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Research Paper

Effect of rubber size on the behaviour of sand-rubber mixtures: A numerical investigation

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ABSTRACT

Mixtures of sand and rubber particles were simulated using DEM. Rubber content varied from 0% to 50%. The numerical samples were sheared in the range of 10^{-5}–10^{-2}% of ε_1. The macro-mechanical response changed depending on the size of rubber particles. As the size of the rubber particles increased, the effect of rubber in the internal structure was attenuated, facilitating the force transmission through sand-sand contacts. Largest rubber particles showed the most advantageous mechanical behaviour. Nevertheless, the selection of both rubber size and content will depend on the intended purpose of use for the mixtures.

1. Introduction

The employment of granulated rubber or waste tire shreds as a new geo-material or in the form of mixtures with soil has become a popular approach in ground–improvement [5,11,63]. The rubber is seen to reinforce sand meanwhile it still keeps its lightweight ability. The application of it could certainly be advantageous in engineering projects such as: (i) reduction of lateral earth pressures on retaining walls [18,24,25,27]; (ii) reduction of settlements for embankments [6,10,12]; (iii) providing filter layers for drainage in landfills [47]; and (iv) providing damping to foundations and for liquefaction mitigation purposes [23,33,37,42,43,51–53,57].

Scrap tyres are shredded to smaller sizes for use in various applications, with the actual size, ranging from cuts (>300 mm), shred (50–300 mm), chips (10–50 mm) to powder (<1 mm), depending upon the intended use. At current practice, the determination of the rubber size is mainly based on the availability and the cost of production. Therefore, the effect of rubber size on the behaviour of sand-rubber mixtures has been of interest. Size ratio of rubber to sand particles has been studied in the range of 0.25 [28] to more than 100 [68]. The size of rubber particles has an important effect on the mechanical response of the mixtures that can result either in decay in strength and maximum shear modulus [1,28,29,57] or in increase in strength and maximum shear modulus [26]. Evans and Valdes [15] carried out numerical one dimensional (1-D) compression tests on sand-rubber mixtures to study the effect of rubber fraction and size ratios of particles on the force percolation and the strain dependent evolution of strength. Numerical simulations reported by Lee et al. [30] also corresponded to 1-D compression tests, but only a size ratio of rubber to sand particles of 1.0 was considered in that work with a particular focus on the effect of rubber content on the overall fabric of the samples. Special attention has also been paid to other important parameters, such as the shear modulus measured at very small strains where pure elasticity dominates the behaviour of the mixtures (less than 0.001%) and at small to medium strains where the stiffness already starts to degrade (for example in the range of 0.001–0.1% of shear strain). The small-strain and the small to medium strain shear moduli are usually required in advanced modelling for the accurate prediction of ground deformations [60]. A number of experimental works have been carried out ranging from very small strains up to strains greater than 20% [1,13,14,26,28,29,32,40,52,57]. However, numerical investigations on rubber and sand mixtures have been mainly focusing on medium to large strains up to 20% [30,64].

In this study, mixtures of rubber and sand particles are simulated in three dimensional triaxial constant volume tests by

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Nomenclature

a_n	normal contact force anisotropy
d	particle diameter
G^p	particle shear modulus
G	elastic secant shear modulus
G_{max}	maximum elastic secant shear modulus
I	inertial number
p'	mean effective stress
p'_0	mean effective stress after isotropic compression
q	deviatoric stress $q = \sigma'_1 - \sigma'_3$
Z_m	mechanical coordination number
$\dot{\varepsilon}$	strain rate
$\varepsilon_1;\ \varepsilon_2;\ \varepsilon_3$	major, intermediate and minor principal strains ($\varepsilon_2 = \varepsilon_3$)
ε_q	shear strain $\varepsilon_q = 2/3(\varepsilon_1 - \varepsilon_3)$
μ	inter-particle friction coefficient
v	particle Poisson's ratio
ρ	particle density
$\sigma'_1;\ \sigma'_2;\ \sigma'_3$	major, intermediate and minor principal stresses ($\sigma'_2 = \sigma'_3$)
$(\Phi_1 - \Phi_3)$	deviatoric fabric

employing the discrete element method (DEM) to investigate the effects of rubber content and the relative size of rubber and sand particles at small strains. As noted by Lee et al. [30], the response of granular materials at different strain levels would underlie a different response at the micro-mechanical level. The purpose of this contribution is to explore the micro-mechanics that are developed in a range of strains usually experienced by geo-materials, i.e. pre-failure response and in particular to investigate the contribution that is made by each type of contact, i.e. sand-sand, rubber-sand or rubber-rubber to both the micro and macro-mechanical responses. Sand particles are modelled as rigid particles with high stiffness, whereas rubber particles are modelled as soft particles having low stiffness. Macro- and micro-scale responses of sand-rubber mixtures will be explored. The DEM simulations allow the tracking of the particle contacts and the distribution and magnitude of the forces at all test stages, which is not feasible in laboratory experiments.

2. The discrete element method

The simulations presented in this study used the DEM proposed by Cundall and Strack [8]. The calculation cycle applies a force-displacement law to the particles and updates the particle positions by the Newton's second law. A soft contact approach is used where particles are treated as rigid but allow overlapping among each other at a contact point occurring over a small area. Normal and tangential forces generated at contacts are calculated respectively as $f_n = k_n\delta_n$ and $\Delta f_t = k_s\Delta\delta_s$ where k_n and k_t are the normal and tangential stiffness, respectively, δ_n is the contact overlap and $\Delta\delta_s$ is the tangential displacement increment. The maximum tangential force allowed is given by $f_{t\ max} = \mu\ f_n$ with μ being the interparticle-friction coefficient. k_n and k_t are calculated using the Hertz-Mindlin contact model as: $k_n = \frac{2G^p}{1-v}\widetilde{R}^{1/2}\delta_n^{1/2}$ and $k_t = \frac{4G^p}{2-v}\widetilde{R}^{1/2}\delta_n^{1/2}$, where G^p is the particle shear modulus, v the particle Poisson's ratio and R is the equivalent radius in between two particles in contact i and j obtained as: $\widetilde{R} = \frac{R_iR_j}{R_i+R_j}$. This contact model uses an approximation of the theory of Mindlin and Deresiewicz [35] where the contact model excludes the continuous nonlinearity in shear while only the initial shear modulus is used. This contact model has been widely adopted in DEM simulations which have successfully captured typical soil behaviour characteristics [2,20,61,66].

The use of a local damping facilitates the kinetic energy dissipation allowing the system reducing the number of calculation cycles required for the system to reach equilibrium. The damping force is calculated as $F_d = d|F_u| \pm (V)$, where d is the local damping ratio. It is proportional to the unbalanced force F_u and applied opposite to the velocity direction V.

The simulations shown in this study were carried out in the open-source code LAMMPS (Large-scale Atomic/Molecular Massively Simulator) [44] which is a classical molecular dynamics (MD) code capable of simulating soft matter and coarse-grained systems. LAMMPS can run on single or in parallel using MPI techniques allowing its use on massively-parallel high-performance computers. The MD method is algorithmically similar to DEM and a number of implementations were made onto LAMMPS to allow the simulations of granular assemblies by using DEM. Details of this modified version of LAMMPS can be found in Huang [22]. Additional implementations include the possibility of simulating a granular system composed of two different materials where, in the case of a contact shared by the two materials, the shear modulus and Poisson's ratio is taken as the average of the two materials. Besides, the tangential force arouse from a contact between the two different materials is limited by the minimum inter-particle friction coefficient among the materials.

DEM employed in this study can capture part of the behaviour of discrete materials such as soils, and can provide useful information associated with micro-quantities. It should be noted that in this study particles are modelled as perfect spheres with which the effect of the particle shape on the response of granular materials is not captured [65]. Nevertheless, DEM has proven to be an appropriate tool for modelling the different phenomena that characterize granular systems as was summarized by O'Sullivan and Bray [39]. In this regard, a careful calibration of the system was conducted, in particular for the pure sand (assembly of stiff grains) and the pure rubber (assembly of soft grains) with respect to the small-strain stiffness of the samples based on literature data derived from resonant column tests.

3. Numerical simulations

The particle size distribution (PSD) used for the simulated sand is plotted in Fig. 1, which is representative of a uniform sand of fluvial origin tested by Anastasiadis et al. [1]. Rubber particles were created following three different PSD parallel to the sand PSD, having ratios of mean size of rubber to mean size of sand (D_{50R}/D_{50S}) of 1.0, 2.5 and 5.0, as seen in Fig. 1. A total of 15 mixtures were prepared, 5 for each D_{50R}/D_{50S}, with rubber contents varying from 10% to 50% by mixture weight, in increments of 10%. Views of the numerical samples for the clean sand and the mixtures at 100 kPa of isotropic confining pressure are also included in Fig. 1.

Each sample consisted of a total number of particles ranging from 10,184 to 20,692. Particles were placed initially as non-contacting spherical particles, and enclosed within a cuboidal periodic cell to avoid boundary effects [21,62]. The stresses within the periodic cell were determined from the stress tensor as