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Accumulative strain of clays in cold region under long-term low-level repeated cyclic loading: Experimental evidence and accumulation model

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ABSTRACT

In cold region, the seasonal effects like changes in freeze–thaw should be investigated with respect to their influence on permanent settlement of foundation under long-term low-level repeated cyclic loading. Thereby, the influence of freeze–thaw processes on the accumulative axial strain of clays under long-term low-level repeated cyclic loading was investigated by conducting cyclic tri-axial tests and a numerical model for calculating the accumulative axial strain was proposed based on the experience observation in this paper. The normalized accumulative axial strain of clays increases significantly subjected to one freeze–thaw cycle, then decreases and tends up to be stable with the subsequent freeze–thaw cycles. The normalized accumulative axial strain increases with the increasing repeated cyclic stress amplitude, moisture content of samples and the number of loading cycles, but decreases with the increasing confining pressure. The modification parameters η_{FT} and functions f_{ampl}, f_C, f_W and f_N were proposed to consider the effects of the influence factors and were implemented into the accumulative strain model. In this model, all of the calculating procedures were explicit and all material constants of clays were presented. Therefore, the accumulative strain model can be used to predict the settlement of foundation under long-term low-level repeated cyclic loading in cold region.

1. Introduction

The settlement prediction of the foundation under long-term low-level repeated cyclic loading induced by high-speed railway or other vibrations is important for its evaluation of long-term serviceability, including in cold region. Besides the traffic, long-term low-level repeated cyclic loadings are also induced by roads and subways, waves, wind, construction work (e.g. pile driving, tunneling or blasting) or heavy industry (e.g. machine foundations). The residual strain induced by one cycle of low-level repeated cyclic loading is slight and it can be ignored. As a result, this repeated cyclic loading was defined as 'low-level'. On the other hand, the residual strain of soils induced by accumulative effect under long-term low-level repeated cyclic loading should not be ignored because that may exceed the acceptable limit and the geostructure may lose serviceability. Therefore, the study on the accumulative behavior of clays under long-term low-level repeated cyclic is significant. During the current decade, few studies have focused on the effect of peculiar influence factors in cold region on accumulative strain of soils under long-term low-level repeated cyclic loading and few corresponding accumulative strain models have been proposed.

In cold region, the soils of the surface layer are exposed to at least one freeze–thaw cycle each year. Therefore, the freeze–thaw is the most important influence factor on the soil performance compared to that in unfrozen region. Recent efforts on the effect of freeze–thaw on soils have been done by many researchers and a general conclusion that not only the physical characteristics such as moisture content, hydraulic permeability, void ratio but also the mechanical properties of clays or silts such as stress–strain behavior, failure strength and elastic modulus are substantially affected by the freeze–thaw process has been accepted. Chamberlain and Gow (1979) observed that the hydraulic permeability of the clays which had subjected to freeze–thaw cycles would become large and the increase intensity was related to the plasticity index. Several works studied the permeability variation mechanism with freeze–thaw cycles and thought that it was mainly due to the ice that pushed the soil particles apart, void spaces gradually increased in freeze–thaw cycle. If the void ratio became small, permeability variation was due to the micro-crack or the large void spaces which formed in freeze–thaw process (Viklander, 1998; Qi et al., 2008). The effect of freeze–thaw cycle on void ratio was different because of different compaction degrees of soils. The loose soils tended to be densified, but the dense soils would become looser after freeze–thaw cycles. Both of the loose

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and dense soils would approach a same void ratio after a number of freeze–thaw cycles (Chamberlain and Gow, 1979; Qi et al, 2008; Viklander, 1998; Wang et al., 2005). In addition, the variation of physical characteristics would become stable after 5 to 7 freeze–thaw cycles. On the other hand, the mechanical properties of soils also exhibited variation after freeze–thaw cycles. Alkire and Morrison (1983) founded that the stress–strain relation of loose reconstituted clays exhibited strengthened behavior after freeze–thaw cycles under drained tri-axial test. Some other researchers obtained that the stress–strain relation form of soils after freeze–thaw cycles is the same with that of soils without freeze–thaw cycles. But the values changed because the failure strength and elastic modulus changed after freeze–thaw cycles (Qi et al., 2008; Wang et al., 2005). Previous experiment results indicated that the elastic modulus of soils would reduce after freeze–thaw and the reduction degree was related to the soils types (Lee et al., 1995; Simonsen et al., 2002; Wang et al., 2005). The strength behavior of soils also varied after freeze–thaw. Yong et al. (1985) founded that the strength of soils would increase after freeze and thaw. Wang et al. (2005) founded that the strength of Qinghai–Tibet clay reduced after one freeze–thaw cycle and tended to be stable after a critical number of freeze–thaw cycles. Different freeze–thaw conditions or different soil types may contribute to the appearance of different conclusions.

Comparatively little research has been done in the field of laboratory investigation on the dynamic behaviors of soils which have subjected to freeze–thaw process, including the long-term dynamic behaviors. Jiao et al. (2010) studied the dynamic behaviors of warm–frozen silt after freeze–thaw cycles under cyclic loading and founded that the accumulative strain of silt which had experienced 10 freeze–thaw cycles was larger than that of the silt without freeze–thaw cycle. Zhang (2009) carried out some cyclic tri-axial tests to study the effect of freeze–thaw cycle on the dynamic behaviors of Mable Creek silt. He founded that the damping ratio and the shear modulus increased with the number of freeze–thaw cycles for shear strain larger than 0.01% and when the number of freeze–thaw cycles increased from 2 to 4, slight increase in damping ratio and shear modulus were observed. In addition, one freeze–thaw caused a decrease in cyclic-loading-induced volumetric strain, but the subsequent freeze–thaw cycles did not further decrease the effect on cyclic-loading-induced volumetric strain. Zhang (2012) also studied the effect of freeze–thaw cycle on the damping ratio and shear modulus of frozen and unfrozen sandy soils. He founded that the shear modulus of frozen soils decreased and the damping ratio of frozen soils increased with increasing number of freeze–thaw cycles. The shear modulus of unfrozen soils increased firstly and then decreased slightly with increasing number of freeze–thaw cycles. The damping ratios exhibited increasing trend with increasing number of freeze–thaw cycles. Liu et al. (2010) studied the dynamic properties of cement- and lime-modified clay subjected to freeze–thaw cycles by conducting cyclic tri-axial tests. They proposed a definition of the critical dynamic stress attenuation coefficient and founded that the critical dynamic stress attenuation coefficient of soils after one freeze–thaw cycle was close to that after ten freeze–thaw cycles. In addition, after three freeze–thaw cycles, the trend of the decreasing effect of modified soil on critical dynamic stress became more stable, whereas the clay soil did not begin to stabilize until six freeze–thaw cycles.

Since the elasto-plastic properties of soils may vary significantly due to freeze–thaw effect, non-negligible influence on strain accumulation can be expected (Karg and Haegeman, 2009). Being different from the soils in cold region which should consider the effect of freeze–thaw cycles, numerous models for the prediction of the accumulative strain of soils without freeze–thaw cycles have been proposed to predict the settlement of foundation (Karg et al., 2010; Li and Selig, 1996; Niemunis el at., 2005; Suiker and De Borst, 2003; Wichtman, 2005). In general, for the phenomenological description settlement problems either hysteretic models or accumulative strain models may be used. In hysteretic models, stresses and strains are calculated incrementally following the hysteresis loop for each cycle. Residual strains are achieved by a not perfectly closed hysteresis loop. For long-term cyclic loading, calculating the accumulative strain by hysteretic models such as elasto-plastic multi-surface model is unreasonable because of too much computation time and too large accumulative systematic error of the constitutive model or the integration scheme taking place. As a result, most of the accumulation models have been proposed based on experiment observations and they are called "empirical model". An empirical model treating the accumulation of residual strains under repeated cyclic loading is similar to the problem of creep under constant loading.

The aim of the present paper is to develop an empirical accumulation model for the residual axial strain of clays in cold region under long-term low-level repeated cyclic loading based on experiment observations, in which some essential influencing factors (e.g. the repeated cyclic stress amplitude, confining pressure, moisture content and the number of freeze–thaw cycles) are considered. In addition, the investigation will lead to a better understanding of the accumulation behavior of clays after freeze–thaw cycles under long-term low-level repeated cyclic loading and provide method for predicting the settlement of foundation in cold region.

2. Laboratory test program

2.1. Materials

The soil used in the current study is Northeast China clay soil, which has been obtained from the embankment along the Harbin–Daqin railway. The grain-size distributions of the materials are presented in Fig. 1. Other physical, mechanical indices of the soils, such as liquid limit, plastic limit, optimum water content, maximum dry density and natural salt content are shown in Table 1. In addition, the soil contains some salt and most of them are Na_2CO_3 and $NaHCO_3$, which may affect the freezing temperature of the soil (Bing and Ma, 2011).

2.2. Test device

The tests were conducted in the State Key Laboratory of Frozen Soil Engineering of Chinese Academy of Science. The tri-axial Material Test Device of MTS-810 made in USA, is equipped with an automatic numerical control system and a data collection system. The confining pressure ranges from 0 to 20 Mpa; the test temperature varies from room temperature to −30 °C; the maximum frequency is 50 Hz; the maximum axial load is 100 kN; and the maximum axial displacement is ±85 mm.

The freezing process was carried out in the refrigerator with an automatic temperature control system. The negative temperature can reach to −30 °C, and the degree of temperature accuracy is 0.1 °C. The

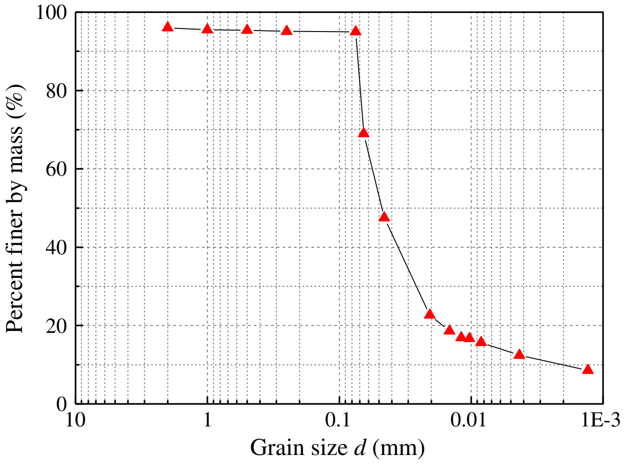

Fig. 1. Grain size distribution curve of the clay.