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Experimental study on dynamic cumulative axial-strain performance of freezing–thawing saturated sandy silt

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ABSTRACT

Depending on artificial freezing method adopted in subway tunnel construction, a series of frost heave and stress-controlled cyclic triaxial tests were conducted on saturated freezing–thawing sandy silt to investigate their unconfined frost heave performance and plastic strain behavior. In terms of practical engineering, this study focuses on four significant influencing factors which are freezing temperature, dynamic stress amplitude, cell pressure and loading frequency. The results indicate that the remolding–stripping device provide an effective way for remolding soil sample, particularly dense sand and silt. Besides, the freeze–thaw action can truly has influence on the unconfined frost heave rate, and undisturbed or remolded soil with higher freezing temperature possesses smaller volume frost heave rate. In addition, the value of freezing temperature has significant influence on strain of remolded saturated freezing–thawing sandy silt with higher freezing temperature possesses larger accumulated axial strain, the accumulated plastic strain decreases remarkably with the increasing of dynamic stress amplitude and cell pressure, the loading frequency has considerable effect on accumulated axial strain of soil that is lower frequency can generate larger accumulated plastic strain. Finally, an improved semi-logarithmic empirical formula of cumulated permanent axial strain on freeing-thawing saturated sandy silt is proposed, and verified by experimental data, which could exactly forecasting development trend of dynamic permanent axial strain.

1. Introduction

With the development of social economy, large-scale urban construction has caused “urban diseases” (housing-intensive, narrow streets, etc.) of the urban areas in the eastern coastal soft soil areas of China. In order to manage the situation of increasing crowds, constructions such as underground streets for pedestrians, cross-river tunnels, and subways have been constructed. In the development of underground spaces, the artificial-freezing method is a better choice considering the ground consolidation effects. The method is largely used in underground commercial street escape channels, tunnel bypasses, and underground pumping houses. The artificial-freezing method has advantages such as good safety, strong applicability, high flexibility, and cost-effectiveness. However, the field measured results indicate that frost heave and thaw settlement leads to larger axis settlement of tunnel under subway loading (Tang et al., 2012). While excessive deformation leads to damage to the tunnel structure and settlement of surrounding area, accompanying with serious economic loss.

Due to the complex dynamic characteristics of the silt and the limited testing procedures, current research largely have focused on the dynamic performance of the freezing–thawing saturated muddy clay, scarcely on the freezing–thawing saturated silt (Li et al., 2015; Cui et al., 2014). In addition, extensive studies have conducted to characterize the micro-structure, physical properties, and strength of the silt. Booth (1981) discovered distribution regularity of ice in the freezing zone of silt. The dispersed ice probably exists in the entire soil sample, which is reflected in the lower strength of the freezing–thawing silt. Kværnø and Øygarden (2006) found that the freezing–thawing cycle damages the cohesion of the silt particles, leading to anti-erosion performance degradation. Ogata et al. (1985) reported that the freezing–thawing silt exhibits properties such as decreased cohesion and increased internal friction angle. Penner and Ueda (1977) presented extensive frost heave rate experiments during full freezing–thawing cycle and verified that the frost heave rate of the silt decreases proportionally with the increase in the overburden pressure. Chamberlain and Gow, 1979; Chamberlain et al., 1990) investigated the physical properties of the freezing–thawing fine-grained soil and found that the

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freezing–thawing cycle could reduce the void ratio and increase the permeability coefficient. Ito et al. (2006) conducted a site test and confirmed that the freezing could improve the permeability coefficient of fine-grained soil by up to 20–100 times the undisturbed soil. Although the shear strength and modulus of the freezing–thawing silt are important parameters, studies on the same are limited. Alkire and Morrison (1983) studied shear performance of triaxial undrained on remolded freezing–thawing silt and found that the shear strength of the freezing–thawing silt was superior to the undisturbed soil sample. Simonsen et al. (2002) showed that the modulus of the soil decreases by 25–60% after the freezing–thawing cycle. The more the fine grain content, the more was the decrease in the modulus.

With regard to the dynamic elastic modulus and damping ratio, some analyses have been conducted to describe the dynamic performance of the frozen silt subjected to cyclic loading. Vision, 1977; Vinson et al., 1983) studied the variations in the dynamic elastic modulus, damping ratio, and different influence factors such as freezing temperature, cell pressure, and moisture content. Czajkowski and Vinson (1980) took advantage of the triaxial system to analyze the dynamic characteristics of the frozen silt subjected to an earthquake. The detailed results showed that the decrease in the dynamic elastic modulus is accompanied with increases in the axial strain and freezing temperature, the variations of which are similar to that in the vibration frequency. Damping ratio is largely controlled by the vibration frequency, moisture content, and cell pressure.

For the application of the artificial freezing method on underground engineering, a series of dynamic triaxial tests were conducted to study the dynamic strain characteristics of the freezing–thawing saturated sandy silt. First, device of remolding and stripping and method of saturating, freezing and thawing for sandy silt were designed. The cell pressure, freezing temperature, cyclic stress amplitude and loading frequency were considered to investigate their effects on the accumulated axial strain. Based on the experimental data, an improved Stewart semi-logarithmic empirical formula is developed to describe the relationship between the plastic axial strain and the influence factors mentioned above. The results of the frost heave and accumulated axial strain obtained via the dynamic tri-axial test system provide meaningful insights into the dynamic response of the freezing–thawing saturated sandy silt.

2. Test overview

2.1. Experiment material

The undisturbed saturated sandy silt classified by the Geotechnical Engineering Investigation Standard (GB50021-2001) (2009 edition) and the ASTM D2487 taken from the ②$_{3-1}$ stratum in Shanghai at the depth of 5—15 m under the ground near railway station of metro line 1. With the thickness of 7 m, the sandy silt stratum contain mica, shell debris, upper part with thin muddy clay and lower part with thin-layer muddy clay belongs to the $Q_4{}^2$ coastal shallow marine deposit which have characteristics of non-uniform, slight or moderate dense, shake reaction quick, soil section rough and minor dry strength and toughness. The particle size distributions of the clay (< 0.005 mm), silt (0.005–0.075 mm), and sand (0.075–0.5 mm) were 0.63%, 68.93%, 30.47%. Sampling method of virgin Sand-sampling tool was taken, while the length and diameter of the sample are 80.0 mm and 39.1 mm, respectively, fulfill the geotechnique test regulations of China Nation Standard (CNS). The basic physical properties of soil are shown in Table 1. The main control index of dry density (1.43) and void ratio (0.85) for sandy silt were chosen to remold soil sample.

2.2. Device for remolded sandy silt

2.2.1. Device for remolded sandy silt

The process of obtaining sand and silt samples is difficult. The physical and mechanical properties of this type soil are strongly susceptible to disturbance. There is a potential risk of using incorrect parameters in the design and construction of a project. Moreover, the operator should employ a standard operating procedure. Otherwise, the silt would be severely disturbed, leading to incorrect test data of the physical and mechanical parameters of the soil sample. Furthermore, the conventional remolding method of the silt easily causes problems such as stress release and uneven compaction. For sand and silt, the physical and mechanical properties for dense and loose conditions are quite different. Thus, it is necessary to accurately design the devices to study the remolding non-cohesive soil sample.

The remolding device of the triaxial sand and silt soil sample comprises an upper rigid beam, a rigid base, a rigid thread column, an upper forcing mechanism, a sample tube, and three loading blocks named with 1#, 2#, 3#. The stripping equipment comprises a top cover, guide, and ejection element. A slot is provided to fix the split mold. The upper rigid beam is connected to the base through a rigid screw column and can move up and down. The upper rigid beam is set with an internal screw hole, and the urging force mechanism passes through the internal screw hole and the T nut. Hence, the axial force could be applied to the soil particle of the sample tube through the loading block. When stripping the soil sample, the stripping device placed at the bottom of the manual hydraulic jack slowly presses out of the soil samples. The design of the stripping device must meet the following requirements. The soil sample must be maintained vertical during the stripping process. The soil particle should not be affected by any additional external force. The entire soil sample should be stripped out at once. Fig. 2 shows the detailed schematic of the stripping device.

2.2.2. Quality evaluation of remolded sample

(1) Uniformity check

Visual observation: the repeated tests verified that the connection zone of the remolded soil sample should be chiseled before the subsequent process. The treatment depth of the sandy silt should be controlled in the range of 3 mm–5 mm. The qualified soil samples should not exhibit stratification phenomenon. The dry density dispersion should be controlled to < 1%. Fig. 1(b) shows the qualified remolded soil samples. Size control: the changes in the diameter and height were approximately 0.2 mm and 0.1 mm, respectively. Porosity parameter: Lunne showed that the change rate of the soil pore could reflect the degree of soil disturbance (Lunne et al., 1996). When $\Delta e/e_0$ is between 0.04 and 0.07, good soil samples are obtained. When the remolded sandy silt samples were loaded into the in situ effective stress, the deviation rate of the porosity ratio was approximately 0.06, and the quality of the remolded soil samples was excellent.

(2) Quality assurance by mechanical parameter

Small strain test: three resonant column soil samples were prepared using the remolded sample and stripping device, and the dynamic elastic modulus and damping ratio parameters were computed. The values fluctuated within the range of 4%, thus satisfying the dynamic triaxial system test condition.

Table 1
Physical and mechanical properties of sandy silt.

Natural moisture content (%)	Void ratio (e)	Specific gravity	Compressibility (MPa^{-1})	Natural unit weight (kg.m^{-3})	Internal friction angle (°)	Cohesion (kPa)
28.4–31.4	0.83–0.87	2.71	0.32	18.5	27.2	5