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A Study of the Parameters of Coefficient of Friction, Porosity, Particle Diameter, Density and Dispersity on Wave Propagation Velocity

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In the present paper, discrete element method (DEM) is used to study wave propagation phenomenon in granular soils. The effect of factors such as coefficient of friction, porosity, particle diameter, density and dispersity on the wave speed is studied. Using the wall motion based on the sinusoidal function is the method of loading used in this simulation, through which the pressure wave is transferred to particles. Simulations results are well consistent with the results of experiments conducted by other researchers. In addition, the results obtained are shown as graphs to study the effectiveness of each parameter. According to the results, the coefficient of friction, porosity and density have a greater effect on the wave speed.

Key words: Wave Propagation, Coefficient of Friction, Porosity, Particle Diameter, Density, Dispersity.

Wave propagation phenomenon plays a fundamental role in various dynamic issues such as seismic soil-structure interaction, liquefaction and foundation vibration[1]. Mechanical response of granular materials is determined by inter-particle contact behavior among the particles. The distinct nature of such materials leads to a discontinuous behavior distinct from charge transfer. This can be due to the structure of micro-materials or their fabric. It is well proved that charge transfer in non-cohesive materials occurs in a complex network of distinct paths. Considering the wave propagation, granular materials create a structured wave conduction network transferring the mechanical energy. Along a given wave path, the dynamic charge transfer is determined using the interaction among adjacent particles, the characteristics of propagated wave speed, damping range and dispersity of local fabric-related wave along the created wave paths. Over the years, researchers have combined the granular materials of micromechanical models including the local mechanics on the particles' surface to predict the macro-structure response[2-4].

It should be noted that the study of the correct nonlinear behavior of soil is still a controversial issue in the analysis of the dynamic behavior of soil. Distinct element method is known as a powerful tool to analyze the granular materials in small and large strains. This method is pioneered by Cundall and Strack[15] and many researchers have so far attempted to develop it[5]. DEM-based analysis is often used in qualitative analyses. The advantage of DEM-based analysis is that a set of

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discrete particles are capable of simulating the complex behavior of real materials at the micro scale using relatively simple assumptions and a few parameters. In addition, a typical simulation using DEM provides a large amount of data at both micro and macro scales. At any particular time of the simulation, we can retrieve these data and get full access to the results[6, 7, 8, 16, 17, 18].

Several experiments have been conducted in vitro to evaluate the wave propagation in granular materials. First experiments were conducted using the resonant column method to measure the wave speed. This method includes the excitation of a column of granular materials in a frequency. This method involves exciting a column of granular materials over a range of frequencies. A peak detected in the amplitude determines the resonant frequency. This frequency is combined with the sample length and leads to the wave speed. Duffy and Mindlin applied this method to a column formed from a ball packed into a cubic lattice. They showed that the wave speed scales with confining pressure to 1.4 power for both wet and dry sand[9, 10].

Numerical and experimental studies conducted by Shukla et al. (1993) investigated the effect of particle shape and particle surface hardness on the inter-particle charge transfer, speed and length of a stress wave transferred through the granular medium under the impact loads. In this research, dynamic photoelastic test is used as a laboratory technique and the granular medium is composed of spherical and elliptical particles with different contact hardness to examine their effects. The results showed that the particle shape and the particle surface hardness affect the wave speed[11].

Studies conducted by Thomas *et al*. (2009) evaluated dispersion in the resonant column test in granular soil. The analysis is performed in a time domain and two-dimensional way using PFC 2D. Voids ratios of 0.27, 0.1 and 0.65 were studied. This research investigated the effect of factors such as sample width, voids ratio, viscous damping and wavelength on the harmonic longitudinal wave propagation in a rectangular sample. Speed decreases with the decrease of the particle diameter. The increased viscosity and frequency and denser deposit will lead to the increased speed[12].

In studies conducted by Zamani and Shamy, a three-dimensional cuboid model of granular soil was made. Simulation was performed to investigate the soil behavior under sinusoidal excitations with different amplitude and frequency (shear wave). Three types of soils with porosities of 35.5 %, 36.5% and 38% and different boundary conditions were investigated on different beds including rigid rock bed, elastic bed and infinite medium. The analysis was performed in a time domain way to consider the effect of the nonlinear behavior of the soil. Dynamic characteristics of granular materials are affected by parameters such as confining pressure and porosity observed in the experimental results. Reduced shear modulus ratio increases with the increase of soil porosity at constant shear strain while damping ratio decreases. The reduced shear modulus ratio increases with the increase of confining pressure at constant shear strain while damping decreases. The soil response under different boundary conditions is well consistent with analytical results. The maximum and minimum ranges of motion belong to the rigid and infinite beds due to damping effect, respectively. The results are compared with the results of the equivalent linear method performed using SHAKE software. SHAKE and DEM are generally consistent except when the loading frequency is close to the resonant frequency[13].

Studies conducted by Hostler (2005) investigated the wave propagation in granular materials using both experimental method and DEM. Simulation and wave propagation are two-dimensional and horizontal respectively. Boundary excitations are used to apply loading. Loading is applied in a sinusoidal and pulse form. The number of particles is 4000. The phenomena of dispersion and frequency-dependent wave speed are studied. The diameter of particles is 0.5-5 mm. Group and phase speeds are studied. The granular diameter is assumed almost identical. Factors affecting the speed including the particle diameter, the increased depth and frequency are investigated[9].

The results showed that the wave speed is independent of the frequency. Particle size does not affect the wave speed. The increased depth slightly affects the wave speed[9].

Modeling Processes

Particle Production

Creating a sample with the desired porosity and dimensions is the first step of modeling. There are several methods to produce a deposit. The method of particle production through increasing the radius is the method used in this modeling. In this method, several spherical particles having no contact with each other will first be randomly produced in a specific space. Then, the particles will become enlarged enough to achieve the desired porosity. It is a trial and error process that will continue till achieving the desired porosity. Therefore, the particles will overlap and produce a great repulsive force. Consequently, the particles will have a high input speed removing even the particles from the boundary walls. In order to solve this problem, the kinetic energy is reduced to zero several times until the system reaches equilibrium. Table 1 shows the deposits after settling under gravity.

Applying Boundary and Initial Conditions

Walls are used to create boundary conditions. At first, walls are created as boundaries to create a sample with specific dimensions. Tensions initial conditions in a deposit depend on the way of producing and densifying the particles. To achieve the desired level of initial tensions, porosity is slightly changed since slight changes in porosity lead to great changes in tensions.

Selecting Contact Models

The conduct model describes the physical behavior occurring in the contact site. A deposit may show a complex nonlinear behavior, however this behavior is achieved using simple contact models. The contact stiffness model leads to an elastic relationship between the contact force and the relative displacement. Shear and normal stiffnesses correlate the shear and normal components of force with its corresponding displacement. In this study, hertz-mindlin non-linear model is used to desirably show the non-linear behavior (14).

Assigning properties to materials

Selecting the right amount of materials parameters is difficult. Considering continua codes such as finite elements and finite difference, input material properties such as moduli and resistances can be directly obtained from the results of experimental measurements. However, this method requires micro-material properties. This research has assigned a number of available micro properties to the materials. The remaining properties were achieved using the inverse modeling and the modeling comparison and the actual and desired results were identified and assigned to the materials.

Damping

The energy applied to the particles is depreciated using the frictional sliding; however this rate of energy depreciation is not sufficient to reach a steady state in a number of analysis cycles. Therefore, a mechanical damping is required to depreciate the kinetic energy. In this simulation, viscous damping was selected after conducting studies, since this type of damping creating dashpot in both normal and shear directions in the particles' contact site leads to forces proportional to the relative speed differences between the two contact sides (particle-particle or particle-wall). This type of damping performs better than local damping, hysteric damping, etc. for simulations including the free movement of particles or dynamic loading (sinusoidal).

Loading

In this simulation, loading is performed through the boundaries excitations. The movement speed of the wall is based on the sinusoidal function through which the pressure wave is transferred to the particles attached to the wall, and consequently, these particles transfer the stress wave to the particles attached to them.

RESULTS

A Study of the Effect of Coefficient of Friction or Particle Surface Stiffness on Wave Propagation Speed

The coefficient of friction is one of the factors affecting the wave propagation speed. In this research, the simulated model is first created according to the above-mentioned steps; then, this model is compared with the laboratory model created by Hostler in 2005 and ensuring the accuracy of the modeling, the effect of this parameter on the wave speed is investigated through changing the rate of contact surface stiffness.

In the laboratory model created by Hostler, the coefficient of friction is considered equal to 0.1 and consequently, the wave speed is reported equal to $170\frac{m}{s}$. In the simulation performed considering the same material properties of the laboratory model, the wave speed is obtained

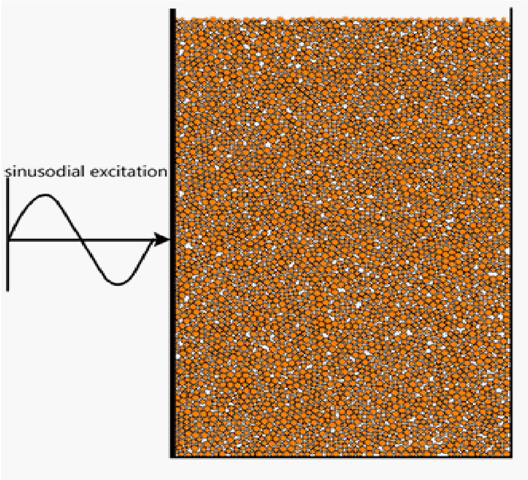

Fig. 1. A schematic diagram of the deposits

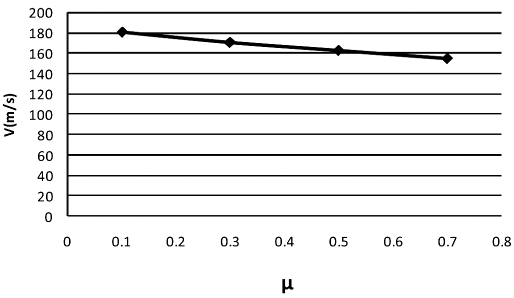

Fig. 2. Changes in velocity versus the coefficient of friction

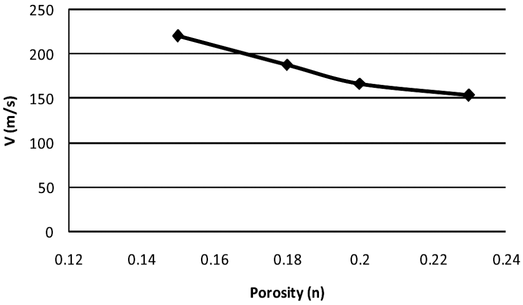

Fig. 3. Changes in velocity versus porosity

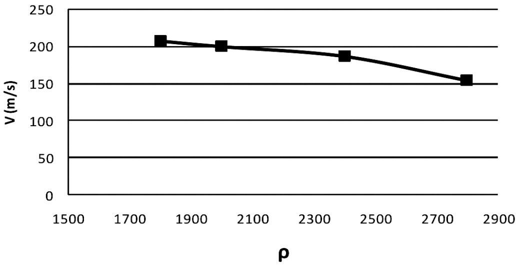

Fig. 4. Changes in velocity versus density

equal to $181\frac{m}{s}$ and the experimental results and the simulation performed are well consistent.

Now, simulations are performed using the coefficients of friction of 0.3, 0.5 and 0.7 to investigate the effect of the coefficient of friction on the wave speed. The results obtained from the analyses are shown in Figure 2. Considering the results presented, the wave propagation speed decreases with the increase of the coefficient of friction (particle surface stiffness). This may be due to the fragile nature of the particles' jagged edges, since these edges are crushed when the wave passes the particles' contact site and finally lead to the reduced stiffness in the contact site leading to the reduced wave speed. Meanwhile, this result is consistent with the results of experimental studies conducted by Shukla et al (1993) (11).

A Study of the Effect of Porosity on Wave Propagation Speed

Soil porosity is one of the factors affecting the wave propagation speed. In this section, four types of soil with porosities of 0.15, 0.18, 0.2 and 0.23 are investigated and the results are shown in Figure 3. As it can be observed, the wave propagation speed increases with the decrease of soil porosity. This result is consistent with the results of experiments and simulations conducted by Zamani and Shamy (2011) and Thomas et al (2009).

In fact, the deposit density and the confining pressure increase with the decrease of porosity. Finally, these factors increase the wave speed.

A Study of the Effect of the Particle Density on Wave Propagation Speed

The particles' material properties are one of the factors affecting the wave propagation speed. Density is one of these properties. In this section, four types of densities – 2800, 2400, 2000 and 1800 – are investigated and the results are shown in Figure 4. As it can be observed, the wave propagation speed increases with the decrease of density. This process is expectable since the increased wave speed in particles $C_0 = \sqrt{\frac{E}{\rho}}$ is directly associated with the reduced density of particles. Finally, the wave speed in the deposit increases with the decrease of the particles' density.

A Study of the Effect of the Particle Diameter on Wave Propagation Speed

This section investigates the effect of the particle diameter on the wave propagation speed. Therefore, three diameters of 25, 35 and 45 mm of deposits are created to investigate the effect of the particle diameter on the wave propagation speed. Performing analyses, the results obtained are shown in Figure 4. As it can be observed, increase or decrease in the particle diameter does not significantly affect the wave speed. The result obtained from simulations is consistent with the experimental results obtained by Hostler[10].

A Study of the Effect of D' on Wave Propagation Speed

The dispersity, *D'*, is given as a percentage of the mean particle diameter around which the particle diameters are randomly distributed. This variation mimics real granular materials. The dependence of the results to changes in the polydispersity is not examined in the current study and the dispersity is set to 10% for all simulations. Sensitivity of the results to the degree of dispersity may be of interest for future study. The geometric packing of a granular bed is also marked by irregularity. The initialization of the simulation attempted to capture this irregularity. The particles start in a regular grid, well separated in both directions. They are given random initial velocities and allowed to settle under the effect of gravity. The wave disturbances are introduced at the left wall only after the settling of the bed has ended. This procedure creates a unique bed for each simulation.

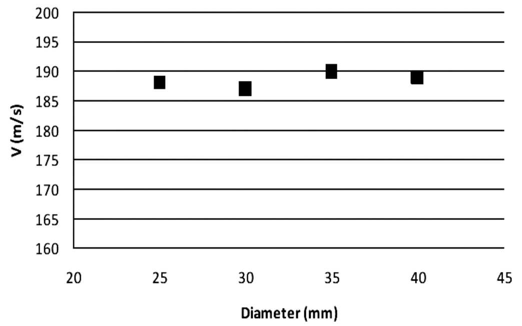

Fig. 5. Changes in speed versus the particle diameter

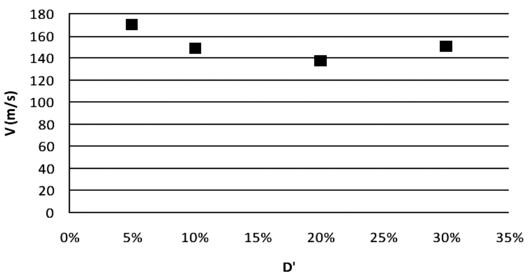

Fig. 6. Changes in speed versus dispersity (D')

Four types of soil with D' of 5%, 10%, 20% and 30% were studied to investigate the effect of D' on the wave speed. The results are shown in the following figure. As shown in Figure 6, there is no clear relationship between D' and wave speed. This can be due to the existence of other factors affecting the wave speed.

CONCLUSION

Discrete element method (DEM) was used to investigate the factors affecting the wave speed in granular soils. The effect of factors such as coefficient of friction, porosity, particle diameter and dispersity on the wave speed was studied using the simulations performed.

Considering the results obtained, the wave propagation speed decreases with the increase of the coefficient of friction (particle surface stiffness). This may be due to the fragile nature of the particles' jagged edges, since these edges are crushed when the wave passes the particles' contact site and finally lead to the reduced stiffness in the contact site leading to the reduced wave speed.

Results show that the wave propagation speed increases with the decrease of the soil porosity. In fact, the deposit density and the confining pressure increase with the decrease of porosity. Finally, these factors increase the wave speed.

The wave propagation speed increases with the decrease of density. This process is expectable since the increased wave speed in particles $C_0 = \sqrt{\frac{E}{\rho}}$ is directly associated with the reduced density of particles. Finally, the wave speed in the deposit increases with the decrease of the particles' density.

Analyses show that increase or decrease in the particle diameter and dispersity does not significantly affect the wave speed.

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