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Liquefaction characteristics of gravelly soil under cyclic loading with constant strain amplitude by experimental and numerical investigations

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ABSTRACT

In order to investigate the liquefaction behavior and meso-mechanism of gravelly soil under cyclic loading with constant strain amplitude, the undrained dynamic triaxial test, CT scan test and numerical simulations by discrete element method (DEM) are performed. Effects of gravel content and the evolution of liquefaction nmeso-mechanism are analyzed respectively. Test Results show that the liquefaction resistance of gravelly soil increases considerably with the increasing gravel content due to growing in number of gravel-to-gravel contact. DEM simulations reflect the macro mechanical property of saturated gravelly soil in the cyclic triaxial test, and show anisotropy is the most important mechanical properties of gravelly soil liquefaction under cyclic loading with constant strain amplitude. In process of the liquefaction, the backbone force-chain is gradually destroyed, and magnitude of normal contact force decreases to zero until initial liquefaction. Both of the fabric and force-chain evolution demonstrate a consistent deflection of the principal stress axis.

1. Introduction

Gravelly soil is often mistaken as non-liquefiable because of its coarser particles, and good permeability. As the natural foundation or earthwork filling materials, it is widely used in constructions of the dam filling, marine reclamation land, and highway and high-speed railway roadbed due to good qualities such as high strength, low compressibility, low cost and so on. However, the phenomenon of gravel soil liquefaction had been observed in worldwide earthquakes during the last 50 years [1–9]. In fact, a few of laboratory tests also proved the possibility of its liquefaction. Wong et al. [10], Baneriee et al. [11] performed a series of undrained cyclic triaxial tests, and found that gravel soil has "initial liquefaction" phenomenon as same as sand. Liu et al. [12], Wang et al. [13] performed comparison of the shaking table test and undrained cyclic triaxial test of gravel soil liquefaction. And test results showed the liquefaction properties were mainly determined by coefficient of permeability and drainage conditions, and related to the relative density and volume compressibility. Evans et al. [14] carried out a series of undrained cyclic triaxial tests on gravelly soils with gravel contents of 0%, 20%, 40%, 60%, and 100%. And results showed the liquefaction resistance of sand-gravel composites increased significantly with the increasing gravel content. Hatanaka [15] performed a series of large dynamic triaxial tests of nature and remolded specimens of gravel soil, and study the effects of sample disturbance on the liquefaction strength. By the cyclic triaxial tests on reconstituted gravel soil specimens, Kokusho et al. [16] concluded that the undrained cyclic strength of such soils mainly depended on the relative density rather than particle gradation. Chang et al. [17] performed a series of undrained dynamic simple shear tests to study the liquefaction characteristics of gap-graded gravelly soils with no fines content in K_0 condition. And the test results revealed that a linear relationship existed between shear wave velocity and sand content for the gravel-like sandy gravels at a given gravel skeleton void ratio, and also existed between shear wave velocity and the gravel content for sand-like gravelly sand at a given sand skeleton void ratio.

In the last decade, some studies on the liquefaction discrimination method have been carried out for gravelly soil. Lin et al. [18] performed Instrumented Large Hammer Penetration Test (LHPT) and shear wave velocity (Vs) measurements in a liquefied gravelly deposit site during the Chi-Chi earthquake to evaluate the liquefaction resistance. Cao et al. [19] developed a probabilistic dynamic penetration test for predicting liquefaction resistance of gravelly soils based on the field

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test during 2008 Wenchuan earthquake of China. It should be noted that most of the studies focused on the liquefaction resistance strength, development features of pore pressure and liquefaction evaluation, but few concerned the meso-mechanism of gravelly soil liquefaction. Typical gravelly soil is composed of a large number of solid particles, due to the inhomogeneity of particle shape, size, location, and random distribution, so it is a multi-scale structure necessarily, including the macrostructure, mesostructure, and microstructure. Generally, the macrostructure element size of soil mass is between 2 mm-10 m; the size of mesostructure is between 0.05–2 mm; and the size of microstructure is usually less than 0.05mm [20]. In this paper, the liquefaction property and meso-mechanism of gravelly soil under cyclic loading with constant strain amplitude are emphatically investigated. A series of undrained dynamic triaxial tests on saturated gravelly soil with different gravel content under the constant-amplitude strain cycle mode were performed with the GDS dynamic triaxial system. Before the tests, the initiating structure of the samples with different gravel content was scanned by computed tomography technology (CT). Then numerical simulations on the tests of saturated gravelly soil liquefaction were conducted by the Particle Flow Code(PFC). Through comparative analysis, a number of features of liquefaction behavior and the evolution law of meso-mechanism on gravel soil were studied.

2. Experimental procedures and results

2.1. Sample preparation

Gravelly soils sampled from the Hub Dam (Site II) of Shitou Gorge in Menyuan County, Qinghai Province of China with grain sizes not exceeding 20 mm were used. Next, the dried soil samples were screened with 20 mm, 10 mm, 5 mm, 2 mm, and 1 mm screens successively. The size of particles between 2 mm and 20 mm were selected as gravel, whereas those particles less than 2 mm were selected as sand and fine.

Undrained dynamic triaxial tests were carried out to examine the effect of gravel content on the liquefaction characteristics of saturated gravelly soil under cyclic loading with constant strain amplitude. In the test, cylindrical specimens 101 mm diameter and 200 mm high were used. In preparing the specimen, sand and gravel components of the soil were mixed that the gravel contents by weight P_2 were 50%,60%,70%,80%. Grain size distributions are shown in Fig. 1 and grain size parameters are listed in Table 1.

To determine the relative density of the gravelly soil, maximum and minimum dry densities were obtained from 50–80% of gravel contents. The maximum density was determined by the surface vibratory compaction method. The minimum density was determined by the fixed volume method. Fig. 2 shows the relationship between the maximum and minimum dry densities versus gravel content for the materials tested. The maximum dry density increases significantly with increasing gravel content from 50–60%, when gravel content beyond 60% the trend was reversed, and the maximum dry density decreases with increasing gravel content. While the minimum dry density decreases monotonously with increasing gravel content from 50–80%.

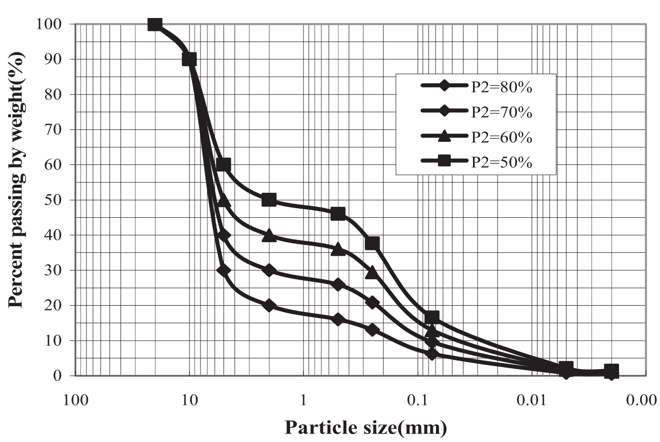

Fig. 1. Grain size distribution curve of test soil.

Table 1
Grain size parameters of test soil.

Gravel content P_2 (%)	d_{10} mm	d_{50} mm	d_{70} mm	d_{60} mm	d_{30} mm	C_u	C_c
80	0.139	6.524	7.863	7.170	5.000	51.505	25.044
70	0.078	5.988	7.579	6.779	2.000	86.925	7.567
60	0.068	5.000	7.170	6.183	0.262	91.580	0.164
50	0.066	2.000	6.503	5.000	0.156	75.742	0.074

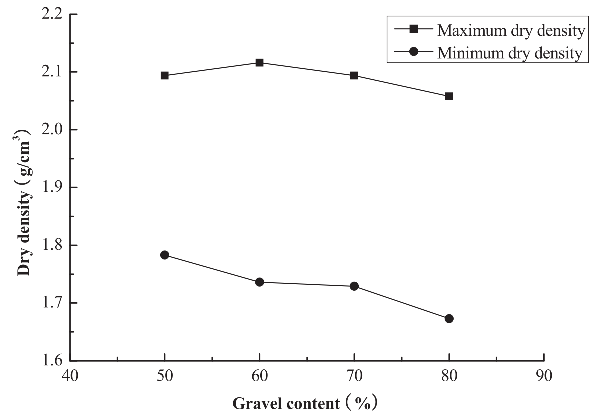

Fig. 2. Maximum and minimum densities versus gravel content.

Specimens are prepared to a constant relative density equal to 55%. The remolded samples are prepared by using multi-level wet pounding method, and the samples are composed of three layers. According to dry density and the design of each layer of soil moisture content of the soil samples, the weight of each layer is determined and the soil of each layer is compacted to corresponding height. The interface between the two layers is scarified to ensure the upper and lower layers are in good contacts.

2.2. CT scan tests

In order to study the microstructure of the gravelly soil with different gravel content, the computed tomography (CT) was applied to obtain CT images at different depth of the gravelly soil specimens for a constant value of relative density. Scanning position diagram is shown in Fig. 3. Three scanning layers were set in every specimen. CT scanning images at different depth of the gravelly soil with different gravel content are shown in Fig. 4. For gravel contents between 50% and 80%, it appears that sand particles float in the gravel matrix, gravel-to-gravel contact is separated by the sand and fines at lower

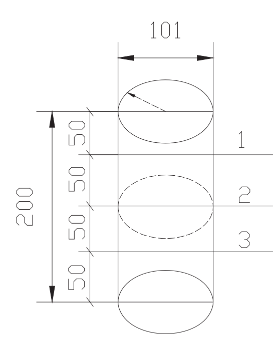

Fig. 3. Scanning position diagram (Unit: mm).