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Long-term behavior of clay-fouled unbound granular materials subjected to cyclic loadings with different frequencies

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ABSTRACT

Experimental studies were conducted to investigate the engineering geological characteristics of clay-fouled unbound granular materials (UGMs) under different-frequency cyclic loadings. The computed tomography (CT) scan was firstly conducted to examine the inner structure of UGMs with various fines contents; then a series of drained large-scale tri-axial tests were conducted on the clay-fouled UGMs under cyclic loadings with various frequencies ($f = 0.2$ Hz, 1 Hz and 3 Hz). The combined effects of the fines content and the cyclic loading frequency on the excess pore water pressure, accumulated strain and resilient modulus were analyzed. Test results showed that the dominant effects of fines on the UGMs transited from the lubrication, densification to suffocation as the fines content increased. The lubrication effect led to the increase of the accumulated axial and volumetric strain; the densification effects reduced the accumulated strain; and the suffocation effects resulted in the accumulation of excess pore water pressure and thus rapid deterioration of UGMs. The transition point of these effects were closely related to the loading frequency and loading amplitude. The drainage conditions of clay-fouled UGMs transited from full drainage to partially drainage as the fines content, loading amplitude and frequency increased.

1. Introduction

With the rapid growth of transportation demand, the volume of the traffic on the roads becomes heavier and the speed of the traffic become higher. As the key structure to bear the traffic loading and transmit it downward, the road base is subjected to cyclic traffic loading with increasing amplitude and intensity. The road base and subbase are composed of unbound granular materials (UGMs) such as gravels and coarse sands. In order to ensure the pavement's durability and serviceability, enough bearing capacity, limited deformation and well drainage condition of the road base and sub-base should be guaranteed.

During the operation period, the unbound granular materials (UGMs) of the road base may be fouled by fine particles resulting from particle breakage, the invasion of external fines from surface cracks, subgrade pumping and so on. Consequently, the performance of road base and subbase deteriorates under the long-term traffic loadings (Ionescu, 2004; Huang et al., 2009; Indraratna et al., 2013; Rahman, 2013; Ebrahimi et al., 2014; Chen and Zhang, 2016; Cai et al., 2017a). The invasion of fines has several adverse effects on the engineering characteristics of UGMs including the change of inner structure, the deterioration of strength and stiffness and the reduction of permeability. For example, Çabalar and Mustafa (2015) indicated that the use of rounded sands in a clay matrix led to the development of higher undrained shear strength values; Monkul et al. (2017) found that influence of silt characteristics on static liquefaction of sands became more considerable with decreasing fines content at loose states. The interaction between the coarse particles changes substantially as the invasion of fine particles changes the pore matrix of the ballast assembly and reduces particle interlock. As pointed out by Guo (1998), the structure of UGMs transited from skeleton structure, skeleton-void structure to suspended skeleton structure as the percentage of fines increased. Meanwhile, the invasion of fines may change the permeability coefficient of the UGMs significantly. Several studies showed that the invasion of fines, especially clay fines, would lead to significant reduction of permeability coefficient of the road base (Babić et al., 2000; Tennakoon et al., 2012; Rahman, 2013; Cabalar and Hasan, 2013).

Some experimental tests have been conducted to investigate the internal friction angle and shear strength of fines-fouled UGMs under the monotonic loading (Indraratna et al., 2013; Chen and Zhang, 2016).

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It was found that the invasion of clay into unbound aggregate subbase decreased the peak strength and critical strength of the UGMs (Chen and Zhang, 2016), while at a high normal stress (above 200 kPa), the shear strength of ballast remained relatively unaffected (Indraratna et al., 2013). It was also observed that excessive fouling deceased both the rate and the magnitude of dilation at high axial strain and the fines had a cushioning effect to reduce attrition between rough and angular particles (Indraratna et al., 2013). Besides the experimental studies, some numerical studies with the discrete-element methods (Huang and Tutumluer, 2011) had also been conducted to investigate the characteristics of clay-fouled ballasts, considering the factors such as the contact force chains, contact orientations, and evolution of fabric anisotropy of fresh and fouled ballast which could not be captured in the laboratory.

In order to investigate the dynamic properties of the fouled UGMs subjected to cyclic loading, Budiono et al. (2004) presented a study on the effect of coal dust contamination to the permanent settlement and resilient deformation of the ballast. Test results had shown that, with the fouling of the coal dust, the rate of accumulation of plastic settlement increased, and the resiliency and the rate of increase in reloading stiffness of the ballast decreased. Ebrahimi et al. (2014) and Azam et al. (2014) also indicated that fouling content increased the plastic strain of ballast by contaminating the contact points of ballast particles through testing with large-scale cyclic triaxial equipment. While tests presented opposite results when specimens were in the unsaturated conditions. Ohiduzzaman et al. (2012) had conducted the large-scale triaxial test on the fouled ballast under the unsaturated condition, it was found that the axial strain decreased with the increasing fines content at any level of deviatoric stress due to the existence of matric suction. Duong et al. (2016) analyzed the effects of water content and fines content, which were closely linked, on the resilient modulus of the fouled ballast; it was found that under unsaturated condition, the soil containing high fine content had higher resilient modulus due to the contribution of suction, while it lost its mechanical enhancement with a sharp decrease in resilient modulus when approaching saturated due to the disappear of suction and the buildup of excess pore water pressure. On the other hand, the loading frequency is an important parameter reflecting the traffic density and speed. It was found that the loading frequency had an significant effect on the dynamic behaviors of UGMs (Lekarp et al., 2000; Indraratna et al., 2010; Thakur et al., 2013; Sun et al., 2014; Sun et al., 2016). Lekarp et al. (2000) showed that the resilient modulus of UGMs would decrease with increasing loading frequencies; under the saturated condition, the generation of excess pore water pressure would aggravate the influence of loading frequency. Indraratna et al. (2010) investigated the influence of loading frequency on the permanent deformation and degradation behavior of railway ballast during cyclic loading, and it was found that the permanent deformation and degradation of railway base increased with the loading frequency in the range of 10–40 Hz. The above studies mainly focus on performance of clean railway ballast which has high permeability coefficient, while when the UGMs are fouled by fines, the permeability of the UGMs would be substantially reduced and the fouled UMGs may present quite different properties when subjected to cyclic loading with different frequency. Currently, the deterioration mechanism of fouled UGMs under different-frequency cyclic loadings remains unclear. Therefore, there is an urgent need to investigate the properties of the fouled UGMs under different-frequency cyclic loadings for the evaluation and maintenance of road bases.

In order to investigate the engineering geological characteristics of the fouled UGMs under different-frequency cyclic loadings, the CT scan was firstly conducted to investigate the change of the internal structure of UGMs due to the invasion of Kaolin fines. Then a series of consolidated drained large-scale triaxial cyclic tests have been conducted on the crushed tuff fouled by Kaolin under cyclic loadings. Five fine contents combined with three loading frequencies were considered in the tests, and the three-stage cyclic loadings were applied in the tests.

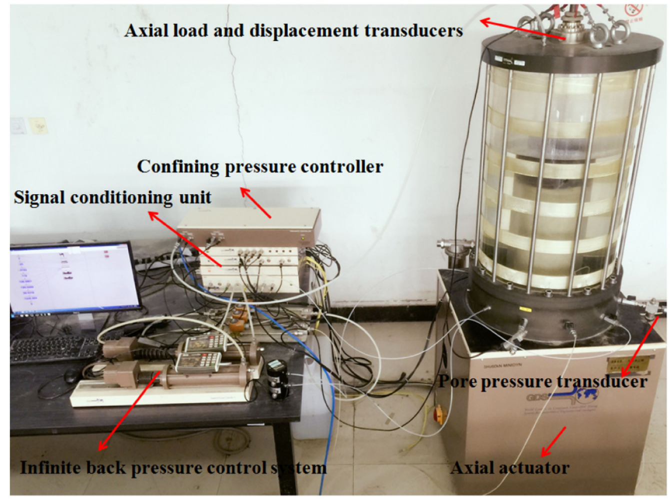

Fig. 1. The overall system of LDCTTS.

The resilient modulus, the accumulated axial strain, the volumetric strain and the buildup of excess pore water pressure of the fouled UGMs were analyzed under cyclic loadings with different frequencies and amplitudes. The combined influence of loading frequency and fines content on the long-term engineering geological characteristics of UGMs were investigated systematically.

2. Laboratory investigation

2.1. Tested apparatus

The large-scale tri-axial apparatus (LDCTTS), which was developed by GDS Instruments Ltd., was used in this study, as shown in Fig. 1. The LDCTTS can accommodate three sizes of specimens. The size of specimen adopted in this test was 300 mm in height and 150 mm in diameter. The apparatus consists of six main components: axial actuator, axial load and displacement transducers, confining pressure controller, signal conditioning unit, infinite back pressure control system and pore pressure transducer. The schematic diagram of LDCTTS is given in Fig. 2. The infinite back pressure control system can realize the infinite switch between two back pressure controllers, which can provide the sufficient volume for the volume change of pore water. The volumetric strain of saturated specimen can be measured based on the volume changes of pore water recorded by back pressure system. The pore water pressure can be measured by the pore water transducer. The axial strain is measured by the axial displacement transducers installed on the top cap.

The NIKON Metrology CT (XT H 225/320 LC) in the MOE Key Laboratory of Soft Soil and Environmental Engineering, Zhejiang University was used to scan the inner structure of fouled UGMs with different fine contents. The X-ray projections were obtained by an exposure time of 0.15 s at an acceleration voltage of 200 KV and 180 μA beam current. The stage was rotated through 360° for each scan and 2000 projections was collected on a Perkin Elmer 2000 × 2000 pixel amorphous silicon flat panel detector with an effective pixel size 37.2 μm. A 3D attenuation contrast image was computationally reconstructed by a filtered back projection algorithm from the projections. CT Pro, VG Studio and software packages were used to generate, visualize and segment the raw data.

2.2. Tested materials

The tested UGMs were crushed tuff taken from a quarry in Wenzhou. The tuff is a very special expansive soft rock, which is wildly distributed in China. As one kind of volcanic rock, tuff presents the