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Dynamic shear modulus and damping ratio of frozen compacted sand subjected to freeze–thaw cycle under multi-stage cyclic loading

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ABSTRACT

Frozen soil plays an important role on the stability of railway and highway subgrade in cold regions. However, the dynamic properties of frozen soil subjected to the freeze–thaw cycles have rarely been investigated. In this study, cryogenic cyclic triaxial tests were conducted on frozen compacted sand from Nehe, Heilongjiang Province in China which was subjected to the closed-system freeze–thaw cycles. A modified Hardin hyperbolic model was suggested to describe the backbone curves. Then, dynamic shear modulus and damping ratio versus cyclic shear strain were analyzed under the different freeze–thaw cycles, temperatures, initial water contents, loading frequencies and confining pressures. The results indicate that the freeze–thaw process plays a significant effect on the dynamic shear modulus and damping ratio, which slightly change after one freeze–thaw cycle. Dynamic shear modulus increases with increasing initial water content, temperature, loading frequency and confining pressure. Damping ratio increases with increasing initial water content, while decreases with increasing temperature and loading frequency. The effect of confining pressure on the damping ratio was found not significant. Furthermore, the empirical expressions were formulated to estimate dynamic shear modulus and damping ratio of the frozen compacted sand. The results provide guidelines for evaluating the infrastructures in cold regions.

1. Introduction

The mechanical properties of frozen soil are very crucial to evaluate the stability of the building foundation, railway and highway subgrade in cold regions. Moreover, the territory covered by frozen soil in China is third largest in the world, including 2.15 million km^2 permafrost region and 5.14 million km^2 seasonally frozen region [1]. Recently, more and more linear infrastructures were built or will be built in frozen regions due to the development of economy, such as Qinghai–Tibet Railway, Qiqihar–Harbin–Dalian High Speed Railway and so on. The traffic stimulation and the dynamic behaviors of frozen soil strongly influence the stress state, deformation and strength of substructure [2,3], and threaten the stability of infrastructures.

The development of frozen soil dynamics are being promoted by the theoretical and experimental advances in soil dynamics, which are being driven by the needs from the engineering practice. In soil dynamics, dynamic shear modulus and damping ratio of frozen soil are two important parameters to investigate the stability of soil. Many experimental studies on shear modulus and damping ratio began around the early 1970s. Vinson et al. [4] studied the dynamic behavior of the frozen Ontonagon clay, and the effect of temperature, water content and frequency were discussed. Li et al. [5] studied the effect of the sand content, temperature, frequency and confining pressure on the dynamic Young's modulus and damping ratio. Al-Hunaidi et al. [6] used the resonant-column test to determine the dynamic shear modulus and damping ratios of naturally frozen soil. Xu et al. [7] analyzed elastic modulus, Poisson's ratio, shear modulus and damping ratio of frozen soil under dynamic conditions. According to the cryogenic cyclic triaxial test, the effect of temperature, water content and confining pressure on the dynamic elastic modulus were studied under the traffic loads for the Qinghai–Tibet Railway [8,9]. Furthermore, Ling et al. [10] found that the stiffness increased and the damping ratio decreased with increasing number of repeated loading cycles. These works provide fundamental for further understanding the dynamic behavior of frozen soil.

However, it is acknowledged that the freezing and thawing is a cyclic weathering process in cold regions. This process can not be ignored since the moisture and temperature cycles may change the physical structure and mechanical behaviors of soil [11]. A large volume of experiments were conducted to elucidate the influence of freeze–thaw cycle on the static strength, cohesion, friction angle and resilient modulus for unfrozen soil [8,12–15,21].

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To investigate the dynamic behavior of unfrozen soil during the freeze–thaw processes, Jiao et al. [22] studied the dynamic behaviors of warm-frozen silt after freeze–thaw cycles, and found that the accumulative strain of silt soil under 10 freeze–thaw cycles is greater than that without freeze–thaw cycle. Hazirbaba et al. [24] observed that Mable Creek silt soil during 1, 2 and 4 freeze–thaw cycles causes an excess pore pressure reduction. Li et al. [23] studied the influence of freeze–thaw processes on the accumulative axial strain of clay under long-term low-level repeated cyclic loading. There are limited discussions on the laboratory approaches to investigate the dynamic behaviors of frozen soil subjected to freeze–thaw cycles. Christ et al. [19] employed the ultrasonic velocity test and uniaxial compression test, and concluded that the acoustic and mechanical properties are depended on temperature, soil type and freeze–thaw cycle. Since then, the research of the dynamic behavior of frozen soil has attracted extensive attentions subjected to freeze–thaw cycle. However, unfortunately, few researches are available on the shear strain dependency of dynamic shear modulus and damping ratio of frozen soil subjected to freeze–thaw cycle.

In the light of the above discussions, this study mainly focuses on the dynamic shear modulus and damping ratio of frozen compacted sand subjected to freeze–thaw cycles. A series of closed-system freeze–thaw cycle tests were conducted on restructured specimens firstly. Then, the cryogenic cyclic triaxial tests were performed under multi-stage cyclic loading. The backbone curves, dynamic shear modulus and damping ratio versus cyclic shear strain of frozen compacted sand were discussed under different freeze–thaw cycles, temperatures, initial water contents, loading frequencies and confining pressures. Finally, the empirical models were proposed and validated to estimate dynamic shear modulus and damping ratio versus cyclic shear strain. Furthermore, some meaningful conclusions are expected to be drawn and provide references for design, maintenance and research on soil mechanics in cold regions.

2. Laboratory experiments

2.1. Physical properties of soil

Soil samples were taken from Nehe in Heilongjiang Province and widely filled in subgrade of Qiqihar–Nenjiang Highway construction in the northeast of China. According to the Test Methods of Soils for Highway Engineering (JTG E40-2007) issued by the Ministry of Transport, China, the grain size distribution of the soil sample is shown in Fig. 1. Uniformity coefficient C_u and curve coefficient C_c were determined as 3.2 and 1.013, respectively. The soil belongs to poorly graded medium sand. The maximum dry-unit weight of soil sample was determined to be 2010 kg/m^3 at the optimum water content of 8.63%.

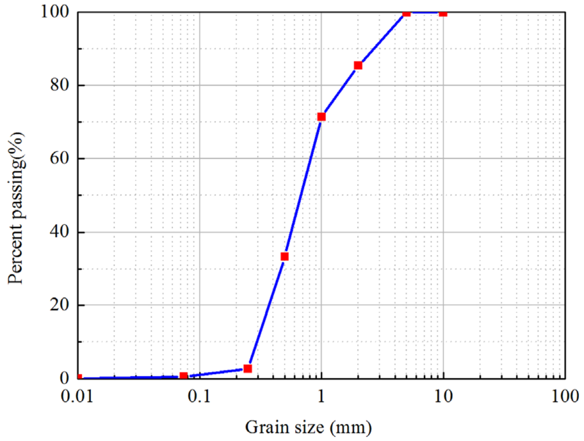

Fig. 1. Grain size distribution curve of soil sample.

2.2. Soil specimen preparation and freeze–thaw cycles

The soil specimen preparation, freeze–thaw tests and cryogenic cyclic triaxial test were carried out in the State Key Laboratory of Frozen Soil Engineering in Lanzhou, China. The procedure of preparing unfrozen samples is performed according to the Specification of Soil Test (GB/T50123-1999) issued by the Ministry of Water Resources, China. The air-dried soil sample was passed through sieve with mesh opening of 0.5 mm, then separated into three parts, and mixed thoroughly with the appropriate amount of distilled water to achieve the initial water content of 8.63%, 9.55% and 10.7%, respectively. Then soil samples were stored in three closed containers for 12 hours to ensure moisture distribute in samples uniformly.

All of the soil samples, with a diameter of 61.8 mm and height of 125 mm, were reconstituted and compacted into cylindrical specimens using the three segment copper molds in same three layers with the dry density of 2.01 g/cm^3. Then the specimens were covered with rubber sleeves, and the top and bottom of them were also covered with the epoxy resin platen to prevent water evaporation. Fig. 2 shows the three segment copper molds and the covered specimen.

The covered specimens were quickly placed into automatic temperature-controlled freezer (Fig. 3) with the temperature of −20 °C and indoor closed-system (no water supplied into specimens) freeze–thaw cycles began. As the three-dimensional and one-dimensional freeze–thaw processes have the similar influence on the changes of hydraulic conductivity [20], the three-dimensional freezing and thawing were taken in this study. Meanwhile, according to the recorded history temperature of Nehe region, the freeze temperature was used as −20 °C. Therefore, the specimens were placed in a freezer at a temperature of −20 °C for 24 hours to experience one freezing process, and then the specimens were moved into a normal temperature room with 23 ± 2 °C for 12 hours to experience one thawing process. This freezing and thawing procedure was repeated until the designed number of freeze–thaw cycles was reached. To compare the influence of freeze–thaw cycle, a control group of compacted soil specimens with the initial water content of 8.63%, 9.55%, and 10.7% did not experience the freeze–thaw cycles.

2.3. Apparatus and testing procedure

MTS-810 (i.e., Material Test System 810) was employed to conduct the cryogenic cyclic axial test program in this study. As shown in Fig. 4, the apparatus is capable of carrying out stress-controlled cyclic and strain-controlled static loading test. The stably confining pressure ranged from 0.3 MPa to 20 MPa, the temperature varied from −30 °C to 30 °C, the temperature error was ±0.1 °C, the maximum axial displacement was 85 mm, the maximum axial load was 100 kN, and the frequency can be changed from 0 Hz to 50 Hz.

The specimens were placed into the thermo-tank with the test temperature for 12 hours, then the specimens were put in the pressure chamber until the temperature in pressure chamber was stable. After the specimens had been isotropically consolidated under confining pressure for 2 hours, a series of cryogenic cyclic triaxial tests were performed.

To obtain the strain-dependent shear modulus and damping in the wide range of strain amplitude, the multi-stage cyclic stress control was adopted as the type of control load [16,9,18]. About 15