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Publisher's version / Version de l'éditeur:

GeoDenver 2007 Conference [Proceedings], pp. 1-7, 2007-02-18

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NRCC-49204

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A version of this document is published in / Une version de ce document se trouve dans:GeoDenver 2007 Conference, Denver, U.S.A., Feb. 18-21, 2007, pp. 1-7

Simulation of the Resilient Modulus Test Using the Discrete Element Technique

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ABSTRACT

This paper presents a numerical technique to simulate the resilient modulus test of aggregate materials based on the discrete element method. This technique enables a realistic modeling that takes into account the nature of the materials and loading conditions, and provides valuable information such as the grain rearrangement at the micro level. Numerical simulations were conducted to idealize the cyclic loading of compacted granular samples. These simulations showed that the discrete element method is capable of reproducing the results of the resilient modulus test and capturing the effect of confining pressure on the resilient modulus observed in actual laboratory testing. The resilient modulus exhibited an increase in value with the increase of the confining pressure. The results also showed that the deviator stress has an effect only at low confining pressures.

INTRODUCTION

The American Association of State Highway and Transportation Officials (AASHTO) introduced the resilient modulus of unbound aggregate materials in the design of pavement in 1986 to account for their response under traffic and environmental loading (AASHTO 1986). This parameter was also adopted in the new mechanistic-empirical pavement design guide (product of the NCHRP 1-37A project). A number of methods, such as laboratory experiments, non-destructive testing and empirical techniques, were proposed to measure this property. Laboratory testing alone does not provide answers to the criticism that the resilient modulus testing has been facing and consequently other methods have been sought to complement it. The finite element method cannot realistically represent the discrete nature of granular materials. Techniques such as photo-elasticity, though very valuable, are time consuming (De Josselin De Jong and Verruijt 1969). Due to the discrete and heterogeneous nature of granular materials, the discrete element method (DEM) emerges as a viable method for complementing laboratory testing. Pursuing an approach that combines both laboratory and numerical techniques, an effort was made in this study to develop a DEM model capable of simulating the resilient modulus test and gather information beyond what could be collected in the laboratory.

RESILIENT MODULUS TEST

The asphalt layer in pavements has been the focus of much research efforts to explain and remedy pavement problems. In contrast, unbound aggregate layers did not receive proper attention because it was believed that they did not have a role and the fact that testing and analyzing granular materials is complex. Recently, the need for a proper characterization of the load deformation response of base and subbase granular materials was recognized through the improvements in pavement design and materials characterization proposed by the American Association of State Highway and Transportation Officials in 1986 and 1993 and the new mechanistic-empirical pavement design guide. The resilient behaviour of aggregate layers was introduced in the design process to account for their mechanical response under traffic loads. In repeated triaxial tests, the resilient modulus (M_r) is defined as the ratio of the deviator stress (σ_d) to the resilient strain (ε_r):

$$M_r = \frac{\sigma_d}{\varepsilon_r}$$

where the resilient strain is the difference between total and plastic strains at the end of the unloading phase.

DEM AND EMPLOYED MODEL

The interpretation of experimental investigations on granular materials is difficult due to the fact that they are composed of particles that have the characteristic of behaving independently while interacting with each other at points of contacts. The flexibility of computational discrete modeling, enabling the adoption of different loading configurations, particle sizes, size distributions, and physical properties of particles, makes the use of such techniques warranted. Numerous computational models for granular assemblies have been presented. In 1978, Cundall and Strack were the first to present a computer program to model granular media based on what is now known as the discrete (or distinct) element method.

A 2-dimensional model was used in this study where granular particles are idealized by discs. The particles are assumed to be rigid but can overlap. The interparticle forces are calculated based on the amount of overlap occurring between the colliding particles. A force-displacement law is used to calculate these forces from the overlap. Thus, the overlap is a function of the stiffness and particle velocity at the time of collision. Particle velocities are computed based on application of Newton's law to discs and a force-displacement law at the contact. Newton's law describes the motion of particles due to the forces acting on them.

Two groups of input parameters are needed to perform numerical simulations using the model mentioned above:

1. Data related to the positions of discs and the position and orientation of rigid boundaries with respect to a co-ordinate system.
2. Physical properties such as the radius, density, friction coefficient, normal stiffness and shear stiffness of discs and rigid boundaries.

For the purpose of simulating the resilient modulus test, stress controlled boundaries are needed to simulate membranes used in laboratory testing. These flexible boundaries are made of straight lines (segments) connecting the centre of external particles of a sample. Forces are externally applied to the boundary particles by specifying the prescribed stress. The forces distributed on the boundary are calculated from the unit vectors normal to the boundary segments and the prescribed stress (Bardet and Proubet 1991). For instance the force applied to the particle centre O in Figure 1 is given by:

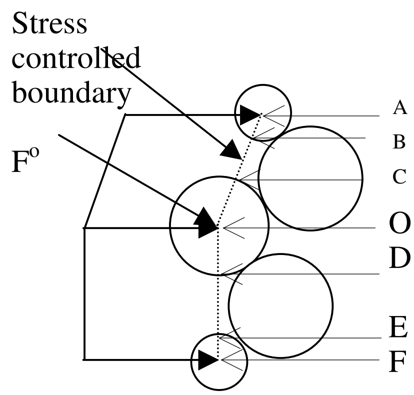

Figure 1. Flexible Boundaries Simulation.

$$F_i^o = BC\sigma_{ij}n_j^{BC}\frac{OC + CB/2}{OA} + CD\sigma_{ij}n_j^{CD} + DE\sigma_{ij}n_j^{DE}\frac{OD + DE/2}{OF}$$

Where σ_{ij} is the prescribed stress and n_j^{BC}, n_j^{CD} and n_j^{DE} are the unit vectors normal to lines. The configuration of these flexible boundaries changes during the simulation and is updated periodically to include an internal particle moving between two external particles.

NUMERICAL SIMULATION OF THE RESILIENT MODULUS TEST

Discrete element method simulation of the resilient modulus test required preparation of a sample and application of repetitive loading. During sample preparation, particles were randomly generated and then compacted by moving lateral rigid boundaries inwards. Once the desired degree of compaction was achieved, the velocities of lateral boundaries were set to zero and iterations were continued until particle velocities converged to zero (equilibrium state). In the compacted sample, boundary particles were identified and used to form flexible boundaries and to apply a confining pressure to the sample. A prepared sample is shown in Figure 2. The lines between particles represent interparticle forces (the width of each line is proportional to the magnitude of the force).

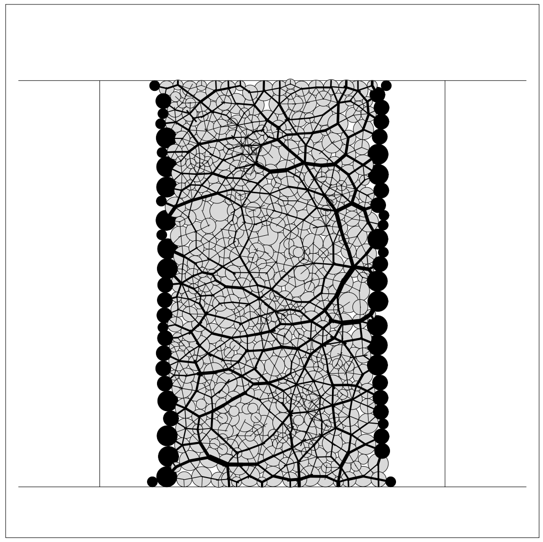

Figure 2. Force Network after Compaction and Application of a Confining Pressure.

During the loading stage, samples (prepared through compaction and confinement) were subjected to a repetitive deviator stress. A haversine loading pulse similar to the one shown in Figure 3 was used to apply the repetitive deviator stress. Loading was exerted for a period of 0.1 second, followed by a rest period of 0.9 second. Samples were subjected to 100 loading cycles.

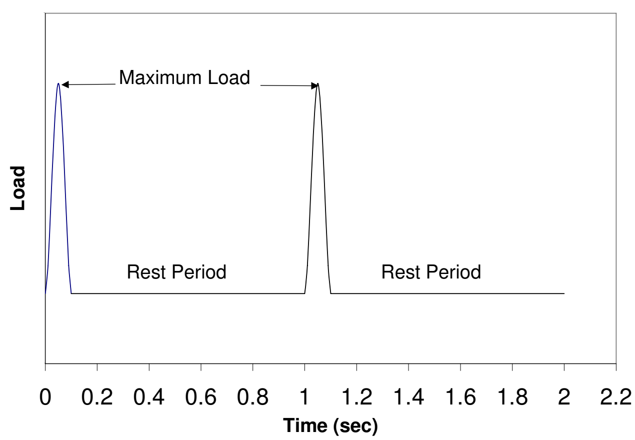

Figure 3. Haversine Repetitive Load Pulse.

EFFECT OF CONFINING PRESSURE AND DEVIATOR STRESS

In order to delineate the effect of the confining pressure and the deviator stress on the resilient modulus, a sample made of 500 particles was generated, loaded and its resilient modulus determined. Three different particle radii were used as shown in Table 1 presenting the grain size distribution. The discs have the properties shown in Table 2. Nine simulations, representing different confining and deviator stress levels, were performed (see Table 3). For the performed nine simulations, the resilient modulus was calculated for each loading cycle. However, only moduli evaluated at cycle 100 were reported here.

Table 1. Particle Size Distributions

Particle Size (mm)	Percentage (%)
10	40
7.5	30
5	30

Table 2. Particle Properties

Normal Stiffness (kPa)	5.0e6 kPa
Shear Stiffness (kPa)	5.0e6 kPa
Density (g/cm^3)	2.73
Friction	0.5

Table 3. Testing Program

Tests	Confining pressure (kPa)	Deviator stress (kPa)
T1	35	35
T2	35	70
T3	35	105
T4	70	35
T5	70	70
T6	70	105
T7	105	35
T8	105	70
T9	105	105

To delineate the effect of the confining pressure, the results of tests performed at the same deviator stress but different confining stress levels were grouped together as shown in Tables 4, 5 and 6. These tables show that increasing the confining pressure of the sample resulted in higher resilient moduli. These results are in agreement with the findings of laboratory testing of aggregate materials (Hicks 1970, Smith and Nair 1973 and Sweere 1990). However, it seems the effect is less important with higher confining stresses.

Table 4. Effect of Confining Pressure at a Deviator Stress of 35 kPa

Test	Confining Pressure (kPa)	Resilient Modulus (MPa)
T1	35	126
T4	70	139
T7	105	143

Table 5. Effect of Confining Pressure at a Deviator Stress of 70 kPa

Test	Confining pressure (kPa)	Resilient Modulus (MPa)
T2	35	133
T5	70	141
T8	105	142

Table 6. Effect of Confining Pressure at a Deviator Stress of 105 kPa

Test	Confining pressure (kPa)	Resilient Modulus (MPa)
T3	35	133
T6	70	141
T9	105	143

To delineate the effect of the deviator stress, the results of tests performed at the same confining pressure but different deviator stress were grouped together as shown in Tables 7, 8 and 9. It appears that the deviator stress effect is negligible for high confining pressures (70 and 105 kPa) and more pronounced for the 35 kPa level. The resilient modulus exhibits an increase with increasing deviator stress. These findings also conform to laboratory findings (Brown 1974).

Table 7. Effect of Deviator Stress at a Confining Pressure of 35 kPa

Test	Deviator Stress (kPa)	Resilient Modulus (MPa)
T1	35	126
T2	70	133
T3	105	133

Table 8. Effect of Deviator Stress at a Confining Pressure of 70 kPa

Test	Deviator Stress (kPa)	Resilient Modulus (MPa)
T4	35	139
T5	70	141
T6	105	141

Table 9. Effect of Deviator Stress at a Confining Pressure of 105 kPa

Test	Deviator Stress (kPa)	Resilient Modulus (MPa)
T7	35	143
T8	70	142
T9	105	143

CONCLUSIONS

Numerical simulations of the resilient modulus test showed that discrete element modeling is capable of reproducing the resilient behavior of aggregate materials under cyclic loading. Nine simulations at three different confining pressures and three levels of deviator stress showed that the resilient modulus exhibited an increase in value with the increase of the confining pressure. The results also showed that the effect of deviator stress is not significant except for low stress levels.

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