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Random generation of the meso-structure of a soil-rock mixture and its application in the study of the mechanical behavior in a landslide dam

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ABSTRACT

A discrete element method (DEM) numerical simulation is used as a tool to study the mechanical behavior of soil-rock mixtures (S-RM) in a landslide dam. A 2D random generation program (R-SRM^{2D}) of the meso-structure of (S-RM) based on random polygonal rock blocks has been developed, and is used to generate the (S-RM) numerical model of the study area. A new multi-circle representation method of polygonal blocks has been developed, which can better model the mechanical properties and failure process of rock blocks. A DEM biaxial test method with a flexible confining stress boundary has also been developed, which can better model the side boundary conditions of the sample. The meso-parameters of the circular particles representing the soil and rock blocks of the (S-RM) have been obtained from laboratory tests and DEM numerical simulations of soil and rock samples. Based on the meso-parameters, a series of biaxial tests of (S-RM) sample have been conducted using the DEM numerical method. The shear strength, failure process and formation mechanism of shear zones in (S-RM) have been studied. With the increase of the confining stress, the rock blocks in or near the shear zones will be broken, changing the shape of the shear zones, and leads to the shear strength of the (S-RM) sample showing nonlinear characteristics. Furthermore, the strength envelope of (S-RM) sample can be fitted through a power law function in the *p*-*q* plane.

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1. Introduction

A soil-rock mixture (S-RM) is an extremely heterogeneous and loose geomaterial formed since the quaternary, and consists of high strength rock blocks with large size, fine soil and pores (Fig. 1). In contrast to block-in-matrix rocks (bimrocks) which are a mixture of rocks composed of geotechnically significant blocks within a bonded matrix,[1–3] the matrix of (S-RM) is unbonded (or loose) soil. (S-RM) is not only a common geomaterial in nature, but also is a type of geomaterial often encountered in various engineering constructions. The Wenchuan earthquake (Ms 8.0), which occurred in Sichuan, China on May 12, 2008, caused a large number of landslides and formed many (S-RM) in the area. The study of the mechanical behavior of (S-RM) is very important for understanding stability evolution of this kind of geomaterial in reconstruction after such disasters.

The meso-structural characteristics of (S-RM) play a major role in the behavior of its deformation and the failure mechanism at the meso- and macro-scales. As the size of rock blocks in (S-RM) is large, it is difficult to carry out field or laboratory tests at full scale. Fortunately, numerical simulations provide a powerful tool for the study of the mechanical behavior of geomaterials under complicated conditions. However, building a reasonable model of the material is one of the most important factors that influences the reliability of the numerical tests.

Many researchers have studied the distribution characteristics of the rock blocks in (S-RM). Through the study of the rock block content, block sizes and other characteristics of the mélanges in Franciscan, Northern California, Medley et al. [1,4] found that the block size distributions was fractal and scale-independent, and the block/matrix threshold size was presented as $0.05L_c$ (where L_c is the characteristic engineering dimension). By using survey tape, photographic technique and sieve analysis methods, Casagli et al. [5] studied the grain size distribution of the (S-RM) of forty-two landslide dams, and found that a marked bimodal distribution was found in the frequency diagrams. Through many field sieve analyses and digital image analysis of the rock blocks size distribution of (S-RM), Xu et al. [6] revealed that there is self-organization of the meso-structure of (S-RM), and the rock blocks size distribution of (S-RM) shows a good linear correlation in log-log coordinates. All

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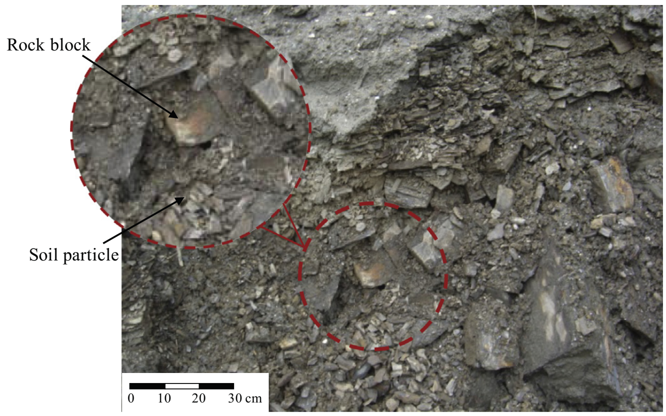

Fig. 1. The basic composition of (S-RM) (from Tangjiashan landslide dam).

these results indicate that the spatial arrangement and size distribution of the internal "rock" blocks have well defined statistical characteristics. Using the statistical characteristics of (S-RM) meso-structure to build the meso-structural model and conducting numerical simulations based on the model, will be very important for the study of the mechanical behavior and strength characteristics of (S-RM).

Randomized computer simulation has provided a powerful tool for the random generation of the meso-structure of materials. It has previously been widely used in the study of the meso-mechanics and failure mechanism of concrete.[7,8] In recent years, based on the spherical rock blocks, Tsesarsky et al. [9] studied the elastic moduli and isotropy of bimrocks. In the study of (S-RM), 2D random models of (S-RM) based on regular shaped rock blocks (such as: circular, triangular, rectangular etc.) have been used,[10] and a series of numerical simulations undertaken to study the mechanical behavior of (S-RM). However, the simplification of the rock blocks' shape may greatly influence the analysis results.

In numerical simulation, the discrete element method (DEM) provides a very useful approach for insight into the failure mechanisms and mechanical behavior of geomaterials, in which the solid material is generally represented by a series of particles and can easily consider the structural characteristics at meso-scale.[11–14] Because the contact detection algorithm between non-round particles is very complex and time consuming,[15] the application of non-round shaped particles has been rather limited,[16] and Disc (2D) and spherical (3D) shaped particles are most commonly used in DEM to simulate particle geometries. However, round particles cannot adequately represent the real particles in geomaterials, such as rock blocks in (S-RM). Using the round particles to represent the real shape of the rock blocks may affect the validity of the analysis results, so it is preferable to model the shape of the particles with more sophisticated shapes. Modeling arbitrary irregular particles has usually integrated a number of circular disks for 2D [17] into one complex particle. There are two methods for representing a 2D irregular particle based on an assembly of circles. One is the overlapping combination, in which two adjacent circles overlap.[13,16,18] The other is the non-overlapping combination, in which no overlap is permitted between any two circles.[17,19,20] The former can represent the polygonal particles well, but cannot adequately simulate fracturing of the particles. Fracturing of the rock blocks will greatly affect the mechanical behavior of (S-RM) sample. To have a good simulation of the mechanical behavior of rock blocks in (S-RM), the non-overlapping combination method was used to describe the polygonal rock blocks, and a new multi-circle method is provided in this paper.

The first part of this paper presents a random generation method of the meso-structure model of (S-RM) based on arbitrary polygonal rock blocks, and an automatic generating software (R-SRM^{2D}) is developed. Using R-SRM^{2D} and the rock block size distribution characteristics of the Tangjiashan landslide dam formed in Wenchuan earthquake, a meso-structure model of the (S-RM) of the landslide dam is generated, and is used for the following DEM numerical simulations. The mechanical behaviors and failure mechanism of (S-RM) were then studied using DEM biaxial tests.

2. Model generation of (S-RM)

2.1. Key problems of the Stochastic model generation of (S-RM)

There are two key problems in the generation of the meso-structure of (S-RM) using stochastic methods: rock block size distribution characteristics, and the spatial location of the generated rock blocks.

2.1.1. Rock block size distribution

The rock blocks size distribution of (S-RM) shows good linear correlation in double logarithmic coordinates according to Xu et al. [6], providing the basis for the generation of the size distribution of rock blocks of (S-RM). According to the study results, the fractal dimension number of rock block size of (S-RM) can be obtained on the basis of statistical analysis of rock block content of (S-RM) through digital image processing (DIP), indoor screening or field screening. The fractal dimension number and the soil/rock threshold (S/RT) of (S-RM), the maximum grain size of rock $d_{\max}$ can then be obtained from the double logarithm coordinates:

$$d_{\max} = d_{S/RT}\left(\frac{100}{100 - R_p}\right)^{1/(3-Dim_r)} \quad (1)$$

where Dim_r is the fractal dimension number of the rock block size; R_p is the rock block content (%), and $R_p=100\text{-}P(d_{\mathrm{S/RT}})$; $P(d_{\mathrm{S/RT}})$ is the cumulative percentage content of grain size finer than $d_{\mathrm{S/RT}}$ (%), or "soil" content; $d_{\mathrm{S/RT}}$ is the soil/rock threshold.

The rock block size is divided into several groups according to the soil/rock threshold ($d_{\mathrm{S/RT}}$) and the maximum grain size ($d_{\max}$). The upper limit value of each group is set to the grain size of that block group, and the rock block group order is sorted in descending order. Therefore, the grain size of first rock block group is $d_r(1)=d_{\max}$ …, and the percentage of rock block content of the i^{th} rock block group in the total sample is:

$$\Delta R_p(i) = 100\cdot\left[\left(\frac{d_r(1)}{d_r(i)}\right)^{-(3-Dim_r)} - \left(\frac{d_r(1)}{d\ (i+1)}\right)^{-(3-Dim_r)}\right] \quad (2)$$

where $d_r(i)$ is the upper limit value of the ith rock block group, $d_r(i) > d_r(i+1)$; $\Delta R_p(i)$ is the percentage of rock block content of the i^{th} rock block group.

2.1.2. Spatial location of rock block

When the geometry model of a single rock block is determined, the spatial position and orientation of rock block need to be determined in the next step, which consists of two parts:

(1) The position of the rock block centroid: it is difficult to express the coordinate of the rock block centroids with a corresponding mathematical function due to the randomness. In order to simplify this process, the centroid coordinate is supposed to satisfy the random uniform distribution in the generation space.
(2) Rock block occurrence: that is, the main axial orientation and inclination of rock block. According to [6], generally, rock blocks

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