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Thermal gradient dependent deformation behavior of frozen soil and its mechanism at temperatures close to 0 °C

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ABSTRACT

A study was initiated to assess the thermal gradient-dependent deformation behavior of frozen soils at temperatures close to 0 °C and to reveal the mechanisms of this behavior. A series of unconfined compression tests (UCT) were performed by using a testing apparatus that was exclusively designed for frozen soils with thermal gradient. The stress-strain test results showed that there was a gradual transition in the soils' characteristics from strain-softening to strain-hardening with the increase of thermal gradient. The increase in the thermal gradient led to a reduction in the soil volumetric dilation, strength and the secant modulus, with maximum decreases of 70%, over 80% and nearly 100% for these parameters as a function of thermal gradient increments of 0.2 °C/cm. The non-uniformity in radial deformation with the increase of axial strain was enhanced as the thermal gradient increased. Fracturing of the soil column accompanied by a large lateral deformation was observed in the tested specimens and the mean height of the fractured zone accounted for 30% of the height of the deformed specimen. The tensile strength accounted for nearly 20% of the compressive strength in the frozen soil subjected to a thermal gradient , which partially governed the sample fracturing and dictated the height of the fractured zone, thus producing the unique thermal gradient-dependent deformation behavior.

1. Introduction

More than 20% of the land in China contains permafrost, and 70% of this permafrost with a mean annual ground temperature (MAGT) ranging from −3.5 °C to 0 °C is located on the Qinghai-Tibet Plateau (Jin et al., 2000). In addition, the potential warming associated with climate change and disturbances from ongoing engineering construction,such as the Qinghai-Tibet railway (Highway), Qinghai-Kangding Highway, and oil product pipeline from Golmud to Lhasa, has further contributed to the increase in the temperature of this permafrost, causing its present temperature to be closer to 0 °C (Ma et al., 2011).

The destruction and failure of the foundations directly affect the normal operation of the above engineering structures. Based on the numerous investigations on the embankment of the Qinghai-Tibetan railway, Ma et al. (2011) found that the magnitudes of settlement and differential settlement between right and left embankment shoulders were significant and still increased quickly for traditional embankment in permafrost, particularly in warm and ice-rich permafrost regions. This phenomenon was also found in Roadbed-bridge Transition Section, optical cable, tower footing for the power transmission line, and pile foundation (Wu and Niu, 2013). The subsidence of foundations in permafrost zones was dominated by deformation of frozen soil with temperatures near 0 °C, together with the freezing and thawing-induced deformation of the thawed soils (Zhang, 2004). The deformation can produce non-uniform variation in the elevation of the ground surface and then cause tensile fracturing in foundations (Ma et al., 2013), which is always irreversible and initiates instability in the neighboring engineering structures situated in the permafrost (Zhang, 2004; Sun et al., 2014; Wang et al., 2014; Li et al., 2015). Therefore, research on the subsidence-dependent compressibility and deformability of frozen soils at temperatures near 0 °C is of the utmost practical importance in conducting stability analysis and the constitutive modeling of soil masses in permafrost.

To date, numerous investigators have conducted tests on frozen soils at various temperatures higher than −2 °C focusing on the deformation responses and strength behaviors of these materials (Arenson and Springman, 2005; Qin et al., 2009; Azmatch et al., 2011; Zhang, 2013; Yamamoto and Springman, 2014; Yang et al., 2015). The experimental results showed that the warm frozen soil was particularly sensitive to both load and temperature increases and small increments of load and temperature could produce a rapid increase in the deformation amplitude and a loss in the strength of the soil (Qin et al., 2009; Azmatch et al., 2011; Zhang, 2013).

The deformation of frozen soils at temperatures near 0 °C was believed to be closely associated with the presence of the substantial quantities of liquid water (unfrozen water) in the soil (Azmatch et al., 2011). Accordingly, under load, this pore water may flow from zones

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of high stress to the zones of low stress due to the compression-induced pore-water pressure and the relatively high permeability of the soil at high temperatures. It has been observed from test that the water flow as well as drainage of the pore-water governed the subsequent soil deformation behavior (Miyata and Akagawa, 1997; Mohammadali, 2012; Zhang, 2013; Zhang, 2014). Although the physical processes at temperatures near 0 °C control the soil's deformation behavior, the available research concerning this subject is little. In addition, the nature of the deformation of the warm frozen soils has not yet been fully explained. The main reason for these lacks of understanding is the difficulties encountered in conducting experiments on soil at temperatures close to 0 °C.

According to the field measurement results from the MAGT tests conducted on the Qinghai-Tibet Plateau, the temperature near the permafrost table (0 °C isotherm) is usually characteristically non-uniform (Ma et al., 2008; Sun et al., 2014; Liu et al., 2014). The presence of thermal gradient and its variation have been found to further complicate the difficulty of performing testing at temperatures close to 0 °C. Although the reported test was conducted on the frozen soils with thermal gradient under a mean temperature of −20 °C and penetration fractures were observed in the deformed specimen (Zhao et al., 2010; Zhao et al., 2016), there have been no report concerning testing of frozen soils with thermal gradient under a mean temperature higher than −2 °C. Thus, the relationship between characteristics of fractured zone and temperature cannot be established. In fact, the deformation of frozen soils containing a thermal gradient has been found to be partially responsible for the settlement of the ground surface and has also influenced the re-freezing of the adjacent thawed zones. This is due to the deformation-induced fractures in the soil, which affect the hydraulic conductivity and hence the moisture transfer during freezing and thawing. Additionally, it is widely accepted that the observed fractures or fissures in embankment were closely associated with the non-uniform settlement of the permafrost, but the effects of fracturing in frozen soils with thermal gradient were ignored. Therefore, exploring thermal gradient-dependent deformation behavior in soils and the mechanism of this behavior are the keystones in the understanding and recognition of the deformability of frozen soils with temperatures close to 0 °C.

However, most of researches conducted on frozen soils at temperatures close to 0 °C have been focused on the stress-strain responses of the soil, whereas no work has been done to specifically measure the geometry of the frozen soils subjected to compression, especially the compression-induced cracks and penetration fractures. This fractures might form as a result of freezing or thawing of geo-materials (Azmatch et al., 2011; Wu and Prakash, 2015; Kogbara et al., 2016), in which cases they might be referred to as desiccation cracks or thermal contraction cracks. In fact, the mechanical loading has a more remarkable influence than soil freezing or thawing on the fracturing, but corresponding experimental observations of this phenomenon is relatively rare.

In this reported study, an experimental test apparatus was designed exclusively for testing frozen soils with thermal gradient. This apparatus was equipped with a digital camera and then used to perform a series of compression tests on frozen soils containing a thermal gradient at temperatures close to 0 °C. The influences of thermal gradient (Grad*T*) and mean temperature (T_θ) on the deformation response of the soil were examined and investigated. Furthermore, quantitative interpretations of the compression-induced fracturing and the fractured zone in the soil samples were presented.

Especially, there were several innovative aspects for the current research, including testing method and deforming responses related to the heterogeneous material, distinguished from the previous studies. First, the deformation profile and fracture process have been successfully measured by digital processing technology (DPT) for frozen soil samples with mean temperature $T_\theta \geq -2$ °C, while these cannot be observed directly due to the opaque cell and the opaque liquid hydraulic oil in the performed experiments for frozen soil samples with mean temperature $T_\theta = -20$ °C. Second, although the thermal gradient gave rise to the decrement of strength for frozen soils with low temperature, it could lead to a complete loss of strength for frozen soil samples with thermal gradient under mean temperatures close to 0 °C. This indicated the mean strength and the potential threshold govern the deforming and mechanical behaviors of such heterogeneous materials. Third, the observed deformation localization dependent phenomenon and behaviors in frozen soil samples with mean temperature $T_\theta \geq -2$ °C (fracturing in extremely narrow zone) were different from that in frozen soils with mean temperature $T_\theta = -20$ °C (penetrated fracture). Finally, the performed indirect tensile test for frozen soil samples with temperatures near 0 °C implied that the increase of the tensile strength led to a decrement of the fracturing rate and an apparent small fractured zone and decreased the potentiality of the penetrated fracturing.

2. Testing assembly

2.1. Testing apparatus

The testing apparatus developed for this study was based on the traditional tri-axial testing device and was used exclusively in testing frozen soils (Shao, 2014; Lu, 2015). The loading system was driven by stepping motor and had a maximum displacement of 60 mm with a precision of 0.18 mm. The strength of the frozen soils with temperatures near 0°C can be quite low, so a load sensor with a measuring range of 0.5 kN was used to improve the resolution and precision of the load measurements. Two refrigeration circulators with a temperature fluctuation of ±0.05 °C were connected to copper plates and these plates were placed at the top and bottom ends of the specimen to produce the desired thermal gradient. A high-power fan and improved duct for heat exchange were utilized to produce a stable and uniform air flow throughout the incubator, which minimized temperature fluctuations around the specimens. Using this system, the temperature in the incubator was controlled to ±0.05 °C. The temperature at upper refrigeration plate was kept higher than the bottom plate and the corresponding flow direction for cold air in the incubator was from downside to upside. Therefore, the direction of the thermal gradient around the specimen as a result of heat loss from the flowing air was identical to that in the specimen. This process helped to decrease the lateral heat loss in the soil specimen and thereby maintained the sample's thermal gradient. All the temperatures in incubator were monitored using thermistors with a precision of 0.01°C.

2.2. Thermal gradient and mean temperature

Three thermal gradients were imposed on the samples, i.e., 0.0 °C/cm, 0.1 °C/cm, 0.2 °C/cm and four mean temperatures, i.e., −0.2 °C/cm, −1.5 °C/cm, −1.0 °C/cm, −0.5 °C were used for the testing. The expected temperature distribution in the specimen was plotted in Fig. 2, where Grad*T* is the thermal gradient and T_θ is the average temperature, h_s is the distance between the location of the measuring point and the bottom of the specimen. Furthermore, the highest sample temperature was located at the upper side of the specimen and the lowest temperature was located at the bottom of the specimen. The results shown in Fig. 2(e) indicated that, based on the thermistor measurement, the temperature fluctuation at each measuring point was less than ±0.1 °C, and the measured thermal gradient deviation in the specimen was about ±0.02 °C/cm. Besides, the radial temperature difference between the outer surface and the internal point fluctuated around ±0.07 °C, and the corresponding radial thermal gradient (the distance between the outer surface and the internal point was 3.09 cm) was about ±0.02 °C/cm. Considering of the measurement errors and system precision, the control precision for temperature agreed well with the anticipated results and met the testing requirements for frozen soil at temperatures higher than −2.0 °C.