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Mechanical properties of a silty clay subjected to freezing–thawing

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ABSTRACT

The structure of soil will change a lot after freezing and thawing. The mechanical properties and the microstructures are quite different from those of the undisturbed soil. Based on the static triaxial tests and dynamic triaxial tests, this paper studied the mechanical characteristics of a silty clay and quantitatively analyzed the scanning electron microscopy (SEM) images of the silty clay before and after freezing and thawing. According to the static triaxial test and the disturbed state concept (DSC), the constitutive relationship of the thawing soil was investigated. The dynamic triaxial tests were conducted to study the dynamic constitutive relationship of the thawing soil and the mechanical parameters were compared with those of the undisturbed soil. The parameters of the microstructures of silty clay were extracted to analyze the influences of the freezing and thawing on silty soil.

1. Introduction

With the large-scale exploitation of underground space, freezing method has been widely used for tunneling in the soft soil area, especially in soil body reinforce of tunnel by-pass and underground pumping room, etc. But it had ever caused serious geological hazard and deformation or leakage around tunnel after operation. Thus it is important to understand how to use freezing method for tunneling safely, economically and reasonably in engineering construction. In addition, after the excavation of tunnel, a plenty of frozen soil, which will melt and result in the deformation of tunnel, remains around tunnel.

There are two major problems for the soil after freezing and thawing. The one is the action of freezing and thawing and the other is the effect of cyclic dynamic loads. For the former, the internal structures and the joint forces of undisturbed soil were destroyed during the period of freezing and thawing (Graham and Au, 1985; Konrad, 1989), and thus the action of freezing and thawing has great influence on the physical properties and mechanical features of soil, such as hydraulic permeability, unfrozen water content, strength, compressibility, and bearing capacity (Leroueil et al., 1991; Liu and Peng, 2009; Mahmoud and Mahya, 2013; Qi et al., 2006, 2008). Because of many factors which affect the nature of the thawing in the tests (e.g. the test conditions and the initial state of thawing soil), the understandings of the actual nature of thawing soil were not the same. After freezing and thawing, the changes of elastic modulus (Elliott and Thornton, 1988; Simonsen and Isacsson, 2001; Simonsen et al., 2002) and shear strength (Bondarenko and Sadovsky, 1991; Brams and Yao, 1964; Ono and Mitachi, 1997; Yong et al., 1985) were not exactly identical. The changes of them are related to the soil types (Simonsen et al., 2002) and the freeze–thaw conditions (Li et al., 2013), for example after freezing and thawing, loose soils tend to be densified and dense soils may become looser. Moreover, both loose and dense soils may attain the same void ratio (Konrad, 1989). The main reason is that part of the water in the soil will be frozen to ice in the period of freezing; the volume increment caused by the ice will have a significant effect on the surrounding soil structure. Therefore, for clay and silt with smaller pores, the action of ice will greatly disrupt the structure of soil particle and make soil loose; while for sand with larger pore diameters, the action has little effect on it.

For the latter, the frequency (Ling et al., 2013), vibration number and amplitude (Inozemtsev, 1986) of dynamic loads, and confining pressure (Simonsen and Isacsson, 2001) can affect the changes of soil properties. The soil may exhibit pronounced nonliner and hysteretic behavior under dynamic loads (Lai et al., 2000; Ling et al., 2009, 2013). Although the residual strain induced by repeated cyclic loading is slight and it can be ignored, the residual strain induced by accumulative effect under long-term repeated cyclic loading should not be ignored (Li et al., 2013). Also, the dynamic creep properties of soil under dynamic load will significantly influence the failure strain (Lai et al., 2013). Lai et al. (1999) has made the nonlinear analysis of the tunnel for the coupled problem of temperature and seepage fields in cold regions. Lai et al. (2000) also has derived the mathematical mechanical model and the governing differential equations of the coupled problem of temperature, seepage, and stress fields, to determine the initial stresses of tunnels in cold regions. The soil after the artificial freezing has to withstand the two effects simultaneously. Therefore, in order to study the influence of the two effects on soil, static triaxial and dynamic triaxial tests were carried out for a freezing–thawing silty clay.

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Studies on the soil properties can be conducted from both the macroscopical phenomenon and the microcosmic mechanism. The changes of soil macroscopic properties are the direct results of the changes of microstructure, and the engineering characteristics of soils are controlled by the state of pore structure of soils to a great extent. Therefore, many macroscopic properties of soil can be explained by its microstructure. Currently, scanning electron microscopy (SEM) has become a common method to analyze the microstructure of soil. Delage et al. (1996) compressed clay samples with different water contents, and explained the change of permeability according to the amount of clay particles. Pusch and Schomburg (1999) had investigated the inapplicability of correlations between macro parameters and permeability coefficient, compressibility. Cui and Tang (2011) studied the microstructure of different soil layers in the region owning high-rise buildings by SEM and the mercury intrusion porosimetry test (MIP). SEM has not only applied on ordinary soil but also on improved soil. Murat (2013) studied the effect of the additives on clays under freeze–thaw conditions. Zhang and Feng (1993) analyzed the attenuation mechanism of cement-modified loess after subjection to freeze–thaw cycles by means of SEM photographs.

In this paper, the static triaxial and dynamic triaxial tests were carried out for a freezing–thawing silty clay. The stress–strain relationship and the pore water pressure–strain relationship were studied, and the influences of the freezing and thawing action on the engineering properties and the effect of cyclic dynamic loads were explored. Based on the disturbed state concept (DSC), the stress–strain relationship under dynamic loads with different frequencies obtained by fitting the test data was studied. The changes of soil properties before and after freezing and thawing under dynamic loads were comparatively analyzed. The microscopic parameters were extracted from SEM images, and the effect of the freezing and thawing on soil microstructures was studied by processing the SEM images before and after freezing and thawing.

2. Sample preparation and test scheme

The undisturbed soil samples were frozen for 12 h in the freezing chamber, and the freezing temperature of the samples was −20 °C. Then the frozen soil samples were sealed in a plastic bag and conservated for 72 h in the water of room temperature. After fully thawing, the soil samples were processed into 80 mm in height, 39.1 mm in diameter by soil cutter. Then, the samples were placed in the saturator for above 24 h. The filter papers 10 mm in width, 60 mm in length were affixed around the samples, to ensure good drainage in the process of consolidation. Finally, the soil samples were consolidated under equipressure consolidation condition.

The static triaxial test was conducted using the scheme of consolidated undrained. Different confining pressures were employed to 6 samples, namely, 100 kPa, 150 kPa, 200 kPa, 250 kPa, 300 kPa and 350 kPa, respectively.

The dynamic triaxial test was conducted by American C.K.C dynamic triaxial apparatus. Its frequency range is 0–2 Hz. The range of confining pressure is 0–1.2 MPa. The maximum exciting force can reach 2500 kN. The dynamic wave in the experiment can be sine wave, rectangular wave, or triangular wave. In the test, the exciting force was sine wave and the frequencies of exciting force applied to the test were 1.0 Hz, 1.5 Hz, and 2.0 Hz, respectively, with the confining pressure of 220 kPa. Each level of vibration loads were carried out for 5 cycles, to obtain the averages of dynamic stress and dynamic strain.

3. Data analysis of static triaxial test

Fig. 1 illustrates variations of stress with strain of the thawing soil under different confining pressures, namely, 100 kPa, 150 kPa, 200 kPa, 250 kPa, 300 kPa and 350 kPa, respectively. The dynamic stress has been found to increase with an increase in the dynamic strain. It has been noted that the tangent modulus decreases continuously with

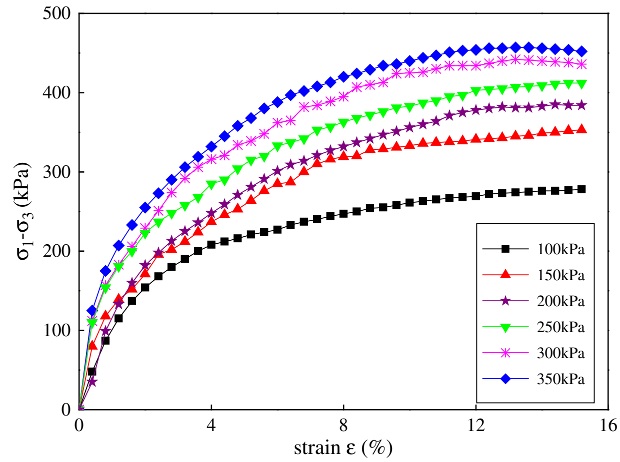

Fig. 1. Variations of Stress with strain.

an increase in the dynamic strain. Then the soil is destroyed gradually. The strain increases sharply, and the stress tends to be constant. The curve is fitting for hyperbola curve. Comparing the 6 curves, it is readily apparent that the peak strength and the initial tangent modulus both increase with an increase in the confining pressure.

Fig. 2 presents the variations of pore water pressure with dynamic strain under different confining pressures. In the beginning, the pore water pressure increases rapidly, then it increases slowly and tends to be stable with the increasing of strain. The trend of pore water pressure–strain curve is the same as the stress–strain curve, the stable value and the initial rate of pore water pressure will increase with an increase in the confining pressure.

Fig. 3 shows the variations of pore water pressure with stress under different confining pressures. The trends of 6 curves are the same and the confining pressures exhibit little effect on the relationship between pore water pressure and stress. For different confining pressures, the pore water pressure and the stress experience different maximums. As can be seen from the length of the curves, the greater the confining pressure, the longer the curve, that is the greater the maximums of the pore water pressure and the dynamic stress.

4. Study on constitutive relationship

4.1. Disturbed function

Disturbed state concept (DSC) was first proposed by Desai. Its basic idea (Wu, 2002) is that the material can be regarded as a mixture

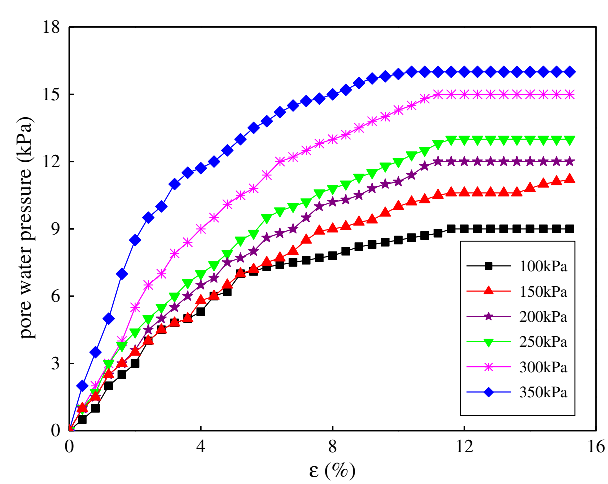

Fig. 2. Variations of pore water pressure with strain.