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Cumulative plastic strain of frozen aeolian soil under highway dynamic loading

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ABSTRACT

Dynamic triaxial experiments were conducted to investigate the cumulative plastic strain behavior of frozen aeolian soil. Under highway dynamic loading, the effects of several factors including frozen temperature, dynamic amplitude and loading frequency, water content and confining pressure on the cumulative plastic strain of frozen aeolian soil were studied. The results show that the cumulative plastic strain of frozen aeolian soil increases as the temperature and water content rise and as the confining pressure decreases, while the cumulative plastic strain increases slightly as the loading frequency decreases. Besides, with the increase of the dynamic amplitude, especially when the dynamic amplitude is greater than 0.08 MPa, the effects of water content and confining pressure on the cumulative plastic strain become more significant. Finally, the function of the cumulative plastic strain of frozen aeolian soil was obtained through back-fitting a series of testing results.

1. Introduction

With the increase of traffic, the problem of highway subgrade settlement caused by the traffic loading has become increasingly prominent. The research on dynamic behavior and stability of soil under traffic loading is becoming a popular and key topic in recent years (Li et al., 2011; Ling et al., 2009; Wang, 2013). The cumulative plastic strain is one of the most important dynamic parameters of soil and it plays an important role in soil dynamics. Some researchers have paid more attention to the cumulative plastic strain of unfrozen soil. Through undrained cyclic triaxial tests, Huang et al. (2006) and Chen et al. (2008) investigated the cumulative deformation behavior of Shanghai soft clay and found that the cumulative plastic strain depended on the applied cyclic stress, number of cycles, and the initial static deviatoric stress level. Wang et al. (2007), Zhu et al. (2005), and Zhang et al. (2009) explored the deformation behavior of saturated soft clay under cyclic loading through dynamic triaxial experiments. The cyclic strain was found to be composed of two parts: a reversible strain and an accumulated plastic strain, and a function of the cumulative plastic strain was proposed to describe the above behavior. Liu et al. (2009) and Xiao and Liu (2009) investigated the cumulative plastic deformation behavior of silt subgrade soil at different degree of compaction, water content, and dynamic stress levels. It was found that with the increase of the loading rate, silt subgrade could be stable when its natural water content is close to the optimum water content and its compacting factor is larger than 0.9.

The above researches mainly focused on the cumulative plastic strain of unfrozen soil, and there were few studies on the cumulative plastic strain of frozen soil. Based on the dynamic triaxial creep experiments, Zhu et al. (1997) analyzed the effects of temperature and confining pressure on the cumulative plastic strain of frozen loess and proposed a cumulative plastic strain constitutive model of frozen loess. Zhu et al. (2010) analyzed the effects of temperature, moisture content, loading frequency, and confining pressure on the cumulative plastic strain of frozen silt clay. The subgrade displacement of Qinghai–Tibet railway was predicted accordingly. Zhao et al. (2011) studied the permanent strain and strength through dynamic creep test of frozen silt under long-time dynamic loading. It was implied that the variation tendency of cumulative strains was similar irrespective of the dynamic amplitude.

The aeolian soil is broadly distributed which has remarkable structural characteristic, such as large pore size and loose structure. The internal structure of the aeolian soil would easily be changed under the highway dynamic loading, which causes uneven sedimentation of the subgrade and has serious consequences. However, the studies on the cumulative plastic strain of aeolian soil, especially experimental studies on the cumulative plastic strain of frozen aeolian soil under highway dynamic loading, are limited.

This paper addresses the above concern by investigating the cumulative plastic strain of frozen aeolian soil and its influence factors through dynamic triaxial experiments. The effects of frozen temperature, dynamic amplitude, water content, confining pressure, and

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loading frequency on the cumulative plastic strain of frozen aeolian soil are analyzed. Based on a large dataset of dynamic triaxial tests, a function of cumulative plastic strain of frozen aeolian soil under highway dynamic loading is proposed and validated.

2. Dynamic triaxial tests

2.1. Experimental equipment and sample preparation

As shown in Fig. 1, the testing system was consisted of the FST-200 dynamic triaxial testing machine (A), the XT5718ULT-R70-E3000 Refrigerated Circulators Machine (B), the data processing system (C), the confining pressure loading system (D), the controller (E), the sensor (G), and the axial loading system (H). The maximum confining pressure of the dynamic triaxial testing machine is 35 MPa. The applied axial load ranges from 0 to 250 kN and the maximum axial displacement is 50 mm. The accuracy of the applied axial load is ±1% and the measurements accuracy of confining pressure is ±0.5%. The temperature range of the refrigerated circulators machine is between −70 °C and + RT (room temperature). The temperature stability is ±0.5 °C and the temperature controlling accuracy is ±0.1 °C.

The soil samples were taken from the highway subgrade in Fuxin area, Liaoning Province (P. R. China). The process of sample preparation was as follows: (1) obtaining the dry density of the undisturbed soil by the ring sampler method; (2) crushing down the undisturbed sample with a wooden hammer, then placing the crushed soil in a dry electric oven at a preset temperature of 105 °C for 12 h; (3) obtaining the particle size distribution by sifting 400 *g* of the dried soil sample with three sieve hole diameters of 2 mm, 0.5 mm, and 0.075 mm; (4) placing the dehydrated soil into agitator and mixing the appropriate amount of distilled water to produce the soil samples with the water content of 12.13%, 15.12%, 17.25%, 20.31%, and 22.45%, then agitating the soil for 5–6 h; (5) compacting the sample in the standard compacting apparatus for 24 h; then cutting the mixed soil into cylindrical samples with 50 mm in diameter and 100 mm in length; (6) placing the cylindrical samples in regular-temperature environment for at least 24 h. Table 1 is a summary of the physical properties of the soil samples.

2.2. Experimental procedure

The experimental procedure was as follows: (1) the controller was open for 30 min; (2) the standard cylindrical sample was put into the test cell of FST-200 triaxial testing machine; (3) by setting the refrigerated circulators machine, the sample was frozen at the designed temperature; (4) the designed confining stress σ_3 was applied by adjusting the height of oil cylinder inside the dynamic triaxial testing machine, and the designed static stress σ_1 was applied using a computer-controlled piston; (5) the dynamic loading was applied to the soil sample; and finally, (6) the testing data were automatically recorded into the computer. The cumulative plastic strain of frozen aeolian soil amounts to the minimum dynamic strain under each loading-unloading cycle.

Table 1
Grain composition and physical properties of the unfrozen aeolian soil.

Grain composition (%)				Dry density (kg/m^3)
<0.075 mm	0.075–0.5 mm	0.5–2 mm	>2 mm	1800
7.03	38.25	39.21	15.51	

The vehicle loading applied in the experiment took the sine wave form (Seed and Idriss, 1971; Pan and Pande, 1984; Liang and Cai, 1999), and the function of axial dynamic loading is expressed as

$$P(t) = \sigma_1 + \sigma_{\mathrm{dmax}} \sin(2\pi f t) \tag{1}$$

where $P(t)$ is the vehicle loading; t is the time of loading; σ_1 is the vehicle static load; σ_{dmax} is the dynamic amplitude; and f is the frequency of vehicle loading, which can be obtained as $f = v/L$, where v is the vehicle velocity and L is the vibration wave length of the load. When the vehicle moves at a constant velocity v, the vibration wave length L is measured by the vibration pickup. The dynamic stress amplitude on the subgrade surface can be defined as $\sigma_{\mathrm{dmax}} = ma(2\pi f)^2$, where m is the vehicle unsprung weight and a is the amplitude of the vibration wave length. The magnitude of dynamic stress decreases with depth and it also decays rapidly with the increase of the rigidity of the pavement and subgrade materials (Chen and Su, 2011; Zhang, 2011).

The frozen temperature, confining pressure, water content, dynamic amplitude, and the frequency of dynamic loading are the important factors affecting the dynamic behavior of the soils (Chen et al., 2006; Ling et al., 2009; Wang, 2013). The loading was performed continuously to better simulate the vehicle loading and in situ situation of practical engineering. The following measures were adopted based on the measurements of subgrade vibration caused by the passing vehicle (Ma et al., 1995; Huang et al., 2006; Wei and Huang, 2009; Tang et al., 2009; Ling et al., 2009), including (1) the static stress σ_1 that was taken as 0.1 MPa and (2) the vibration number that was set for 10,000 circles. A summary of the parameters including the frozen temperature, dynamic amplitude, water content, confining pressure and loading frequency is shown in Table 2. The dynamic axial strain threshold of 15% or the vibration number of 10,000 was adopted for test termination.

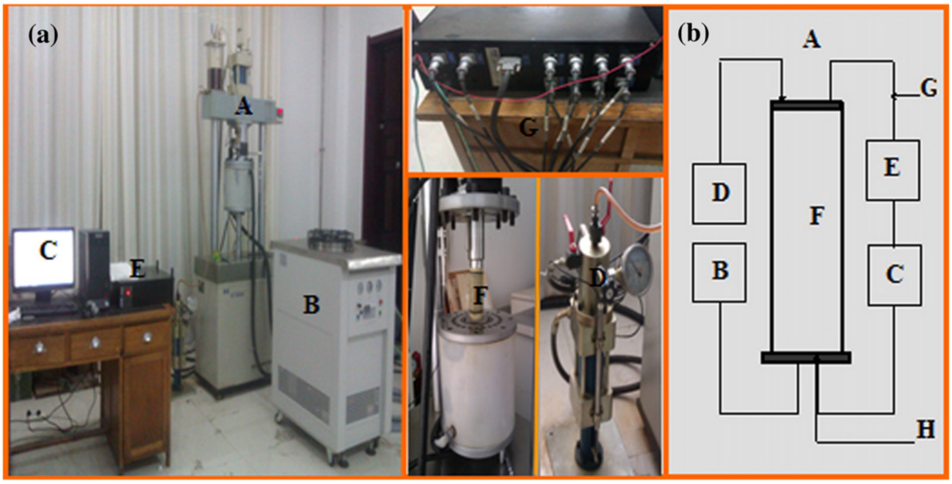

Fig. 1. Testing system and sketch of the testing setup: (*a*) testing system, and (*b*) sketch of the testing setup (Note: F stands for the aeolian soil sample).