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Research Paper

Three-dimensional discrete element modeling of direct shear test for granular rubber–sand

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ABSTRACT

Three-dimensional discrete element modeling of direct shear test conducted on granular rubber–sand is presented. Excellent agreement was attained between the simulation and test results, verifying the model's capacity of examining mixtures shear behavior. Important particulate-scale observations were attained, including the inter-particle contacts force, particles displacement and rotation, porosity and their variation with rubber particle contents. The observations demonstrate that the rubber particles inclusion amends the mixture stiffness, grading and packing at the particulate level, leading to a corresponding variation in the material shear behavior. Some interesting particulate-level simulations were examined to gain further insight into micro-mechanic characteristics of the mixtures.

1. Introduction

There are approximately 48 million tons of waste tires per year generated in Australia; a low percentage is recycled or managed properly [1]. An important solution to increasing the recycling rate is to process the wheels tire into a range of smaller pieces of rubber (e.g., shreds, chips, particles or fine powers) and incorporate the sliced rubber elements as reinforcements into soils [2–4]. The formed mixtures outperform the soils in respect to resilience, strength, ductility and damping [5–7]. The demonstrated advantages arises from the rubber material's capacity of increasing inter-particle interactions which were confirmed in triaxial [3,5,8,9], direct shear [10–13] and uniaxial pull-out tests [14].

Rubber particles can be mixed with sand into rubber–sand fill [11]. The fill exhibits better workability than the shred- or chip-based mixtures [15]. For the same reason the granular rubber–sand mixtures avoid segregation problems and aim at applications where otherwise are difficult to access. Additional value lies in the rubber–sand being lighter in weight by 20–40% than the sand backfill depending on the materials per cent used [16]. The use of the lightweight material reduces loads acting on the surrounding infrastructures or utilities (e.g., retaining walls or pipelines). Rubber–sand is also graded to facilitate water percolation and drainage and thus avoid environment or climate related concerns such as frost heave. Direct shear tests conducted on rubber–sand samples suggested that the material shear strength remains similar in magnitude to that of sand, demonstrating a substitute for sand backfills [3,16,17]. To understand the shear behavior, discrete element modeling was conducted on rubber–sand mixtures subjected to direct shear tests [3,8,12,18,19]. These studies gained insight into the inter-particle interactions and demonstrated the role of rubber particles in changing the material fabrics and the material stiffness. Most of the discrete element simulations were implemented in a two-dimensional plane which under-represents the three-dimensional shape of the particles and neglects the boundaries associated with the samples [20–22]. The purpose of this study is to conduct three-dimensional numerical simulations on the rubber–sand subjected to direct shear tests. The discrete element method is used to conduct the simulations. The simulations are validated against laboratory test results and then deployed to examine how the rubber particles inclusion influences the material shear behavior.

2. Materials and method

The materials include sand and rubber particles. The respective gradation curves are shown in Fig. 1. The sand ($D_{50} = 0.58$ mm) is well graded to fit into the pore space of the rubber particles ($D_{50} = 5$ mm). Define specific volume fraction χ = the rubber particle specific volume over the total specific volume of the mixture. Design a series of samples with $\chi = 0, 0.19, 0.34, 0.47, 0.58$ and 1, respectively, where $\chi = 0$ and $\chi = 1$ define the pure sand and the pure rubber particle samples, respectively. A mixture with $\chi > 0.6$ was not viable due to particles segregation [15,23]. The corresponding weight fraction is 0, 0.1, 0.2, 0.3, 0.4 and 1, respectively. A mixer was used, following the steps shown in Ghazavi [11], to gain a uniformly distributed mixture.

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Nomenclature

d	particle diameter
D_{50}	50% pass particle size
F	sum of normal force at contact
G_s	specific density of solid
k_n	normal stiffness at contact
$k_{n,1}$	normal stiffness of entity 1
$k_{n,2}$	normal stiffness of entity 2
k_s	shear stiffness at contact
$k_{s,1}$	shear stiffness of entity 1
$k_{s,2}$	shear stiffness of entity 2
N_c	number of rubber–rubber contacts on shear plane
N_r	number of rubber particles on shear plane
V	sample volume
χ	specific volume fraction
δ	shear displacement
μ	inter-particle friction coefficient
μ_1	surface friction of entity 1
μ_2	surface friction of entity 2
σ_m	mean stress at contact
v	vertical or normal load
ζ	damping coefficient

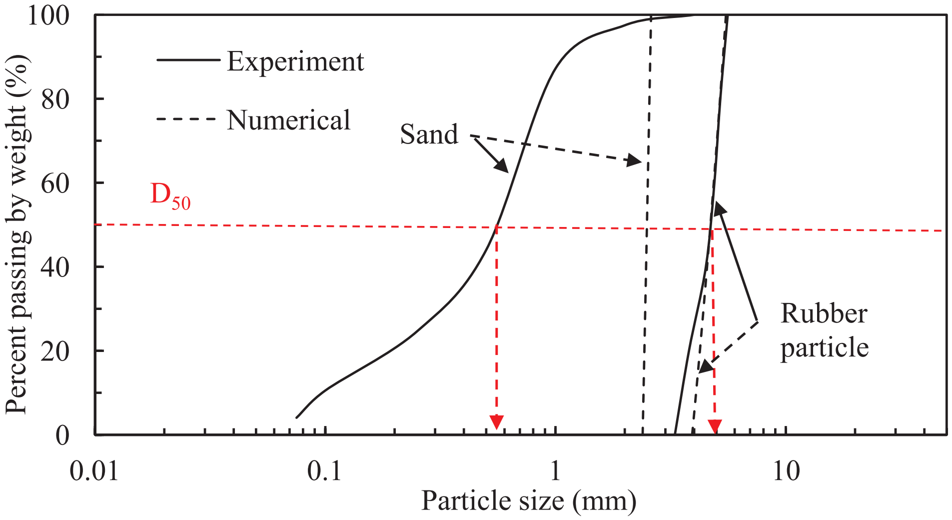

Fig. 1. Particle size distribution of sand and rubber particles.

Standard direct shear tests were performed. The sample size measures 60 $W \times 60L \times 40D$ mm, which was chosen to satisfy the sample size vs. particle size criterion. Pour the sample into the shear boxes, and even and level the materials, enabling a uniform distribution. Prepare four identical samples for one fraction χ and subject the four samples to vertical load $\sigma_v = 100$, 200, 300 and 400 kPa, respectively. Shear the samples at a rate of 1 mm/min until the occurrence of the greatest shear stress or 5 mm displacement, whichever occurs earlier.

Discrete element simulation was conducted using a commercially accessible software package Particle Flow Code (PFC) 3D. Assemble together ten pieces of wall (a PFC simulation object) to form a compartment, with respective dimensions representing the shear boxes, as shown in Fig. 2. Inside the box compartment is the spherical particles assembly, with the particle sizes designed in agreement with main portions of rubber particles and sands, respectively. A mass scaling [19] was applied to the particle sizes, enabling a better computer simulation, as having been attained in other studies [8,24]. The scaling results are provided in Fig. 1. Depending on the mixture examined, there are about 6000 sand particles and 1000 rubber particles created to fill up the boxes space. The mixture in the shear boxes is shown in Fig. 2. After placing the particles inside the shear boxes, apply the servo-control method [25] to release excess sphere contact forces where there were.

The linear elastic model of PFC3D was used to replicate the shear stress–displacement relations. The linear model outperforms the non-linear Hertz model in respect to the use of the servo-control, which is a model in-built developed to maintain a load acting onto the material

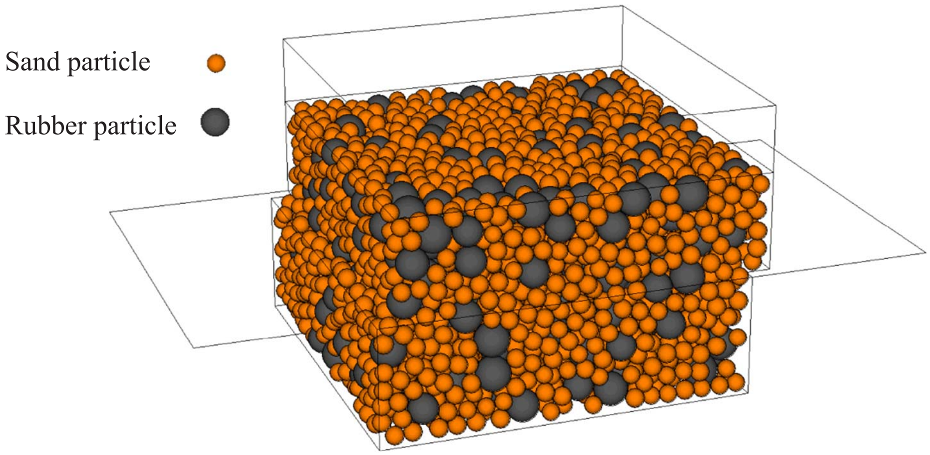

Fig. 2. Material assembly in direct shear boxes.