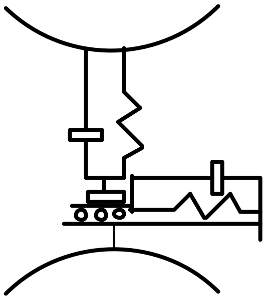

Figure 1: Particle to Particle Contact

4. CLUSTERING

While grains of some soils can be satisfactory modelled by discs, particles found in processed (crushed in a carry) granular materials seldom fit this idealisation. As can be seen in Figure 2, a particle of an arbitrary shape is poorly represented by a circular element (Jensen et al, 1999). This translates into missing the effect of particle shape that can be of a big influence on packing of granular assemblies and on their interlocking capabilities. Ting et al. (1993) reported excessive rolling of circular elements due to their limited interlocking characteristics.

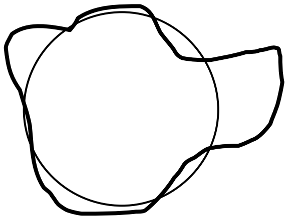

Figure 2: Circular Element Superimposed on a Particle of an Arbitrary Shape (Jensen et al. 1999)

The representation of natural particles can be improved by making use of an association of circular elements of different or same sizes as shown in Figure 3 (Jensen et al. 1999).

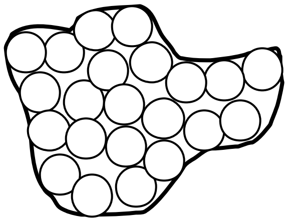

Figure 3: Association of Same Size Circular Elements to Improve Shape Idealisation

Since this paper is reporting preliminary results, it made use only of one special association of three particles prescribing a big triangular element as shown in Figure 4.

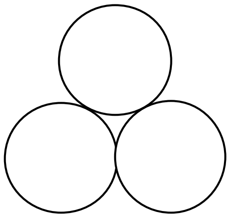

Figure 4: Three Particles Association

Using particles association allows keeping the same detection scheme as well as the force calculation algorithm used with individual particles. The extra requirement consists of forcing the particles of an association to behave as one rigid body. In, other words, the interior contacts of an association will be able to take tension and will not be governed by the elastic–perfectly plastic law used for individual particles; no sliding is allowed in interior contacts (Jensen et al. 1999).

5. RESILIENT MODULUS TEST SIMULATION

Discrete element method simulation of the resilient modulus test required preparation of a sample and application of repetitive loading. Sample preparation involved two stages, compaction and confinement. During the compaction phase, particles were randomly generated and then compacted by moving lateral rigid boundaries inwards. Ounce the desired degree of compaction was achieved, the velocity of lateral boundaries were set to zero and iterations were continued until particle velocities converged to zero (equilibrium state).

During the confinement phase the compacted sample was subjected to a confining pressure obtained by using the boundary particles of the sample. The configuration of the flexible boundary (made of these boundary particles) was updated at regular intervals to include any internal particle moving between two external (boundary) articles. Lateral rigid boundaries used during compaction were moved outwards and they did not have any role in the confinement and loading stages.

During the loading stage, samples prepared through compaction and confinement were subjected to a deviator repetitive stress. A triangular loading function is applied for a period of 0.1 second, followed by a rest period of 0.9 second.

Similar to laboratory testing (repeated triaxial test), the resilient modulus (M_r) is calculated as the ratio of the deviator stress (σ_d) to the resilient strain (ε_r):

$$M_r = \frac{s_d}{e_r}$$

6. TESTING PROGRAM

To investigate the effect of particles shape on the behaviour of granular materials, the following two samples were studied:

- assemblage of 400 individual particles with a radius of 4.31 mm each
- assemblage of 400 three-particle associations (1200 individual particles with a radius of 2.0 mm each)

For both samples, the particles or the associations were generated randomly (Figures 5 and 6) and the particles have the properties of Table 1.

Table 1: Particle Properties

Normal Stiffness (kPa)	10^5
Shear Stiffness (kPa)	10^5
Density (g/cm^3)	2.63
Friction	0.5
Cohesion	0.0

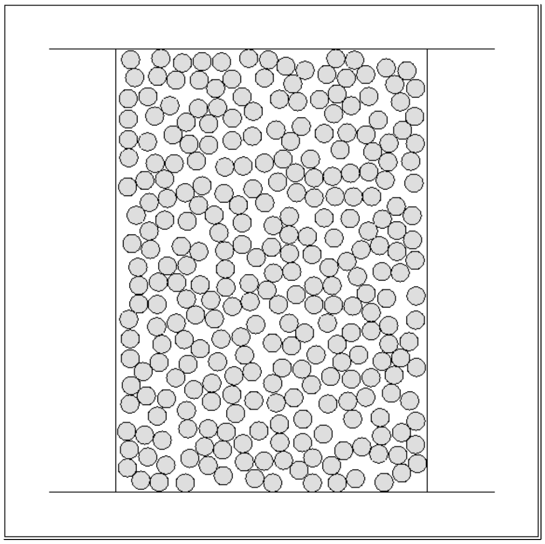

Figure 5: Randomly Generated Loose Sample - Individual Particles

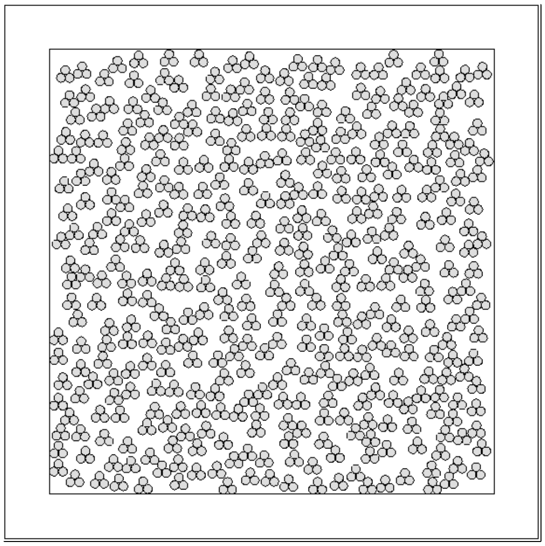

Figure 6: Randomly Generated Loose Sample – Association of 3 Particles

The two assemblages were subjected to the same hydrostatic confining pressure of 34.5 kPa and the same level of deviator repetitive stress (34.5 kPa). Figures 7 and 8 present the confined states of the two samples analysed. The lines between particles represent interparticle forces (the width of each line is proportional to the magnitude of the force).

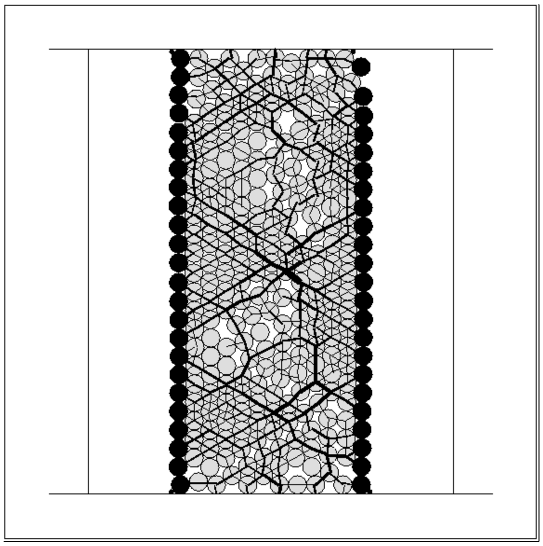

Figure 7: Interparticle Forces after Confinement - Individual Particles

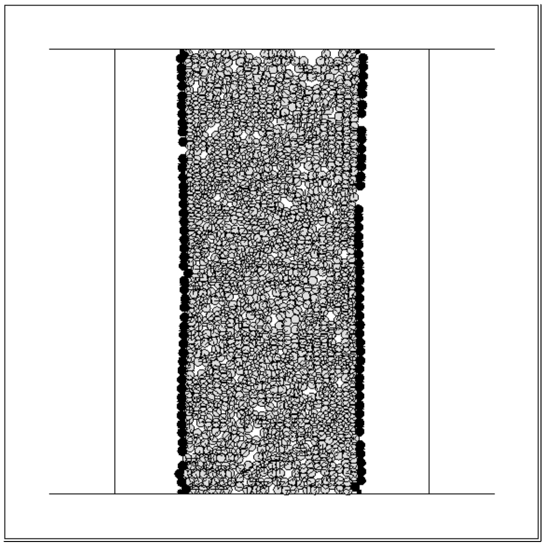

Figure 8: Interparticle Forces after Confinement - Association of 3 Particles

7. RESULTS

For both assemblages, the stress strain response was monitored and it was noted that the loop stabilised after few loading and unloading cycles. Furthermore, the resilient modulus was calculated for each calculation cycle. However, only stabilized moduli were reported here (see Table 2). The resilient moduli were calculated in the same way as in laboratory testing.

Table 2: Resilient Modulus Test Results.

Sample	Modulus (MPa)
Individual particles	250
Three-particle Associations	325

8. CONCLUSIONS

This paper reports preliminary results of numerical simulations performed on 2 assemblages. One made of individual particles and the other made of 3 particle clusters. The findings suggest that the shape of particles has an effect on the resilient response of aggregate materials.

9. REFERENCES

AASHTO, 1986, Guide for Design of Pavement Structures, American Association of State Highway and Transportation Officials.

AASHTO, 1993, AASHTO Guide for Design of Pavement Structures 1993, American Association of State Highway and Transportation Officials.

Cundall, P.A. and Strack, O.D.L. (1978) The Distinct Element Method as a Tool for Research in Granular Media, *Report to the National Science Foundation Concerning NSF Grant ENG76-20711,* Part I.

Cundall, P.A. and Strack, O.D.L. (1979) The Distinct Element Method as a Tool for Research in Granular Media*, Report to the National Science Foundation Concerning NSF Grant ENG76-20711*, Part II.

Cundall, P.A. and Hart, R.D. (1989) Numerical of Discontinua", *1st U.S Conf. on. Discrete Element Method*.

Jensen, R. P, Bosscher, P. J, Plesha, M. E. and Edil, T. B. (1999) DEM Simulation of Granular Media-Structure Interface: Effects of Surface Roughness and Particle Shape, Int. J. Num. Anal. Meth. in Geom., 23, 531-547.