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Investigation of scale effect of numerical unconfined compression strengths of virtual colluvial–deluvial soil–rock mixture

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ABSTRACT

A series of numerical unconfined compression tests for virtual pseudo three-dimensional colluvial–deluvial soil–rock mixture (CDSRM) specimens with different areal block proportions (*BP*s), sizes and slenderness ratios were conducted to study the variations of strength, deformability and failure process. Surrogate models of the specimens were generated on the basis of statistical characterization of the mesostructures extracted from the outcrop images of Baishuihe landslide site located in Three Gorges Reservoir Area of China. We find that the strength exhibits reduction for higher *BP*s and exhibits enhancement for lower *BP*s when the size increases and become asymptotic eventually. The deformability shows a monotonically increasing linear correlation with the specimen size for most *BP* scenarios. Simultaneously, the strength and deformability values decrease with the specimen slenderness monotonously. These findings are different from the previous assumption that the geo-mechanical behavior of bimrock is scale-independent. Comparing the observations of this study with the reported scale effect of other geotechnical materials, we conjecture that the scale effect is due to the block size and distribution.

1. Introduction

The soil–rock mixture (SRM) is a term describing the distinctively chaotic geo-materials composed of a variety of stronger blocks (rock) with different lithologies and sizes embedded in pervasively fine-grained weaker matrix (soil) [1–4]. Despite of a few researches focused on this geo-material, different terminologies have been used in the literature for mixed geo-materials similar to SRM, such as bimrock [6–28], mélange [6–14], rock and soil aggregate [30], conglomerates [33], to name a few. Similarly, Medley defined the mixed soils such as colluvium and glacial till as bimsoils (block-in-matrix soil) as well [9].

Among them, the colluvial–deluvial SRM (CDSRM) is the main composition of debris landslides, which are extensively distributed in Three Gorges Reservoir Area (TGRA) of China. It is reported that the debris landslides account for 64% share of the 1736 landslides discovered in the upstream area of the Yangtz River [5]. Therefore, it is of great importance to understand the geological properties as well as the mechanical and hydrological behaviors of this complex material. Relatively speaking, CDSRM discussed in this research is more of an interpretation of bimsoil.

The studies on the aforementioned geo-materials can be summarized primarily based on two categories including the inherent attributes of the geo-material (study-A) [8–11,28,36], and the geo-mechanical response subject to various external driving forces (study-B) [1–4,6–7,12–27,29–34].

With respect to study-A, several methods can be employed for characterizing the block inclusions, involving the one-dimensional (1D) scanlines (boreholes) method [8,9], the two-dimensional (2D) image process technology [19,31,32], as well as the three-dimensional (3D) sieving method. The 1D scanlines (boreholes) method and the 2D image process technology can be utilized as equivalent of the volumetric proportion of brock inclusions according to the law of stereology [14]. Sonmez [15] also indicated that if the shape of blocks of a bimrock was approximately equal-dimensional in 3D, the block proportion obtained from 2D measurement can be considered equivalent to the 3D volumetric block proportion. As for the 3D sieving method, it can be easily performed at the laboratory scale, but for larger volumes it becomes cumbersome and very expensive. Moreover, this technique is unable to investigate the morphological and spatial variability of this geo-material [19]. Consequently, although the 2D image process technology has its limitations, it is a relatively fast, non-destructive and inexpensive method for extracting and studying the morphological properties of SRM. Based on the methods, some main definitions of typical bimrock have been established [8,14]. For instance, the maximum and minimum sizes of the

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blocks are conventionally assumed to be 5% and 75% of the characteristic engineering dimension respectively (L_c, the scale of engineering interest such as the tunnel diameter, thickness of a landslide, laboratory rock specimen diameter, etc.).

With respect to study-B, different testing methods such as uniaxial compression, tri-axial compression, and direct shear are usually conducted in physical and numerical experiments. Physical experimental approaches are essential to study geo-mechanical behavior for geo-materials. Direct observations by means of laboratory experiments [6,7,15–17,21,22,24,29], and in-situ mechanical experiments [1,4,18,30] have provided a great deal of insights into the complicated geo-mechanical behaviors of SRM. In summary, volumetric block proportion (*VBP*) has the most remarkable influence on the overall strength and deformational modulus of mélange [6,7], Ankara Agglomerate [15–17], rock and soil aggregate [1,30] and shale-limestone chaotic complex bimrock [19].

Numerical experiments have become increasingly popular in the study of geo-mechanical response of SRM by virtue of various methods like the finite-element method [2,3,20,23,26,27,30–32], the discrete-element method [33,34], and the finite-difference method [25,27,35]. The numerical approach is capable of reproducing the typical phenomena in the physical experiments without limitation of the experimental conditions and specimen dimensions. Thus some new conclusions involving the influence of block inherent attributes might be drawn. For instance, Pan et al. [35] simulated 2D tri-axial compression tests with different *VBP*, shape and orientations of polygonal blocks using a 2D finite-difference code. The results showed an increase in the Young's modulus when *VBP* exceeded a limit above which the inter-block contacts started to dominate the mechanical behavior. Moreover, the strength and the Young's modulus were significantly affected by the orientation of blocks. Of course, any numerical experimental results, no matter how good they are, must be eventually tested against the physical experiments to ensure their credibility.

Up to now, there are only a handful of studies focusing on the influence of specimen sizes on the geo-mechanical response of SRM subject to external forces, namely scale effect. Medley [8] pointed out that mélange were self-independent, having the same general appearances regardless of scale, with a few large blocks and an increasing number of smaller blocks. Log-histogram [36] was utilized to investigate the observed maximum dimension of blocks of mélanges outcrop exposures with several orders of magnitude as well. The slope of the right linear limb (excluding the blocks smaller than $0.05L_c$, which were assigned to the matrix) of the log-log plots is the fractal dimension. The results of surveyed blocks showed significantly similar shapes and nearly the same fractal dimensions of the blocks despite the extremely different measure areas [8]. Based on this study, other researchers assumed the geo-mechanical behavior of other chaotic geo-materials also as scale-independent, and the reported experiments usually investigated the relative dimensions of specimens and the maximum blocks, thus did not address the scale issue [1,18,30]. For instance, Xu et al. [1] proposed that the height of a specimen should be five times larger than the maximum fragment diameter in an in-situ test. Coli et al. [18] studied the blocks with a maximum dimension of about 1/10 of the specimen volume in an in-situ shear test. Nevertheless, the nature of scale-independency is a statistical criterion based on the block dimension distribution without considering other morphological characteristics of blocks such as orientation angle and distribution location. Moreover, the criterion may not be applicable for other geo-materials other than mélanges.

The purpose of this research is to investigate the geo-mechanical scale effect of the CDSRM extensively distributed in TGRA of China under external forces using a numerical approach, which can be utilized to efficiently simulate a vast number of possible cases. Specifically, we will consider unconfined compression tests for CDSRM specimens in this study. Further research on other types of tests will be reported elsewhere. The size effect of the specimens on uniaxial compression process has been investigated extensively in other geotechnical materials such as rock [40–43], jointed rock mass [44], and concrete [45]. Those researches provide useful datasets for comparison with our study.

This study has three objectives. Firstly, to generate the virtual CDSRM surrogate models based on the statistical characterization of the block mesostructures extracted from outcrop photographs from a typical landslide (Baishuihe landslide) in TGRA. Secondly, to conduct numerical unconfined compression tests for the CDSRM specimens with various sizes and slendernesses (height/length ratios) to observe the possible scale effect on strength, deformability and failure process. Thirdly, to compare the results of CDSRM specimens with different block proportions and the results of other geotechnical materials for better understanding of the mechanism.

2. Mesostructural characteristics of CDSRM based on image process

2.1. CDSRM image sampling and process and mesostructural indexes extraction

To better understand the mesostructural characteristics of CDSRM in TGRA, the 2D digital images process was utilized for analyzing the images of the accessible outcrops sampled in Baishuihe landslide, located in Zigui County, Yichang City, Hubei province of China, an area within TGRA (Fig. 1). The landslide site is on the south bank of the Yangtze River, 56 km west of the Three Gorges Dam. The landslide covers an area of 0.42 km^2 with an estimated volume of 12,600 m^3. The fan-shaped landslide extends from an elevation of 75 m to 410 m above mean sea level. Five drill holes had been performed in the main deformation zone to investigate the lithology and to arrange the monitoring devices. The drilling logs and recovered drilled cores (Fig. 1) illustrated that the argillaceous siltstone and silty mudstone rock fragments are randomly distributed throughout the clayey soil matrix without any specific orders. The thickness of the CDSRM varied from 3 m to 25 m, with thinner in back edge, and thicker in the front. Our field investigation and the drilled cores also indicated that the maximum observed dimension of the blocks in the mixture was mainly in the range of 20–200 mm, with a few blocks close to 300–500 mm in dimension.

We selected six outcrops (the sampling location noted in Fig. 1) in this region because most of the area was covered by thick vegetation and was inaccessible. The actual dimension of the sampled photos lied between 1.2 m and 2 m because of the dimensional restriction of accessible outcrops. According to the field investigation and drilled cores, all the photographing outcrops can be regarded as representative samples of the site.

The 2D image process was then be utilized to isolating the blocks from the matrix through numerical codes [19,31]. The image process primarily consists of pretreatment and segmentation procedures. The pretreatment procedure includes noise removal, monochromatic gray-scale image conversion, gray value transformation, filtering and contrast enhancement. The segmentation procedure is subsequently used to convert the monochromatic gray-scale image to a binary image composed of black and white pixels ("0" and "255"s) by defining a grayscale cutoff point. The pretreatment and segmentation procedures can be performed using open-sourced software ImageJ [46].

Sometimes the program cannot automatically detect the ideal effective edges between two regions for certain image samples because of the light reflection differences caused by roughness of outcrops and the illegible edges between matrix and blocks. For