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Discrete element modelling of a soil-rock mixture used in an embankment dam

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ABSTRACT

The deformation and failure mechanism and the mechanical behavior of soil and soil-rock mixture used in an embankment dam was studied using numerical testing, based on a discrete element method (DEM). In this work, a 3D random meso-structure modelling system of soil-rock mixture is developed and used to generate a meso-structural model of soil-rock mixture. A non-overlapping combination method was used to model convex polyhedron rock blocks for the DEM numerical simulation. Based on the Voronoi cell, a method representing volume strain at particle scale is proposed. Results show that there is close contact between macro mechanical behavior and deformation localization of the sample. Rotation, occlusion, dilatation and a self-organizing force chains are remarkable phenomena of the localization band, and occur simultaneously with localization. Rock blocks influence localization characteristics and distribution of the force chains of the soil-rock mixture sample. Rotation and overcoming of the occlusion of the larger rock blocks in the localization band are more difficult than for small soil particles, which is the important reason for higher shear strength of soil-rock mixture than that of soil. The shearing process leads to anisotropy of the contact force, reaching its maximum at the start point of the plastic deformation, and then begins to decrease in the subsequent process.

1. Introduction

Soil-rock mixture (S-RM) is widely distributed in nature and is widely used as filling material in geotechnical engineering. For example, to improve the mechanical behavior of core wall in higher embankment dams, (S-RM) obtained by mixing oversized particles with a content of 35% to the cohesive soil is used for the first time as the core wall material of the Nuozhadu embankment dam, China. And a series of in-situ direct shear tests have been done to study the mechanical behavior of the (S-RM) used in the core wall.[1] However, given limitations of testing techniques, it is very difficult or nearly impossible to study the meso-mechanics, deformation and failure mechanisms of geotechnical materials by traditional testing methods.

Numerical methods have great advantages for better understanding mechanical behaviors of geotechnical materials from a meso-mechanical point of view. In particular, the discrete element method (DEM), in which geotechnical material is represented as an assemblage of particles that interact with each other,[2] provides strong insight into the shear strength and deformation properties of granular materials. With increasing computational speeds, DEM has interested many researchers in simulating and analyzing the response of geotechnical material to applied loads and deformations.[3] Examples of such studies include the clay aggregate formation process during sedimentation,[4] evolution of microstructure inside and outside the shear band of the granular media,[5–8] micro-mechanical properties and failure process of rock or rock mass,[9–12] and others.

Although there are many criticisms of the direct shear test,[13,14] in terms of simplicity and lower cost, the test is one of the most commonly used field tests for determining shear strength parameters of geotechnical material.[15–17] To gain insight into evolution of the meso-structure and meso-mechanisms of samples during the shearing process, direct shear tests based on DEM have been conducted. Many of these studies focused on two points, influence factors of the direct shear test[26,19] and evolution of the shear band at meso-scale and its relationship with the macro behavior.[17–20] All these studies provide significant insight into the direct shear test in geotechnical material. However, most studies were in two dimension and used fine granular materials; only a few examined coarse-grained materials.[19] Moreover, the shape of large particles were considered the simplest spherical particles (disks for 2D or spheres for 3D), which greatly ignores the important influence of the angularity of large particles on mechanical behavior of the

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materials.

From a mechanical viewpoint, the macro-mechanical behavior of soil-rock mixture (S-RM) is strongly affected by properties of rock block particles such as proportion, size distribution, shape and crushability. Using digital image processing (DIP), the meso-structure of (S-RM) has been created, in which rock blocks with arbitrary shapes are represented by two-dimensional image. Then meso-mechanical behaviors are studied based on the FEM[21] and DEM.[22,23] For the influence of the large rock blocks, mechanical behavior of (S-RM) in 3D may be different from analysis results of 2D simulation. However, there are very few studies of the 3D meso-mechanical behavior of (S-RM).

Based on in-situ direct shear tests by,[1] here we present some preliminary results of an ongoing analysis of the mechanical behavior of (S-RM) that couples physical tests and DEM simulations. The numerical simulations were conducted with an open source programming code YADE.[24,25]

2. Model generation

The structural characteristics of (S-RM), such as shape of the rock block, particle distribution and rock block content, greatly influence its deformation and failure mechanism and macro-mechanical behaviors. Building a meso-structural model is an important precondition for numerical analysis of the meso-mechanics of (S-RM). To study the influence of rock blocks on (S-RM) meso-mechanics, studies have used regular geometrics (such as a sphere or box) of different sizes to represent the rock blocks,[26,27] which greatly ignore their angularity characteristics. However, their angularity is important for influencing of the meso-mechanical behavior of (S-RM).

In present work, a 3D random meso-structure modelling system of (S-RM) (R-SRM^{3D}) has been developed, which can randomly generate the meso-structural model of (*s*-RM) with arbitrary convex polyhedron rock blocks, according to structural characteristics such as rock block size composition, rock block content, and others.

The DEM can have different geometries, but circular (2D) and spherical (3D) particles are the most common shape. Given this condition, the main modelling method to describe arbitrary irregular particles is usually clumping a certain number of disks for 2D[28,29] or spheres for 3D.[30–33] This may greatly simplify contact detection between complicated blocks and greatly reduce calculation cost. There are two methods for representing an irregular particle based on sphere assembly. One is the non-overlapping combination, in which no overlap is permitted between any two spheres[28,30,31,33,34]; the other is the overlapping combination, in which two adjacent spheres overlap.[29,32] In this study, the non-overlapping combination method was used to describe the convex polyhedron rock blocks (Fig. 1). This process was done using the open-source DEM software YADE, via the following steps:

(1) Importing the geometric model of a convex polyhedron rock block, and generating random dense packing of spheres with the given geometric model of the rock block, using YADE.
(2) Taking the geometric surface of the rock block particle as the fixed boundary, the program is run, letting the spheres fill the internal space of the rock block. Very little overlap is permitted between any two spheres by amplifying their radii.
(3) Repeating steps (1) and (2) for all convex polyhedron rock blocks composing the (S-RM) sample.
(4) Since all rock blocks composing the (S-RM) sample are represented with clumps of spheres, sphere particles are generated to describe soil of the (S-RM) sample according to size distribution and porosity.

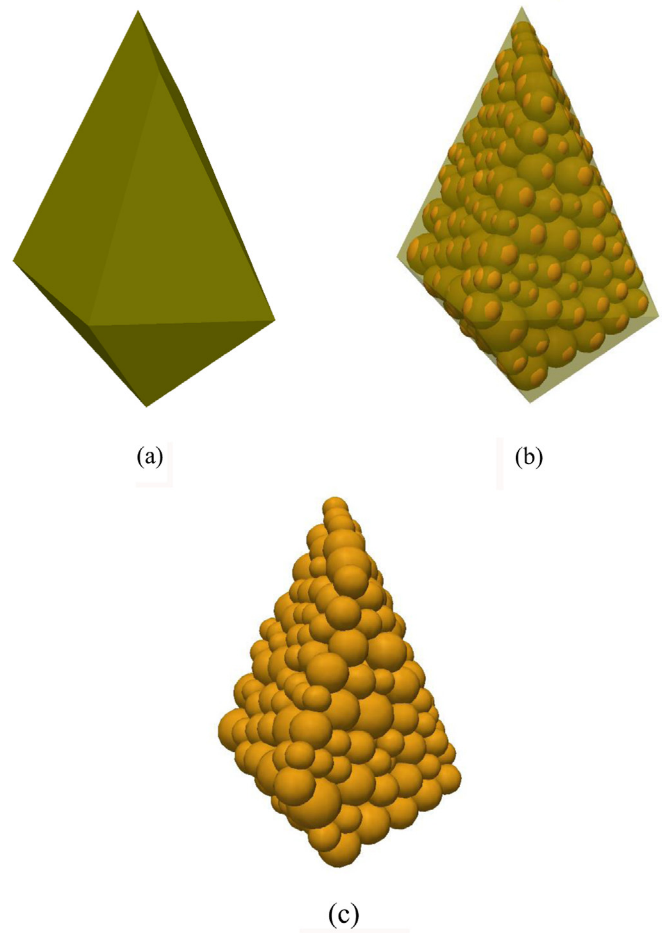

Fig. 1. Description of convex polyhedron rock block using non-overlapping combination spheres: (a) geometric model of rock block; (b) rock block with filling spheres; (c) spheres describing rock block.

According to particle size distribution characteristics of (S-RM) used in the core wall of the Nuozhadu embankment dam, China[1] and studies on the soil/rock threshold of (S-RM),[35,36] the soil/rock threshold was set to 1.5 cm, 0.05 times of the shear box height (0.05×30 cm). That is, particles in the (S-RM) sample with diameter less than 1.5 cm were taken as soil, and the remainder as rock blocks. Furthermore, considering DEM characteristics, soil particles were described by spherical particles with diameter satisfying a uniform distribution in the range of 0.9–1.35 cm. Rock block particles of diameter larger than 1.5 cm, were generated by the R-SRM^{3D} program. Considering the computational time of DEM simulation, shape of the rock blocks was divided into two types: 1) particles with diameter from 1.5 to 3.0 cm were described as spheres; 2) those with diameter larger than 3 cm were described as convex polyhedrons.

The cross-sectional dimension of the in-situ test was 60 cm in length, and 60 cm in width, and shear box height was 30 cm. To facilitate a comparison, the scale of the numerical model of the sample was $60\text{ cm} \times 60\text{ cm} \times 60\text{ cm}$, which maintained consistency with that of the in-situ test. Comparison of particle size distribution of (S-RM) between the numerical model and real sample is shown in Fig. 2. It is seen that the rock block size distribution of the (S-RM) numerical model is very similar to that of the real sample. This not only indicates the validity of R-SRM^{3D} in meso-structure generation of (S-RM), but also ensures the reliability of the numerical tests. Fig. 3(a) shows the spatial distribution of the convex polyhedron rock blocks of (S-RM) generated by the R-SRM^{3D} program, and the corresponding clump model of spheres