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Stress-strain behavior of soil-rock mixture at medium strain rates – Response to seismic dynamic loading

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ABSTRACT

This paper aims to investigate the seismic dynamic responses of soil-rock mixtures (SRM) at medium loading strain rates. A total of 130 SRM specimens with four rock block percentage (RBP) of 20%, 30%, 40% and 50% were produced to conduct the uniaxial compressive strength test, at strain rates of $1\times10^{-5}\,s^{-1}$, $5\times10^{-4}\,s^{-1}$, $1\times10^{-3}\,s^{-1}$, $5\times10^{-3}\,s^{-1}$, and $1\times10^{-2}\,s^{-1}$. From the experimental results, SRM presents particular rate-dependence characteristics that are different from each soil and rock material, the peak stress and peak strain first increase and then decrease with the increase of strain rate. The inflection points of rate-dependence are different for specimens with different RBP. The rate-dependence characteristic of SRM is strongly influenced by the rock blocks in the SRM specimen. In addition, crack initiation stress level σ_{ci}/σ_f and crack damage stress level σ_{cd}/σ_f do not change with the increases of strain rate. What is more, the experimental results also show that the failure pattern of SRM performs as a spitting failure, shear failure, and conical failure at various strain rates. All the test results proved the particular seismic dynamic responses of SRM, and the interactions between the rock blocks and the soil matrix are the primary factor determining the dynamic response.

1. Introduction

The soil and rock mixture (SRM) [1–4] is a complex formation characterized by competent rock inclusions floating in a weaker soil matrix structure. SRM always represents a challenging engineering problem: the mechanical behavior of SRM is controlled by the interaction and the geometrical properties of rock blocks. The mechanical and physical properties of SRM are characterized by the extreme nonhomogeneity, looseness, and environmental sensitivity. Due to the wide distribution of SRM in nature and its close relationship to geological engineering problems, the studies on SRM have attracted more and more attention. Over the past ten years, considerable research has been devoted to characterize SRM behaviors under static loading (i.e., strain rate is generally less than $10^{-5}\,s^{-1}$). Fragaszy et al. [7] conducted consolidated-drained triaxial tests, that have shown that the stress–strain and the volumetric strain–axial strain behavior of the prototype soil are not influenced by subrounded-to rounded grains floating in the matrix. Lindquist [8] conducted a series of triaxial laboratory studies on artificial SRM specimens made up of a sand-cement matrix with elliptical-shaped blocks. Vallejo and Mawby [9] studied the shear strength of saturated cohesive soil with floating rock particles through laboratory shear tests, and they show that the shear strength of clay–rock mixtures gradually increases with increasing percentages of floating particles in unsaturated clays. Springman et al. [10] studied on the physical and mechanical characteristics of the material from an ice-water accumulation slope under saturated and unsaturated conditions, and discussed its failure mechanism under rainfall conditions. Xu et al. [11] carried out a large scale direct shear test, and found that with the increment of the rock block percentage the shear band of the SRM increases. When the rock block proportion lies in the range of 25–70%, the increment of the internal friction angle linearly increases with the increment of the rock block proportion. Slatalla et al. [12] studied the acoustic response of a fault breccias SRM under uniaxial compression, showing that the different geometrical properties, particularly the volumetric block proportions, are reflected by stress concentrations which in turn trigger specific AE signatures. Coli et al. [13] carried out six non-conventional in-situ shear tests to investigate the strength properties of the Chaotic SRM with shale–limestone blocks. They found a good linear positive correlation between the rock block percentage and the friction angle. By means of laboratory uniaxial tests, Wang et al. [3,4] studied the meso-cracking characteristics of SRM using a real-time ultrasonic test and a CT test. The interaction between rock blocks and soil matrix has been revealed from the ultrasonic pulse velocity and CT number. Despite these research efforts, the medium strain rate response of SRM is still not well understood, which points to the need for systematic research on

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the mechanical properties, damage fracture mechanism, and associated dynamic response.

SRM responses to medium strain rate (10^{-4} s^{-1}–10^{2} s^{-1}) is significant to the study of many engineering problems, such as earthquakes, rock bursts, and mine blasts, etc. Generally, the principal frequency of the seismic wave is below 20 Hz, the corresponding strain rate is in range of 10^{-3} s^{-1}–10^{2} s^{-1} [14–17]. In the dynamic disturbance phenomenons, like in many such engineering problems, the rock and soil bodies are under quasi-dynamic loading conditions with a medium strain rate. Under this loading condition, it is not only different to the traditional static loading type, but also to the explosions, air blasts, dynamic compaction, pile driving, and rapid load testing of piles [18], and projectile penetration [19–21], which are under dynamic conditions with a high strain rate ($>10^{2}$ s^{-1}). Currently, most of the studies have been concentrated on rock and soil material at medium strain rates and high strain rates. For soil materials, such as clay sand, apart from the traditional static tests, plenty of scholars [16,20,21,23,24] have already performed medium-high strain tests to study dynamic mechanical properties in conditions of explosion, compaction, etc. The dynamic properties of soft soils and sand in the range of strain rates up to 10^{3} s^{-1} have also been investigated in great detail ([25–27]or rock and rock-like materials, plenty of detailed literatures have reported their mechanical properties under medium and high strain rates in the range of 10^{-4} s^{-1}–10^{1} s^{-1} [16,17,29].

After the above literature review, the tests under medium strain rate are almost all concentrated on rock, soil, and rock-like material. Reports published about the effect of medium strain rate on mechanical properties and dynamic responses for SRM are rare. Although Wang et al. [28] have studied the effects of strain rate on the peak stress and strain of SRM, the change of characteristic stress and strain for typical specimens at different strain rates, and the rate-dependence of SRM are not included. As an extremely important geomaterial, SRM is widely distributed in China and all over the world. Many disastrous landslides are triggered by earthquakes, taking the Wenchuan earthquake China for example, the principal frequency of a seismic wave is in the range of 0.05 Hz and 0.2 Hz, thousands of landslides formed after the earthquake. Among those landslides, the substance composition of landslides is almost SRM. As a result, the study on dynamic responses of SRM under medium strain rates is of great importance. Under such loading conditions, the mathematical modeling, used inthe decision-making process, takes on a greater significance. The models used must adequately describe the SRM behavior at different strain rates. For populating and validating such models and for estimating their accuracy, an extensive database on the dynamic properties of various SRM structure over a wide range of loading intensity and strain rate is necessary. This paper performed a series of systematic uniaxial compressive strength tests at both low and medium strain rates in the range of 10^{-5} s^{-1} to 10^{-2} s^{-1}, for SRM specimens with RBP of 20–50%. Attempts are made to investigate the fracture characteristics of SRM by considering the rate-dependence, failure characteristics and failure mechanism.

2. Specimen preparation and testing method

2.1. The testing material

In this paper, specimens were cylindrical in shape with a diameter 50 mm and a height of 100 mm. According to the geotechnical test technical manuals [31] and soil specimen preparation standard BS1377-1 [30], the diameter of blocks should not be greater than 10 mm; the threshold value for rock and soil is 2 mm. When the grain size was greater than 2 mm, we defined it as a rock block; and when less than 2 mm, we defined it as soil matrix. Ten sieving tests of soil indicated that the soil belonged to clay soil (Fig. 1a). According to the geotechnical testing, some physical and mechanical parameters are shown in Table 1. The soil contained lots of strongly hydrophilic clay minerals, the liquid limit of the hard clay can reach 64%, and the plastic limit can reach to 36%; the plasticity index was about 28 and liquidity index was about 0.05–0.127, these indices indicated that this soil belonged to the typical hard plastic and high plastic clay. To identify the mineral composition and mineral content we both conducted Scanning Electron Microscope (SEM) and X-Ray diffraction (XRD) tests on the soil. According to the result of the SEM tests, as shown in Fig. 2, rodlike and irregular quartz grains with a grain size about 0.01–0.03 mm can be seen and are probably surrounded by clay minerals. The XRD tests revealed the mineralogical composition shown in Table 2. According to Table 2, it is clear that the soil has a higher percentage of clay mineral, such as kaolinite, montmorillonite, or illite.

All the previous studies indicated that rock block percentage, rock block size, and composition of fine grains have a great impact on physical and mechanical properties of SRM. Among those factors, the rock percentage is the most important factor influenced by the mechanical properties of SRM [32,4,8]. So, in this paper, we ignored the other factors influencing the mechanical properties, and the rock blocks used were corundum balls with a diameter of 8 mm (Fig. 1b). The properties of the corundum material are shown in Table 1.

2.2. Remolded specimen preparation

Remolded SRM specimens were produced for the experiments. Compaction tests were used to produce the specimens [33,34,6], and the optimal hammer count was determined according to the relationship between the density and number of compaction. According to Wang et al. [6], the density of SRM with a rock block percentage of 20%, 30%, 40%, and 50% increased with increasing hammer count, the soil density in the corresponding SRM specimens showed a similar trend to the SRM. So, the optimal hammer strike count was determined to be 20 times. During the preparation of SRM specimens, a certain amount of free water was added to the mixture. The optimal water content was determined by compaction test to be 9.5%. The required amount of rock blocks and soil material for each specimen (Table 3) were mixed and homogenized in a mixer. Then, the mixtures were poured into the cast iron test module cylinders that were 50×100 mm in diameter × height (Fig. 3a). The compaction rod was used to compact the mixture with 20 strikes for each of three layers. The specimens were then sealed with plastic wrap and allowed to air-dry (Fig. 3b). For each SRM specimen, the required amount of rock blocks and soil are listed in Table 3.

2.3. Experimental system

The testing system was specially developed by the Institute of Geology and Geophysics, Chinese Academy of Science (Fig. 4). The system is an electro-hydraulic servo controlled by the testing frequency of 0.01–5 Hz and strain rate can be achieved up to 10^{-1} s^{-1}. The main steel frame has a stiffness of 5 GN/m, the maximum axial force can reach up to 1000 kN. The machine is designed with a high-precision double close loop serve-control mode with a channel resolution of 1,000,000 levels, and an electro-hydraulic servo response with a maximum work stress of 35 MPa and a frequency response of 70 Hz. In addition, the high-precision dynamic measurement system and test operational software subsystem ensure the reliance of experimental data at medium strain rates. During the test, two kinds of loading modes can be selected according to the required strain rate. They are the deformation and the displacement controlling modes, respectively. When strain rate $\dot{\varepsilon}$ is less than 10^{-1} s^{-1}, the deformation control method is adopted; while $\dot{\varepsilon}$ is more than 10^{-1} s^{-1}, the displacement control method is used to meet the target strain rate value, which is calculated as the ratio of the strain to the duration time.

The axial and lateral deformations are measured by the linear variable different transformer (LVDT) devices. The sampling interval is