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Effect of freezing-thawing on dynamic characteristics of the silty clay under K0-consolidated condition

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ABSTRACT

The silty clay, as a viscoelastic plasticity soil, is widely distributed in Shanghai. Most of the subway tunnels pass through the silty clay layer and the by-passes are constructed by the artificial freezing method. The freezing-thawing clay remains around the tunnel. In this paper, cyclic triaxial tests were conducted to investigate the dynamic characteristics of K0-consolidated silty clay. The effect of freezing-thawing on the dynamic characteristics of the silty clay was analyzed. The lower the frequency and the larger the cyclic stress ratio (CSR) are, the larger the axial strain, the excess pore water pressure and the damping ratio develop, the smaller the dynamic shear modulus is. The axial strain of freezing-thawing and undisturbed samples under 0.5 Hz is about 65.8% and 116.7% larger than that of the samples under 2.5 Hz, respectively. After freezing and thawing, the excess pore pressure of samples under 0.5 Hz, 1.0 Hz and 2.5 Hz increases by 34%, 41% and 53%, respectively. The lower the freezing temperature is, the higher the excess pore water pressure and the shear modulus develop, while the effects of the freezing temperature on the axial strain and the damping ratio are not obvious. In step-amplitude cyclic triaxial tests, the shear modulus and the damping ratio of freezing-thawing samples are larger than those of undisturbed samples. The backbone curve, the normalized shear modulus and the damping ratio can be well fitted by the H-D model, the hyperbolic function and the quadratic function, respectively.

1. Introduction

The subway has been considered as a significant way to solve the urban traffic problems. However, the subway vibration loading, whose number of vibration often reaches up to hundreds of thousands of times, may result in the degradation or even failure of the stiffness, the strength and the bearing capacity of soil foundations. Besides, the implementation of artificial freezing method in the subway construction may aggravate the foundation deformation in the initial operating period. Therefore, a comprehensive research on the dynamic characteristics of soil before and after freezing-thawing under cyclic loading is necessary.

Dynamic characteristics of soil include the dynamic modulus, the damping ratio, the dynamic strains and the dynamic excess pore water pressure, etc. However, in most geotechnical investigation programs, the in-situ dynamic shear wave velocity tests cannot be carried out due to the cost considerations or the lack of specialized personnel (Hanumantharao and Ramana, 2008). Most of researches are conducted through laboratory tests. Cyclic direct simple shear tests (Vucetic and Mortezaie, 2015), resonant column tests (Schaeffer et al., 2013), torsional cyclic shear tests (Luan et al., 2010) and cyclic triaxial tests (Li and Wang, 2013), which represent different levels of shear strain, are regarded as four reliable ways to study the dynamic characteristics of soils. However, the development of dynamic modulus varies with the properties of soils. For granular cohesionless soil, the degradation of the dynamic modulus was generally characterized at the strain about 10^{-4}% (Seed et al., 1986). There were not rising stages but falling stages in the dynamic modulus curves of fine-grained soil samples under undrained conditions (Okur and Ansal, 2007). Based on Masing's double rule (Masing, 1926), the constitutive model for the dynamic stress-strain curves was established by (Hardin and Drnevich, 1972a, 1972b). Subsequently, Martin and Seed (1982) improved the constitutive model with two more parameters in order to better describe the dynamic stress-strain relationships of soil. Though there were some limitations in describing the undrained shear behavior of soft clay (Puzrin et al., 1995), it is widely accepted that the dynamic modulus and the damping ratio of soils are functions of dynamic shear strain under cyclic loading.

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Under K0-consolidation, the undisturbed soil usually exhibited initial structure and anisotropy. Freezing-thawing may destroy the nature properties of soil in the process of frost heave and thawing settlement. For silty clay, the freezing-thawing process affected the hydraulic conductivity seriously. The soil became looser and the void ratio increased after freezing-thawing, which led to larger strain under loadings (Cui et al., 2014; Kang and Lee, 2015; Zhou and Tang, 2015). Freezing-thawing cycles reduced the elastic modulus and enlarged the damping ratio of soils (Wang et al., 2015). The dynamic modulus increased with the freezing temperature descending (Christ et al., 2009). The non-linear behavior of Taipei silty clay was investigated by Lee and Sheu (2007) through a series of undrained cyclic strain-controlled tests and the equations for describing the modulus degradation and the damping ratio were proposed. After freezing, the strength and stiffness of soil would enhance. With the number of vibration increasing, the damping ratio decreased, while the dynamic modulus improved (Ling et al., 2013). Moreover, the elastic modulus changed significantly when the frozen clay melt (Konrad, 1989). Zhang and Hulsey (2015) studied the effects of freezing-thawing on soil dynamic properties through triaxial strain-controlled cyclic tests. The results demonstrated that the shear modulus decreased when the soil temperature improved from near the freezing temperature to above the freezing temperature and the damping ratio reached a maximum value when the soil temperature was at or near the freezing temperature.

Until now, there have been plenty of researches on the dynamic behaviors of soils under isotropic consolidation under cyclic loading, but the dynamics behaviors of the soils under K0-consolidation have been paid less attention. The effect of freezing-thawing on the dynamic behaviors of the silty clay under the subway vibration loading, including the dynamic Poisson's ratio, the modulus degradation, the damping ratio, the axial strain and the excess pore water pressure, has been less studied. In this paper, the cyclic triaxial tests were conducted to investigate the dynamic behaviors of the K0-consolidation silty clay of layer No. 5 before and after freezing-thawing, along with the effects of different number of vibrations, frequencies, cyclic stress ratios and freezing temperatures. The results can offer a reference to the design of artificial freezing methods in the construction of subway tunnels in the soft soil area.

2. Definition of modulus degradation and damping ratio

In cyclic triaxial tests, a series of continuous hysteresis loops, which gradually move to the right with the increase of number of cycles and dynamic strain, are performed in the dynamic stress-strain curves. These closed hysteresis loops of dynamic stress-strain curves are the basis to determine the dynamic modulus and the damping ratio of soil (Kokusho, 1980). The stress-strain loops could clearly exhibit the reduction of the modulus. The degradation index was introduced by Idriss et al. (1978). It describes the reduction of the secant shear modulus with number of vibration. In actual, the degradation index can be observed to be the normalized shear modulus. For consolidated clay, the modulus degradation index versus number of vibration, in a log-log format, is approximately a straight line (Vucetic and Dobry, 1988). In the stress-controlled triaxial cyclic tests, the cyclic degradation index, δ can be quantified as

$$\delta = \frac{G}{G_0} = \frac{\tau/\gamma}{\tau/\gamma_0} = \frac{\gamma_0}{\gamma} \tag{1}$$

where G is the dynamic shear modulus of each hysteresis loop, G_0 being the initial dynamic shear modulus, τ being the dynamic stress, γ being the shear strain, and γ_0 being the reference shear strain. The reference shear strain is the abscissa of the intersection between two tangents passing through the origin and the vertex of the stress-strain curve.

$$\gamma_0 = \frac{\tau_{\text{ult}}}{G_0} \tag{2}$$

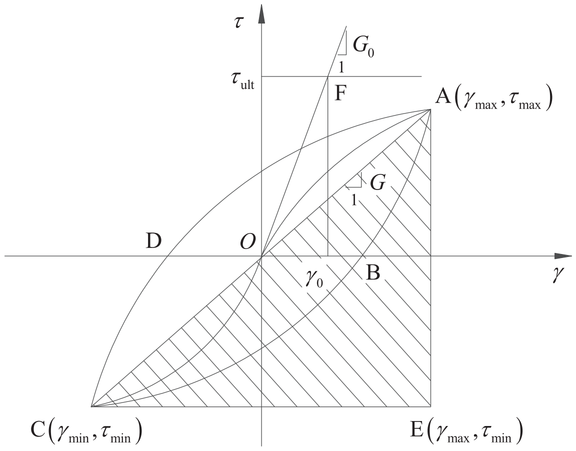

Fig. 1. The hysteresis loop under ideal condition.

where τ_{ult} is the ultimate shear stress, as shown in Fig. 1.

The equivalent modulus called secant modulus is always utilized to investigate the evolution of dynamic modulus of soil, including the dynamic Young's modulus E and the dynamic shear modulus G. There is a mutual transformation relationship between the two modulus.

$$G = \frac{E}{2(1+\mu)} \tag{3}$$

$$\gamma = \varepsilon(1+\mu) \tag{4}$$

where μ is the Poisson's ratio of soil and ε is the axial strain.

As presented in Fig. 1, the dynamic secant modulus is determined by the slope of the straight line connecting the two extremes of the hysteresis loop under the ideal condition.

$$G = \frac{\tau_{\max} - \tau_{\min}}{\gamma_{\max} - \gamma_{\min}} \tag{5}$$

where $\tau_{\max}$ and $\tau_{\min}$ are the maximum and minimum stress in a single hysteretic curve, respectively; $\gamma_{\max}$ and $\gamma_{\min}$ are the strains responding to the maximum and minimum stress, respectively.

It should be mentioned that the dynamic Poisson's ratio of silty clay under K0-consolidation in triaxial tests needs to be studied firstly. If it is a constant, the Young's modulus and the axial strain can be transformed into the shear modulus and the shear strain, respectively. Else, the Young's modulus and the axial strain should be utilized in the degradation index formula.

The damping ratio can represent the capability of soil to absorb energy under cyclic loading. The magnitude of damping can be represented by the damping ratio λ, which is the ratio of the actual damping coefficient to the critical damping coefficient. In cyclic triaxial tests, it can be calculated through the areas enclosed by hysteresis curves in the loading and unloading stages as shown in Fig. 1. Accordingly, the damping ratio can be characterized as

$$\lambda = \frac{1}{\pi}\frac{\Delta A}{A} \tag{6}$$

where ΔA is the area enclosed by a single hysteretic loop and A is the area of triangular ΔACE. The bigger the damping is, the higher the level of viscosity and the better the anti-vibration performance are.

3. Cyclic triaxial tests

3.1. Sample preparation and soil properties

The samples were taken from the grey silty clay of layer No. 5 typically 5.30 m–8.40 m in thickness in Shanghai. In order to keep in undisturbed state, the samples were obtained by thin-walled stainless steel tubes. Both ends of each tube were sealed with wax, transported to