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Experimental study on the creep behavior of frozen clay with thermal gradient

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ABSTRACT

Thermal gradient is one of the main features in frozen engineering, especially in artificial frozen wall (AFW) in deep alluvium. This paper investigated the creep behaviors of frozen soil with thermal gradient. A series of uniaxial creep tests were carried out on frozen saturated clay under various thermal gradients and creep stresses by GFC (freezing with non-uniform temperature without experiencing K_0 consolidation) method. Two stages were observed during the whole creep process, i.e., instantaneous elastic deformation and decaying creep deformation. Radial creep deformation of ε_3 almost increases linearly with an increase in axial creep deformation of ε_1, and the slope of ε_3–ε_1 curve increases as the thermal gradient (or creep stress) increased. Long-term strength decreases as the thermal gradient (or the creep time) increased. Considering the correction equation on thermal gradient, the generalized Kelvin model consisting of one Hooke element and two Kelvin elements has been developed to describe the axial creep deformation. The validity of the model is verified by comparing its calculated results with the results of creep tests under both low and high thermal gradient. It is found that the axial creep deformation behavior of frozen saturated clay can be represented by generalized Kelvin model, and the proposed model reflects thermal gradient effects to the creep deformation well.

1. Introduction

The last decade has seen an increased use of artificial frozen walls (AFW) as an auxiliary ground improvement technique for underground excavation. In contrast to some other soil improvement or support methods, such as grouting or sunk-well, AFW stabilizes and seals the soils only temporarily, that is, without permanently affecting the hydrogeological conditions or the groundwater quality.

The temperature distribution in frozen wall is in general non-uniform when the freezing was completely finished, and that can be regarded as a temperature field composed of different thermal gradients. Therefore, a clear understanding of relationship between thermal gradient and the corresponding deformation or strength of frozen soil, is required in AFW design, including that in stability establishment of AFW during excavation and supporting. As is known to all, the deformation of frozen soil increases as exposure time of AFW increased, and the corresponding strength decreases. Accordingly, the investigations on the creep behaviors, such as the long-term deformation and long-term strength of frozen soil with thermal gradient have great significance, and those are helpful to solve some application problems arising from AFW.

Relationship between the mechanical characteristics of frozen soil and the external variables, such as the load, negative temperature and water content, is an important issue in solution of embankment engineering or temporary supporting structure design (Ladanyi and Morel, 1990; Lai et al., 2009, 2010; Ma and Chang, 2002; Parameswaran and Jones, 1981; Tsytovich, 1985; Wu and Ma, 1994; Wu and Zhang, 1983; Zhu et al., 1992). However, conclusions and deformation mechanism drawn from the frozen soil with uniform temperature cannot be simply applied to artificial freezing engineering due to the lack of considering the thermal gradient. Sheng et al. (1995) performed creep test at un-constant load and un-constant temperature, and his results showed that the frozen soil behaved like aging geotechnical materials during decaying creep stage and the flowing rules were inapplicable for reproducing the creep process ,however ,the aging theory (or hardening theory, or inheritance theory) could be developed to capture the creep characteristics. For stable and accelerating creep stage, creep deformation was controlled by flowing rules. Moreover, the aging theory and Boltzmann's superposition theory were inapplicable either. Sheng et al. (1996) showed that creep deformation of frozen soil with sine variation temperature was controlled by high temperature deformation and low temperature deformation comprehensively, and the creep deformation could be replaced by test results under uniform temperature. Ma et al. (2007) studied the creep behaviors of frozen clay at various temperatures and initial water contents, and the results indicated that warm ice-rich frozen clay presented the decaying characteristic under different experimental conditions. Based on the analysis of the test results, the author employed a phenomenological constitutive model to describe the creep behavior of frozen clay. Qin et al. (2009) carried out an experimental study on the compressible behavior of warm ice-rich frozen soil. They found that the warm ice-rich frozen clay was essentially sensitive to

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both load and temperature; the settlement incurred by the additional load from the built embankment was of considerable magnitude; with the increase in temperature, the settlement would be greatly magnified. Liu and Peng (2009) studied the strength weakening characteristics of frozen soil with a thermal gradient (thawing soil) adopting the modified triaxial apparatus and obtained the effects of initial water amount, cooling temperature and thawing temperature to stress–strain and strength.

The above-mentioned experiments concerned on natural permafrost engineering are always focused on the warm frozen soil with a temperature higher than −2 °C, but the average temperature in AFW is always lower than −15 °C. Zhou et al. (2010) and Zhao et al. (2011, 2012) researched the deformation and strength of frozen sand under different thermal gradient and different test method, and the average experimental temperature was −20 °C. They found that the stress–strain curves and strength in K_0DCGF (freezing with non-uniform temperature under loading after K_0 consolidation) tests were different from that in GFC (freezing with non-uniform temperature without experiencing K_0 consolidation) tests, and relationship of stress–strain curves could be described by exponent and power equations respectively considering the correction equation on thermal gradient. In this paper, a series of uniaxial creep tests performed on frozen saturated clay under various thermal gradients and various creep stresses under an average temperature of −20 °C, and some useful conclusions were obtained. Based on the analysis of experimental results, an equation capable of describing axial creep behavior and reflecting the effects of thermal gradient was developed.

2. Experimental method

In this study, the clay used in the test was taken from a mine shaft at a depth of about 510 m–530 m and the physical parameters were listed in Table 1. The specimens prepared as cylinders with 100 mm in diameter and 200 mm in height. The initial water content and the dry unit weight of the specimens tested were 33.59% and 1.42 g/cm^3, respectively. These specimens were saturated with distilled water under a vacuum of 73 mmHg for 24 h to achieve a saturation degree of at least 0.98.

The uniaxial creep tests were carried out on a multifunctional material testing apparatus for frozen soils consisting of a loading system, a cooling system and a controlling system. Besides the traditional functions such as tests under stress control and strain control modes, three new features make the apparatus different from the other triaxial apparatus for frozen soils, the first is that the temperature of the specimen is controlled from two positions, i.e., the top and bottom ends with cooling liquid cycling. In this way, the thermal gradient in the specimen can be controlled in vertical direction. The second is that a micro-base is connecting with the internal thermal resistors which makes the measurement of the internal temperature of the specimen available (Zhao et al., in press). The third is that a radial deformation measuring device is installed around the specimen at the middle height which makes the measurement of radial strain available together with the axial strain.

The uniaxial creep experiments were carried out by the following three steps:

1) Sample installation. Firstly, the outer thermal resistors (the thermal resistors were placed at 2 cm, 6 cm, 10 cm, 14 cm, and 18 cm heights of the samples) were installed on the surface of the samples. The corresponding internal thermal resistors were installed inside the specimen at the same height before freezing. Then the saturated specimens were mounted on the pedestal of triaxial apparatus;
2) Freezing. Firstly, closing the drainage valve and the entry valves of triaxial cell, and specimens freezing with non-uniform temperature then were conducted. 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 [thermal gradient = [top temperature − bottom temperature] / specimen height]. The detailed comparison between the measured temperature distribution in test and designed temperature distribution was introduced by Zhao et al. (2011). The average temperature [average temperature = [top temperature + bottom temperature] / 2] is designed as −20 °C in all tests.
3) Creep. The axial pressure was applied on the specimen until reaching the given value and was kept constant. The axial and radial creep deformations were automatic collected and stored in personal computer.

Table 1
Physical parameters of clay.

Plastic limit (%)	Liquid limit (%)	Specific gravity	Particle size (μm) content (%)		
			<5 μm	5 μm–75 μm	75 μm–250 μm
23.67	51.88	2.715	47.6	42.3	10.1

3. Test results and discussion

3.1. Axial creep deformation

The axial creep deformation–creep time relationships for frozen saturated clay at typical creep stress and typical thermal gradient are given in Fig. 2(a) and (b) respectively as examples, in which the symbol of ε_1 is denoted as the axial creep deformation, and the symbol of t is denoted as the creep time. Similar behavior was observed on other specimens with different initial experimental conditions.

The axial creep deformation versus creep time relationship is given in Fig. 2(a) for frozen clay with a thermal gradient of 0.25 °C/cm. Fig. 2(a) indicates that the axial creep strain velocity under high stress level is larger than that under low stress level at the same thermal gradient and creep time. Fig. 2(b) shows how the axial creep deformation varies for frozen clay with different thermal gradient. From the data shown in Fig. 2(b), we can found that the axial creep deformation is significantly dependent on the thermal gradient. With the decrease in thermal gradient, the creep strain velocity decreases under the identical creep time.

The creep curves of frozen saturated clay as shown in Fig. 2(a) and (b) can be distinguished into two stages: the initial instantaneous elastic deformation stage, the creep stain rate of frozen saturated clay approaches a constant value; and the decaying creep stage, the initial creep strain rate of frozen saturated clay is very high, but with the increasing in time, the creep strain velocity decreases rapidly. The average temperature used in present experiments (−20 °C) is lower than that (>−2 °C) used by Ma et al. (2007), however, the

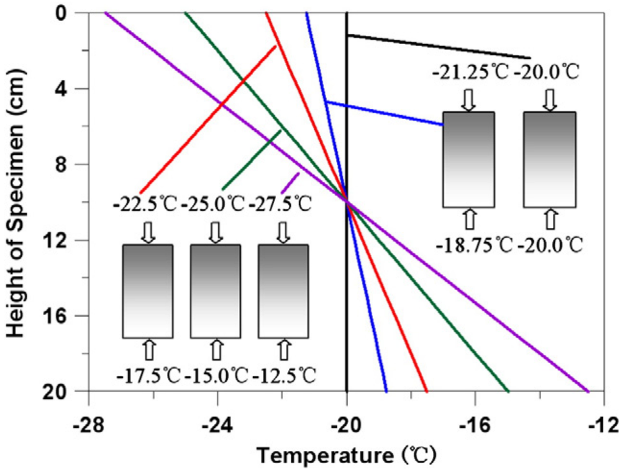

Fig. 1. Thermal gradients.