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Deformation and strength behaviors of frozen clay with thermal gradient under uniaxial compression

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ABSTRACT

Thermal gradient is one of the main features in artificial freezing ground and permafrost regions. The deformation and strength behavior of frozen soils with thermal gradient is of utmost importance for stabilities analysis of frozen engineering. A series of uniaxial compression tests were carried out on frozen saturated clay at various average temperatures and thermal gradients. The experimental results indicated that the uniaxial stress–strain curve for frozen clay with thermal gradient presents elastic-linear strain hardening characteristics, both the hardening modulus and uniaxial compression strength increase as the thermal gradient and average temperature decreased, but the elastic modulus varies little as the thermal gradient increased. The polygonal stress–strain constitutive equations were implemented into the FEM (Finite Element Method) and the local axial strain distribution of frozen clay with thermal gradient was studied. Two stages are observed from the curves describing the relationship between local axial strain and specimen height, i.e., increase stage and decrease stage for the slope of *d*. Characteristic parameters such as the demarcation height of H_d, the maximum slope of $d_{\max}$ are defined and analyzed. It is found that the characteristic parameters are all dependent on the thermal gradient and average temperature. The thermal gradient presents weakening effects to the local axial strain rate at middle specimen height of $\delta\varepsilon'_{a,H=10}/\delta t$ in frozen clay with identical average temperature, and that further lead to the decrease of hardening modulus and uniaxial compression strength.

1. Introduction

The artificial freezing is usually adopted as a method of ground improvement for underground engineering and for strengthening soil around excavations (such as metro engineering, nuclear waste storage project, and mining engineering in deep alluvium). Meanwhile, considerable amounts of engineering constructions will be performed (such as highway or railway tunnel, underground pipe-lines, and mineral resources exploration) in cold regions, especially in the permafrost regions of China (Lai et al., 2003; Lai et al., 2009; Wen et al., 2010). In general, the temperature distribution in frozen soils is non-uniform (Sres, 2009; Pimentel et al., 2012; Kim et al., 2012), and that can be regarded as a temperature field composed of different thermal gradients. Therefore, a clear understanding of effects of thermal gradient to the deformation and strength behaviors of frozen soil is required for stabilities analysis of artificial freezing ground or structures in permafrost regions.

There are two types of methodologies on how to study the non-linear heterogeneities induced by thermal gradient and the corresponding mechanical responses. Large scale of physical modeling is one of the most essential research methods, and that can supply reliable and reasonable verification for the theoretical analysis and numerical modeling results. In recent decades, much attention had been paid on non-uniform deformation characteristics, bearing capacity and overall instability process of frozen engineering obtained by using physical modeling, and the comprehensive computation models considering the temperature distribution, initial earth pressure, excavation height, exposure period and the deformation or strength behavior for the structures were then put forward (Banin and Anderson, 1974; Cui and Lu, 1992; Wang, 2008). Another method is the laboratory experiment on the small scale of specimen with uniform temperature. According to the experimental results under various initial conditions, the corresponding constitutive formulations are developed, and the deformation characteristics on full scale of frozen structures with different geometries and complicated mechanical boundaries are then carried out by implementing developed constitutive equation into the numerical software.

However, strength behaviors and deformation mechanism drawn from the frozen soil with uniform temperature could not be simply applied to the frozen structures in artificial freezing ground or permafrost regions due to the lack of considering heterogeneities induced by thermal gradient (Parameswaran and Jones, 1981; Wu and Zhang, 1983; Tsytovich, 1985; Ladanyi and Morel,

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1990; Zhu et al., 1992; Wu and Ma, 1994; Ma and Chang, 2002; Li et al., 2004, 2009; Ma et al., 2008; Liu and Peng, 2009; Lai et al., 2009, 2010). Although the physical modeling results under non-uniform temperature distribution include the heterogeneities information induced by thermal gradient, the distribution characteristics and evolution process of the heterogeneities are unavailable. Accordingly, the connection between the capacity of the frozen structures and the internal heterogeneities cannot be constructed.

The laboratory experiment on specimen with single thermal gradient is the latest developed test methodology (Zhao et al., 2011, 2013). This method is helpful for us to determine the heterogeneities information induced by thermal gradient, and that make the estimation of deformation responses for frozen clay with combinational thermal gradients become more accurate. Zhao and Zhou (2013) researched the uniaxial creep deformation and long-term strength characteristic of frozen saturated clay with thermal gradient. They observed that the creep process could be divided into two stages: instantaneous elastic deformation and decaying creep deformation, and the uniaxial creep deformation could be described by generalized Kelvin model considering the correction equation on thermal gradient.

In present paper, the experimental investigation of quasi-static uniaxial tests, conducted on the samples of frozen clay under a temperature varying from −20 to −10 °C with a thermal gradient varying from 0.00 to 0.75 °C/cm, was made. The emphasis of this research is to investigate the effects of thermal gradient to the deformation and strength behavior and the corresponding mechanism responses of deformation and strength to the heterogeneities, which is very useful and crucial to geomechanical practitioners and underground structural engineering science.

2. Experiments

2.1. Specimen preparation

The soil fraction of tested materials was taken from a mine shaft at a depth about 510–530 m. Initially, the soil was repeatedly broken into small pieces, air dried, and pulverized using a rubber hammer. The air-dried soil was further pulverized to <US No. 18 sieve size. The soil liquid limit and plastic index were respectively 51.9% and 28.2%. Thus it was classified as CH (high plastic clay) based on the unified classification system (GBJ145-90). The main properties of tested clay were given in Table 1.

The specimens were prepared as cylinders with 100 mm in diameter and 200 mm in height. The average initial water content and the dry unit weight of the specimens tested were 33.6% (33.4–34.8%) and 1.42 g/cm^3 (1.33–1.45 g/cm^3), respectively. These specimens were saturated with distilled water under a vacuum of 73 mm Hg for 24 h to achieve a saturation degree of at least 0.98.

2.2. Testing apparatus

The uniaixial compression tests were carried out on a multi-functional material testing apparatus for frozen soils consisting of a loading system, a cooling system and an auto controlling system (Zhao et al., 2013). Besides the traditional functions such as tests under stress control and strain control modes, two new features make the apparatus different form the other apparatus for frozen soils, the first is that temperature of the specimen is controlled from two positions, i.e., the top and bottom ends with cooling liquid. In this way, the thermal gradient in the specimen can be controlled in vertical direction or radial direction. The second is that the freezing control of the multifunctional material testing apparatus is realized by two stages of refrigeration. On the one hand, the alcohol temperature is maintained constant in the cold bath at an apparent lower value. On the other hand, the alcohol in the cold bath is adjusted to cycle according to the experimental design, and this process makes the temperature in specimen approach the target value.

For the uniaxial compression experiment, we measured the axial force with load transducer of 500 kN, and the axial deformation with the axial linear variable differential transformer (LVDT) of 150 mm. the accuracy of the axial load and the axial deformation were 5 N and 0.01 mm respectively. Furthermore, the vernier caliper with an accuracy of 0.01 mm was used to measure the vertical contraction magnitudes (after experiment) between different specimen heights marked with blue colors for frozen clay with thermal gradient.

2.3. Thermal gradient

In order to examine the influences of thermal gradient (= (top end temperature − bottom end temperature)/specimen height) and average temperature (= (top end temperature + bottom end temperature)/2) on deformation and compression uniaxial strength behaviors, four thermal gradients, i.e., 0.125 °C/cm, 0.25 °C/cm, 0.50 °C/cm, 0.75 °C/cm, and three average temperatures, i.e., −10 °C, −15 °C, −20 °C, were used respectively (Fig. 1).

2.4. Testing procedures

The uniaxial compression tests on frozen saturated clay were carried out by the following three steps:

(1) *Sample installation*. Firstly, the membrane and outer thermal resistors (the thermal resistors was placed at 2 cm, 6 cm, 10 cm, 14 cm, and 18 cm heights of the samples) were installed on the surface of samples. In order to obtain the temperature difference between the internal temperate and the surface temperature, the corresponding internal thermal resistors were installed inside the specimen at the identical specimen height before freezing. Then the saturated specimens were mounted on the pedestal of testing apparatus.

(2) *Freezing*. Firstly, closing the drainage valve and specimen freezing with non-uniform temperature then were conducted. The average freezing time is not less than 30 h, and the freezing time used on the specimen with larger thermal gradient is more than that used on the specimen with smaller thermal gradient. The target thermal gradient as shown in Fig. 1 was formed along the vertical direction, and the temperature was remained uniform along the radial direction at different specimen height. The detailed comparison between the measured temperature distribution in test and designed temperature distribution were introduced by Zhao et al. (2011, 2013).

Table 1
Properties of tested clay.

Plastic limit (%)	Liquid limit (%)	Plastic index	Specific gravity	Particle size (μm) content (%)		
				<5 μm	5–75 μm	75–250 μm
23.7	51.9	28.2	2.715	47.6	42.3	10.1