Cold Regions Science and Technology 146 (2018) 9–18

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

# Effect of freeze-thaw cycles in mechanical behaviors of frozen loess

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## ARTICLE INFO

*Keywords:*
Frozen soils
Freeze-thaw cycles
Mechanical behaviors
Constitutive model

## ABSTRACT

A series of triaxial compression, creep and stress relaxation tests at temperature of $-6$ °C were conducted on frozen loess, experienced different freeze-thaw numbers (0–12times), in order to study the thermal cycling effect in mechanical behaviors. The freeze-thaw process has a strong influence in the mechanical behaviors of frozen loess. The strength, stiffness and viscosity properties of frozen loess weaken gradually with the increase of the freeze-thaw procedure until the cycle number gets to the critical value for steady state of soil sample. The freezing low temperature ranged from $-6$ °C to $-12$ °C has no evident effect in the testing results of same freeze-thaw numbers. The strength distribution loci of frozen loess in the equivalent stress-mean stress space exhibits a unidirectional shrinkage over the range of the freeze-thaw process studied. Triaxial strength characteristics of frozen loess, experienced different freeze-thaw numbers, are more in agreement with the Ma's failure criterion for frozen soils (Ma et al., 1993). The stiffness properties (elastic modulus, elastoplastic coupled degree and damage degree) and the viscosity properties (relaxing stress, stable relaxation time, stable creep rate and viscoelastic modulus) of frozen loess both depend on the freeze-thaw process. The microstructure change of frozen loess induced by the thermal cycling effect is analyzed detailly so as to explore the micro-mechanism of property degeneration. Finally, a developed constitutive model, considering the freeze-thaw and confining pressure effect, is proposed to research and predict the triaxial strength and deformation characteristics of frozen loess experienced different thermal cycling process.

## 1. Introduction

The distribution area of permafrost and seasonal frozen regions accounts approximately 23% of the world's total land area. Frozen soils are a multicomponent geomaterial, which are composed of mineral particles, liquid water, ice inclusions and gaseous inclusions. With the development of engineering constructions such as railways, highways, tunnels and mineral engineering, frozen soils are used widely as the foundation and structures of engineering in cold regions (Ma et al., 2005; Ma et al., 2009; Qi et al., 2006; Yu et al., 2016; Li et al., 2017; Zhang et al., 2012). The design and maintenance of these engineering requires an developed understanding for the strength and deformation characteristics of frozen soils under complex thermal-mechanical conditions (Lai et al., 2016; Liu et al., 2014; Wang et al., 2014; Zhou et al., 2015a; Zhou et al., 2015b; Zhu et al., 2016; Xu et al., 2017). Physical-mechanical properties of frozen soils are dependent on the mineral composition, dry density and moisture (ice) content. In addition, the freeze-thaw process, which results in structural rearrangement of soil particle, has an important influence in the physical-mechanical property of the unfrozen or frozen soils. This thermal cycling phenomenon must be considered in selecting soil parameters for stability and deformation analysis of slopes, embankments and tunnels in cold regions, especially seasonal frozen region. Therefore, it is essential to investigate the freeze-thaw effect in the mechanical behaviors of the unfrozen or frozen soils, especially the triaxial strength and deformation property which are practical problems in the geological and geotechnical engineering. The main goal of the present paper is to explore experimentally the frozen loess's mechanical response for different thermal cycling process.

Previous many works were focused on the micro-structural changes of soil after freeze-thaw process. Edwin and Anthony (1979) adopted the freeze-thaw cycle tests to determinate the variation characteristics of particles size and microstructure skeletons of fine grain sand. It is proved experimentally that the vertical permeability of sand sample increases greatly with the development of freeze-thaw process due to the considerable changes for microstructure. Graham and Au (1985) proposed that the pre-consolidation pressure of the soil sample decreases apparently and the original microstructure of clay soils is damaged gradually after the freeze-thaw cycles. The freeze-thaw effect in the physical-mechanical property for unfrozen or frozen soils has been

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https://doi.org/10.1016/j.coldregions.2017.11.011
Received 9 June 2017; Received in revised form 16 August 2017; Accepted 19 November 2017

studied by many researchers in recent years. Lee et al. (1995) performed elastic modulus tests on five cohesive soils sample taken from the subgrades of in-service pavements, and the freeze–thaw process leaded to significant reduction of elastic modulus. Wang et al. (2007) presented the laboratory test of fine-grained clay exposed to a maximum of 21 closed-system freeze-thaw cycles, the physical–mechanical properties such as elastic modulus, failure strength and friction angle were measured and analyzed. It is found that the elastic modulus and cohesive force of soil sample reduces and the internal friction angle increased after freeze-thaw cycles Liu et al. (2016) conducted the triaxial tests and the freeze-thaw tests on Qinghai-Tibet silty sand to investigate the failure strength as well as the strength parameters (elastic modulus, cohesion and angle of internal friction). The experimental results indicated that the freeze-thaw number has prominent influence on the aforementioned mechanical behaviors, but the freezing low temperature effect is negligible. Johnson et al. (1979) investigate the Poisson's ratio and elastic modulus of unfrozen soils under the different freeze-thaw process by both lab and in-situ test. Testing results indicate that two elastic parameters of both clay and silt should be expressed by a function of dry density, moisture content and stress state, and they are all sensitive to the thermal cycling effect conditions. The above-mentioned studies concerning the freeze-thaw effect has been limited relatively to the mechanical properties such as failure strength, elastic modulus and Poisson's ratio of unfrozen soils (Wang et al., 2007; Liu et al., 2010; Liu et al., 2016). Few attempts have been made to investigate the viscosity property (creep and stress relaxation) and deformation property (stress-strain relationship) of unfrozen and frozen soils by now, which is crucial for the long-term stability and security of engineering construction in the seasonal frozen regions. Therefore, a series of triaxial compression, creep and stress relaxation tests at temperature of − 6 °C were conducted on frozen loess, experienced different freeze-thaw number (0–12times) in this paper. The strength (triaxial failure strength), stiffness (elastic modulus and elastoplastic coupled degree) and viscosity properties (relaxing stress, stable relaxation time, stable creep rate and viscoelastic modulus) of frozen loess in different freeze-thaw cases are investigated experimentally. The degradation micro-mechanism of those mechanical properties caused by the thermal cycling process are discussed and analyzed in detail. The damage characteristics of the mechanical properties as the deformation are probed further in different cases of freeze-thaw cycle. Finally, A modified constitutive model considering the freeze-thaw effect is presented further to simulate the triaxial stress-strain behaviors of frozen loess, and the predictive capability of this theoretical model is verified by using the triaxial testing results in different cases of freeze-thaw cycle.

## 2. Soil sample preparation and testing method

A loess, taken from Jiuzhoutai town of Lanzhou city (a seasonal frozen region in the northwest of China), was selected in present paper. The physical parameters (grain size distribution) of loess are listed in Table 1. The liquid limit and plastic limit of this loess are 17.4% and 25.7%, respectively. The samples were prepared as cylinders with 62 mm in diameter and 125 mm in height, as shown in Fig. 1 (a). The dry unit weight and initial water content of the samples are 17.8 kg/m$^3$ and 16.5%, respectively. Since the negative temperature condition of near 0 °C may lead to the occurrence of incomplete freezing or even no freezing, the samples were frozen at two freezing low temperatures (− 6 °C and − 12 °C) and thawed at normal temperature of 15 °C in order to ensure the sufficient and complete freeze for soil samples. The freezing time and melting time are both 12 h in according to natural period. Soil samples were carefully wrapped with rubber sleeves during the freeze-thaw procedure to avoid the water evaporation. The all-round freezing process at constant temperature was adopted for freeze-thaw procedure in a closed system without water supply. Soil samples experienced different cycle numbers of 0, 3, 6, 9, 12 at the freezing low temperature of − 6 °C and − 12 °C, respectively. After freeze-thaw procedure, the soils samples were set at a negative temperature of − 30 °C for over 48 h. The triaxial tests were performed by applying the MTS-810 low-temperature triaxial apparatus, as shown in Fig. 1 (b). The aeronautic hydraulic oil is adopted in confining pressure system. The maximum axial load is 100 kN, and the variation range of the axial displacement is 0–85 cm. The scope value of the available confining pressure is 0–25 MPa. The alcohol is used as cooling medium in the cooling system. The controllable low-temperature conditions ranges from − 30 °C to 0 °C. In testing process, the frozen samples were rapidly put into a pressure cell of the apparatus in order to prevent the formation of ice lenses and were kept at testing temperature for 12 h before tests. The testing temperature is − 6 °C with a precision of ± 0.1 °C, respectively. After the confining pressure (0–15 MPa) had been applied for 5 min, the triaxial tests were conducted on frozen loess.

In order to research systematically the thermal cycling effect in mechanical behaviors of frozen loess, a series of triaxial compression, creep and stress relaxation tests (including the case of loading–unloading tests), were performed at temperature of − 6 °C. All triaxial tests were carried out at a constant hydrostatic pressure rate of 0.5 MPa/min and a constant axial displacement rate of 3 mm/min. The strength, stiffness and viscosity properties as well as damage evolutions of frozen loess under different freeze-thaw and confining pressure conditions are investigated in detail. Moreover, the failure enveloping surface of frozen loess (experienced different freeze-thaw numbers) in the equivalent stress-mean stress spaces is explored so as to determinate experimentally the response characteristics of triaxial strength caused by the thermal cycling effect.

## 3. Testing results and discussion

### 3.1. Triaxial strength properties

Triaxial compression results of frozen loess under different freeze-thaw and confined pressure conditions are summarized in Fig. 2. The freeze-thaw effects in the strength and deformation behavior (stress-strain behavior) of frozen loess are significant under all eight confined pressure conditions. The stress-strain curve level has a reduction tendency with the increase of freeze-thaw number. When the cycle numbers exceeds to 6, the curves have no obvious difference. The cycle number 4–6 should be considered as the critical value for steady property of loess sample. It can be understood that with increase of the freeze-thaw cycles, the growth of ice crystals, as well as the cryotexture formation in the internal micro-structure, results in the increase of sample porosity. Soil sample is squeezed to form new particle skeleton structure which induces the connection pattern change of soils particles. The repeatedly frost heave process is mainly reason for the microstructure damage and the property degeneration of frozen loess. But when the porosity increases to a certain extent, the change of the ice volume caused by freeze-thaw cycles process has ignorable influence in the soil microstructure. The stress-strain characteristic exhibits slight response for the freezing low temperature value in freeze-thaw

**Table 1**
Grain size distribution of loess (%)

| > 0.25 mm | 0.01 − 0.25 mm | 0.05 − 0.10 mm | 0.0005 − 0.05 mm | < 0.0005 mm |
|---|---|---|---|---|
| 0 | 2.415 | 21.466 | 66.572 | 9.547 |