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Use of X-ray computed tomography to investigate the effect of rock blocks on meso-structural changes in soil-rock mixture under triaxial deformation

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HIGHLIGHTS

- Using X-ray CT to study meso-structural changes of SRM under triaxial loading.
- Scale of localized bands increases with increasing rock block percentage.
- Regions of localization present irregular tortuosity and affected by rock blocks.
- Localized band disappears and appears repeatedly owing to interaction between rock block and soil matrix.

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ABSTRACT

Construction and building of engineering structures in geomaterials with soil and rock mixture (SRM) are often challenging tasks for engineers. While the effects of rock block content on the macroscopic mechanical properties have been widely studied, the physical meso-scale mechanisms governing the SRM deformation are still poorly understood. Here, we applied a high energy X-ray Computed Tomography (CT) imaging method to study the influence of rock block content on the mesoscopic structural changes and the associated strain localization behaviors in SRM. Triaxial compression experiment was conducted for the SRM samples with rock block percentage (RBP) of 0%, 30%, 40%, and 50%, respectively, under a confining pressure of 120 kPa. The meso-structural changes were quantitatively studied using the macroscopic stress–strain descriptions and mesoscopic CT images identification. Under triaxial deformation, the stress–strain curves present strain hardening behavior, strength of the sample increases with increasing RBP, which can be verified from the interlocking of rock blocks, and skeleton role of blocks improves the capacity to resist deformation. In addition, regions of localization are extremely non-uniform and strongly affected by the rock blocks, scale of the localized bands presents a incremental trend as RBP increases. What is more, the most striking observation from the reconstructed images is that zone of localization may disappear during deformation owing to the interactions between the rock block and soil matrix. Through a series of meso-structural evolution analysis, the meso-mechanisms of the effect of rock block content on SRM under triaxial deformation have been documented.

1. Introduction

A special kind of geomaterials with a texture of stiff rock blocks surrounded by weaker soil or soil-like matrix was widely distributed in the nature. This kind of geomaterial is often called as soil and rock mixture (SRM) [1–8], or as bimrocks [9–12]. Not only widely distributes in nature, SRM is also widely used as fillings material in the geotechnical engineering. Design and construction of engineering structures in SRM such as breccias, conglomerates and agglomerates are always challenging tasks for engineers. SRMs are the basic material source of large-scale geology disaster, such as mudflows, landslide and debris flows, etc. In embankment and subgrade constructions, SRMs are usually obtained by mixing oversized particles with a certain content to the cohesive soils [1]. From the structural component, this geomaterial has distinct internal structures consisting of soil particles, rock blocks, pores, and cracks [3–8,9,13,14,15]. Among many factors affecting its mechanical

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properties, the rock block percentage is always the first factor to be considered. The presence of rock blocks greatly influences the stress and strain distribution inside a SRM, especially when the rock block percentage is high enough to form a skeleton with many interactions between the rock blocks, which will largely control the mechanical behaviors of the mixture.

Medley [11] conducted systematic laboratory tests of Franciscan melange samples obtained from core drilling at Scott Dam, Northern California, and studies the relationship between the effective friction angle and the volumetric block proportion, and found that the effective friction angle increases with increasing rock block content only above 20% of the volumetric block percentage. Slatalla et al. [16] used acoustic emission (AE) technique to investigate the response of a SRM in uniaxial deformation, the results show that the volumetric block proportion as the most obvious factor strongly influences the stress distribution in SRM, which in turn trigger the specific AE signatures. Coli et al. [10] and Xu et al. [17] performed large-scale field tests, and their test results show that there is a positive correlation between the internal friction angle and the rock block percentage, but that cohesion changes little when the rock block content exceeds a threshold value. Wang et al. [2] performed a series of meso-numerical tests, their results show that the uniaxial compressive strength of SRM decreases with the increase of rock block percentage, when the soil matrix properties are the same. Afifipour et al. [12] studied the post-peak behavior of SRM under uniaxial deformation, the results show that the samples with the highest RBP (around 90% by mass) show a small decrease in stress with increasing strain in the post-peak region; however, for samples with lower RBP, steep fall in stress and following to residual stress occurs. Zhang et al. [18] performed a series of numerical unconfined compression tests for SRM, they found that SRM strength exhibits reduction for higher block content and exhibits enhancement for lower block content when the size increases and become asymptotic eventually. Wang et al. [5–6] used the ultrasonic measurement to study the ultrasonic and mechanical characteristics of SRM under uniaxial and triaxial compression deformation, results show that the ultrasonic pulse velocity (UPV) decreases, and attenuation coefficient increases with the increase of rock block content. Wang et al. [7] performed a series of systematic uniaxial compressive tests at both low and medium strain rates in the range of $10^{-5}{\cdot}s^{-1}$ to $10^{-2}{\cdot}s^{-1}$, for SRM samples with RBP of 20–50%, results show that SRM samples with lower RBP have a range of strain rates resulting in the increment of peak stress relatively larger than samples with higher RBP. Their results indicate that mechanical properties of SRM at a medium strain rate are strongly relative to the internal structure. They also used 3-D laser to map the roughness of fracture surface and calculate the fractal dimension, results show that fractal dimension of SRM with high RBP is larger than sample with lower RBP under the same strain rate.

Although many significant efforts have been done to investigate the mechanical properties of SRM, almost all the experiments were done using macroscopic experiments [7–17], the physical meso-mechanism governing the SRM deformation are still not well understood. Since it is difficult to observe and monitor the internal structure and to quantitatively characterize its changes in the physical tests. Experimental studies using mesoscopic methods on the mechanical properties of SRM containing different rock block contents are relatively few in literature.

In the recent years, many efforts have been done to monitor the in-situ physical characteristics of deformation occurring within the tested sample: such is the case of acoustic emission monitoring the occurrence and location of cracking events (AE) [12,19–21], of real time ultrasonic testing analyzing the variation of velocity and attenuation (Wang et al. [4]), or 3D laser scanning mapping of roughness of sample surface [5]. Another non-destructive technique is the computerized tomography (CT), which offers real-time information on the variation of some physical parameters occurring in the tested specimen. This technique has been widely used in the rock and soil material and can be found in [22–27]. However, application of X-ray CT in SRM is not common, revealing the structural change evolution of SRM in-situ is crucial to the stability prediction of geological body composed of SRM, and to develop new damage constitutive equations. Wang et al. [2] used CT scanning in SRM, and analyzed the CT number variation during sample deformation, the crack characteristics are only investigated after failure (i.e., post mortem). Zhang et al. [18] conducted triaxial deformation experiment on SRM sample with the same rock block content by different block distribution, by using a medical CT machine, the SRM sample before and after failure have been observed. In data, the meso-structural changes of SRM with different rock block percentage are rarely reported after literature review, and the physical meso-scale mechanisms governing the SRM deformation are still not well understood.

In this work, we study the meso-structural changes in SRMs with RBP of 30%, 40%, and 50% through a series of triaxial tests performed at the same confining pressure of 120 kPa. To well describe the role of rock block controlling the failure mechanism of SRM, a soil sample under the same confining pressure is also tested. The aim of this paper is to present an overview of the deformation process of SRM using a novel specially designed loading device, combination with the high energy X-ray CT scanning technique. Rather than focus on the effect of rock block on the macroscopic stress-strain responses, this work explores how rock block affects the meso-structural changes by interpreting various stages of its progressive failure. The paper presents and discusses the effect of rock block content on the meso-structural mechanical properties of SRM, the influences of rock block on the evolution of the meso-structures and localized bands are investigated.

2. Materials and methods

2.1. The tested material, sampling and preparation

Cylindrical samples with size of 50 mm (diameter) × 100 mm (height) were used in the experiment. Referring to the sample preparation standard (Standard for soil test method, GB/T 50123-1999) [28], diameter of blocks should be less than 10 mm, threshold value for soil particle and rock block is 2 mm. The natural density, dry density, and relative density of the soil is 1.66 g/cm^3, 1.52 g/cm^3, and 2.72 g/cm^3, respectively. The soil contained lots of clayed mineral with strong hydrophilic, the liquid limit and plastic limit of the hard clay were about 63.54% and 26.32%, respectively; the plasticity index and liquidity index were about 37.72 and 0.05–0.127, respectively. Scanning Electron Microscope (SEM) and X-ray diffraction (XRD) tests were conduct to identify the mineral composition and mineral content. From SEM tests, rodlike and irregular quartz grains surrounded by clay minerals can be observed, its size was about 0.01–0.03 mm, as shown in Fig. 1. The XRD tests revealed that the soil has a higher percentage of clay mineral, such as montmorillonite (61.52%), kaolinite (26.73%), and illite (6.25%). Rock blocks used in the test is marble stone with size of 2–4 mm and 6–8 mm, and their mass ratio was 1:1. Natural density of rock blocks is 2.67 g/cm^3, the dry compressive strength is about 94.5 MPa.

Compaction test was used to prepare the SRM samples [3–6,29,30], the optimal hammer count was determined according to the relationship between the density and the compaction count. In order to ensure the homogeneity of the samples, the rock blocks were mixed by hand into the soil for several minutes. During the preparation of SRM samples, the RBP was designed as 30%, 40%,