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A Study of the Wave Velocity in Granular Soils using Discrete Element Method

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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, frequency, normal stiffness and soil gradation 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 and normal stiffness have a greater effect on the wave speed.

Key words: Discrete Element Method, Wave Propagation, Granular Soils.

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 discrete particles are capable of simulating the complex behavior of real materials at the micro

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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[6-8, 16,-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 (1-170).

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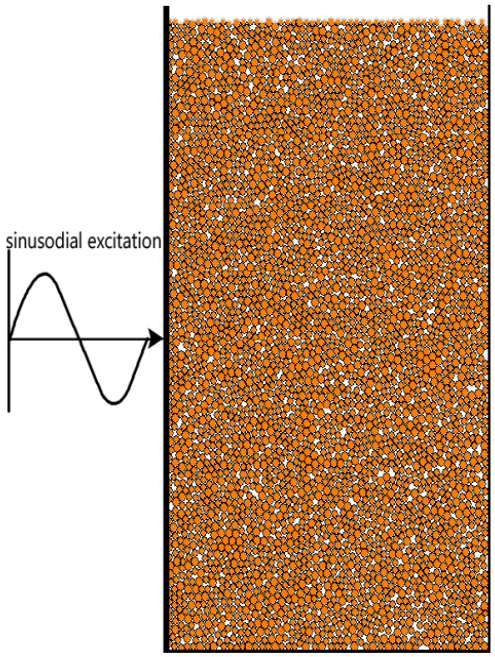

Fig. 1. A schematic diagram of the deposits

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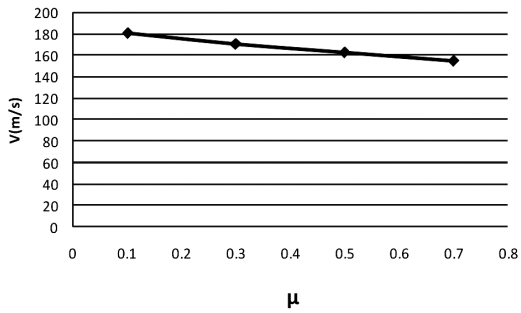

Fig. 2. Changes in velocity versus the coefficient of friction

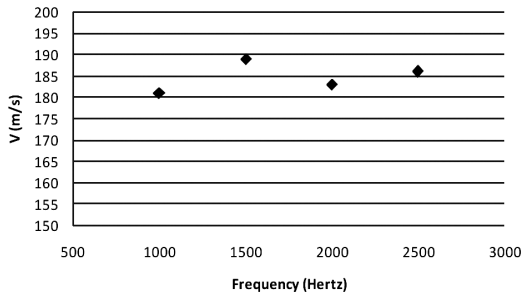

Fig. 3. Changes in velocity versus wave frequency

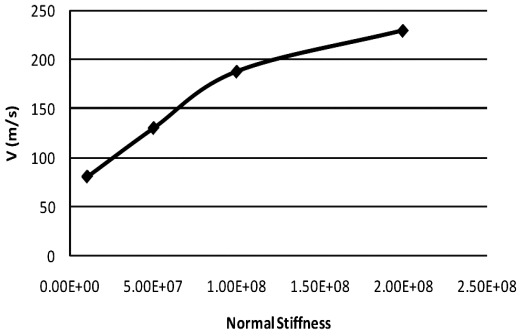

Fig. 4. Changes in velocity resulted from normal stiffness

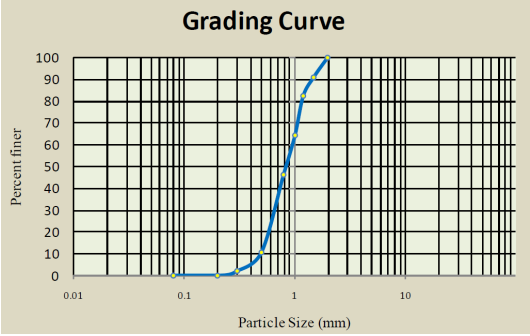

Fig. 5. Grading curve of soil A

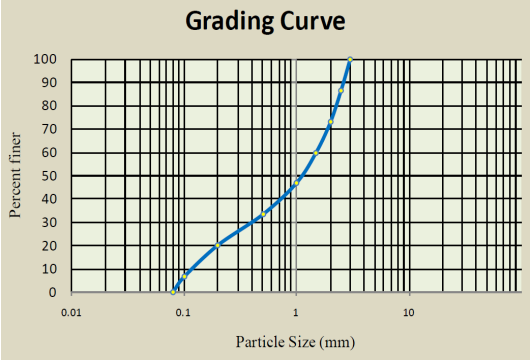

Fig. 6. Grading curve of soil B

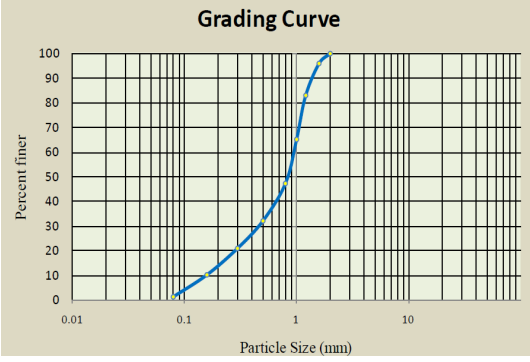

Fig. 7. Grading curve of soil C

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].

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A Study of the Effect of Frequency on Wave Propagation Speed

This section investigates the effect of frequency on the wave speed. In this section, waves with four frequencies of 1000, 1500, 2000 and 2500 Hz are applied to the deposits. The results of the analyses are shown in Figure 3. As it can be observed, increase or decrease in the frequency does not significantly affect the wave speed. This result is consistent with the results of experiments conducted by Hostler.

A Study of the Effect of Normal Contact Stiffness on Wave Propagation Speed

Normal contact stiffness is one of the factors affecting the wave propagation speed. In this section, four deposits with normal stiffnesses of 1×10^7, 5×10^7, 1×10^8 and 5×10^8 are created to investigate the effect of these factors. The results of these analyses are shown in Figure 4. As it can be observed, the wave speed increases with the increase of stiffness. This increase is expectable since normal stiffness is directly associated with elastic modulus and the elastic modulus ($C_0 = \sqrt{\frac{E}{\rho}}$) is directly associated with the wave speed in the particle and finally in the deposit. We conclude that the particles' properties (type) are one of the most important parameters affecting the wave speed.

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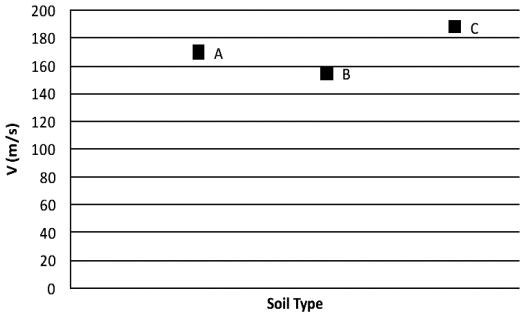

Fig. 8. Changes in speed in the Soils A, B and C

investigate the effect of these factors. The results of these analyses are shown in Figure 4. As it can be observed, the wave speed increases with the increase of stiffness. This increase is expectable since normal stiffness is directly associated with elastic modulus and the elastic modulus ($C_0 = \sqrt{\frac{E}{\rho}}$) is directly associated with the wave speed in the particle and finally in the deposit. We conclude that the particles' properties (type) are one of the most important parameters affecting the wave speed.

Figure 8 shows the wave speed obtained in the three soils. As it can be observed, the wave propagation speed in soil C is greater than that in soils B and C. Deposits of soil C enjoy an appropriate particle diameter and a suitable range of particle limits due to their good gradation. Therefore, settling and achieving a static equilibrium in deposits, more contacts occur among the particles leading to the increased 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.

Investigating the effect of the frequency showed that the increase or decrease in frequency does not significantly affect the wave speed.

The wave speed increases with the increase of stiffness. This increase is expectable since normal stiffness is directly associated with elastic modulus and the elastic modulus ($C_0 = \sqrt{\frac{E}{\rho}}$) is directly associated with the wave speed in the particle and finally in the deposit. We conclude that the particles' properties (type) are one of the most important parameters affecting the wave speed.

The wave speed in well-graded soil is greater than that in poorly graded soil, since in the well-graded soil, more contacts occur among the particles after settling and achieving a static equilibrium in deposits leading to the increased wave speed.

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