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Structural change and volumetric shrinkage of clay due to freeze-thaw by 3D X-ray computed tomography

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ABSTRACT

Artificial ground freezing (AGF) has found extensive applications in construction of civil structures, and has been frequently used in the construction of subways in soft ground within urban settings. Ground heave and subsidence due to AGF of clay soils are of great concern. Understanding of both short-term and long-term settlement mechanisms is still very limited and estimation of settlement amount needs further improvement. This paper describes an apparatus for conducting unidirectional freeze-thaw experiments in a closed system, presents testing results on structural change in terms of moisture redistribution, void ratio and dry density variation within high-quality unsaturated clay specimens, and discusses the mechanism of structural change and limitations of the experiment. In particular, soil specimens before and after freeze-thaw were scanned by three-dimensional X-ray Computed Tomography (X-ray CT) to reveal detailed structural changes. Non-uniform volumetric shrinkage, referred to as freeze-necking, was observed on an unsaturated clay specimen. A short-term volumetric shrinkage ratio was defined and assessed using the three-dimensional X-ray CT image. It was found to be closely related to freezing temperature and have a linear relationship with the freeze equilibrium time. The volumetric shrinkage was likely induced by moisture migration, and could be useful for estimating short-term settlement caused by AGF in unsaturated clay.

1. Introduction

The artificial ground freezing (AGF) method has been widely used in civil engineering construction. This method has the dual effect of ground reinforcement and waterproof sealing, as it can form a coherent and closed waterproof curtain of frozen soils with high stiffness, strength and low permeability. Examples include temporary excavation support, ground stabilization, ground water or seepage barriers, subway tunnel construction, mine shaft sinking in deep soil deposits, etc. (e.g. Braun et al., 1979; Jessberger, 1980; John, 1981; Gates, 1995; Andersland and Ladanyi, 2004; Li et al., 2011; Sopko and Chamberland, 2013; Wagner and Yarmak, 2013; Han et al., 2015). It is particularly effective in the construction of cross passages for shield tunnels in soft ground, and has been successfully used in many cases (Biggart and Sternath, 1996; Haß and Schäfers, 2005; Crippa and Manassero, 2006; Zhou and Zhou, 2012).

Fig. 1 presents an example freeze pipe arrangement of AGF application in subway cross passage construction. While AGF offers significant benefits as stated above, the potential ground movement due to frost heave and subsequent short-term and long-term settlement after thaw can be of great concern to adjacent surface structures such as those observed in Chamberlain (1981) and underground structures including buried utility pipes, as illustrated in Fig. 1. Ground movement due to frost heave results from two different phenomena during freezing: 1) expansion due to phase change of pore water to ice, and 2) ground heaving due to pore water migration and formation of ice lenses in the freezing fringe. Thaw settlement involves a volume reduction due to phase change of ice to water and consolidation due to drainage of excess pore water. There have been extensive studies on assessing the heave rate and the frost susceptibility of silty soils, and thaw settlement of ice-rich permafrost.

Fundamental understanding of the settlement mechanisms of fine-grained soils due to AGF is necessary for improved estimation. Studies have shown that freeze-thaw can severely alter the structure, and hence the consolidation behavior and permeability of fine-grained soils (e.g. Chamberlain and Gow, 1979; Graham and Au (1985); Viklander, 1998; Konard and Samson, 2000; Dagesse, 2015). Nixon and Morgenstern (1973) used a model to characterize the effective stress change during a closed system freeze-thaw cycle and introduced a residual stress that influences the pore pressure generation and subsequent volume change during consolidation. Chamberlain and Blouin (1978) showed that a large decrease in the void ratio of fine-grained

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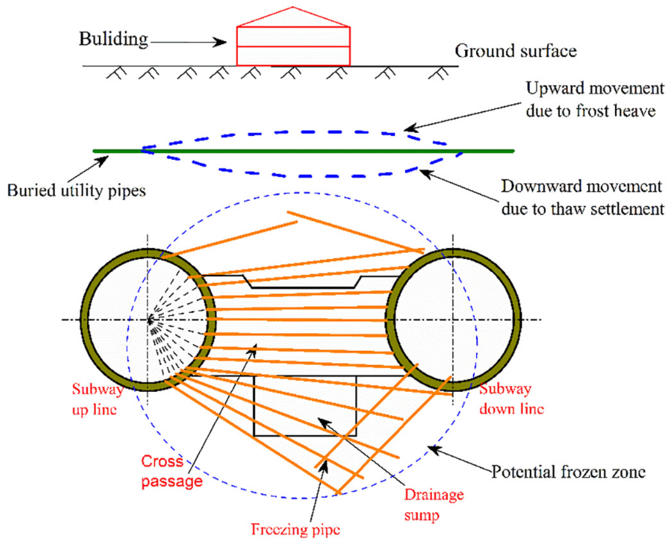

Fig. 1. Schematic of subway cross passage construction by AGF and potential issues.

dredged material slurries could be caused by freezing and thawing, and the volume of this material and several others were reduced by as much as 25%. Chamberlain (1981) noted freezing can cause significant changes in soil structure and density, resulting in adverse settlement during thaw, attributed such settlement to the suction forces that draw pore water to the freezing front, and proposed freezing-induced overconsolidation resulted from an increased effective stress due to these suction forces in unfrozen clay beneath the freezing front. Graham and Au (1985) studied the freeze-thaw effect on natural clay and observed that freeze-thaw causes an increase in compressibility. Viklander (1998) studied the permeability and volume change of non-plastic till due to cyclic freeze-thaw, and reported that initially loose till exhibits volume decrease, while initially dense till exhibits volume increase. Wang et al. (2016) conducted a freeze-thaw cycle study of loess, and observed volume shrinkage and microstructure changes in untreated and stabilized loess. Swan and Greene (1998) and Swan et al. (2013) found that one freeze-thaw cycle can cause severe changes to consolidation behavior of Chicago Blue Clay and Boston Blue Clay, as evidenced by decreased liquid limit and a significant increase in settlement. Paudel and Wang (2010) studied the effect of freeze-thaw on consolidation behavior of fine-grained soils (classified as CL and CH according to the Unified Soil Classification System), and found that the coefficient of consolidation increased sharply by an order of magnitude and hydraulic conductivity by one to two orders of magnitude after freeze and thaw. Tiedje and Guo (2011) found that growth of ice lenses results in substantial decreases in pore pressure and ultimately dewatering and unsaturation in the unfrozen zone in closed-system tests. Zhou and Tang (2015) carried out a centrifuge modeling to investigate the permeability and pore structural change, and proposed a large strain thaw consolidation model. Zhang et al. (2016) found a significant decrease of pore pressure in the unfrozen silty clay and sand samples during freezing tests.

Despite this collection of studies, thaw settlement prediction of cohesive soils such as clay is far from accurate. For example, the actual thaw settlement was significantly less than that predicted in Boston Blue Clay in the Central Artery/Tunnel (CA/T) project in Boston (Chang and Lacy, 2008). In practice, the thaw settlement issues in deep clay deposits, particularly those related to long-term settlement, were mainly dealt with by pre-grouting or passively based on field monitoring after thawing (e.g. Zhou and Tang, 2015).

In summary, understanding of the effects of freeze-thaw on clay soil during AGF is limited, and more accurate estimation of thaw settlement is needed. Most studies took a holistic approach to look at the property changes; thaw settlement was accumulative of both short-term volume change at the end of thaw due to freezing consolidation, and long-term volume change due to structural changes (void ratio distribution, density and permeability, etc.). Very few studies addressed the local structural changes within soil specimens and attempted to investigate short-term and long-term settlement separately, which have important engineering implications. For deep clay deposits with very low permeability (Tavenas et al., 1983) and therefore very limited water supply to or drainage from the affected zone during a relatively short period of time of freeze or thaw in AGF, it is unclear how the pore water migration as induced by AGF will alter structure and the properties of the local soil, and how much short-term and long-term volumetric changes will be induced by AGF.

This paper focuses on local structural change and attempts to quantify the short-term volumetric change of natural clay soil subjected to a freeze-thaw cycle similar to that induced by AGF. The test was carried out in a closed system, i.e. no external water supply and no drainage, to simulate the freeze and thaw of clay soils in an undrained condition. High accuracy three-dimensional X-ray computed tomography (X-ray CT) was used to analyze soil specimens subject to a unidirectional freeze-thaw cycle to reveal the soil structural and dimensional change. A phenomenon, i.e. radial shrinkage at the warm end of the specimen, named freeze-necking, was observed immediately after freeze-thaw together with height reduction. A short-term volumetric shrinkage ratio accounting for both height and cross-sectional area change was defined and analyzed in relation to the temperature gradient. Pore water redistribution and dry density change are also examined to help reveal the causes of shrinkage in clay by AGF.

2. Experimental program

2.1. Soil investigated

Samples were obtained from 30 to 35 m below the ground surface by a thin-walled sampler (11 cm ID) from a site in Ningbo, China. Fig. 2 contains the grain size distribution curve, and Table 1 presents soil index properties. It was classified as lean clay (CL) per Unified Soil Classification System. The saturation ratio was found to be 87.9%.

2.2. Freeze-thaw apparatus

Fig. 3 is a schematic of the apparatus designed for simulating the freeze-thaw process in AGF. It consists of a temperature-controlled environmental chamber, specimen tube, top and bottom plates, temperature and vertical displacement monitoring system. As the concerns were the buried utility pipes and surface structure, which are typically

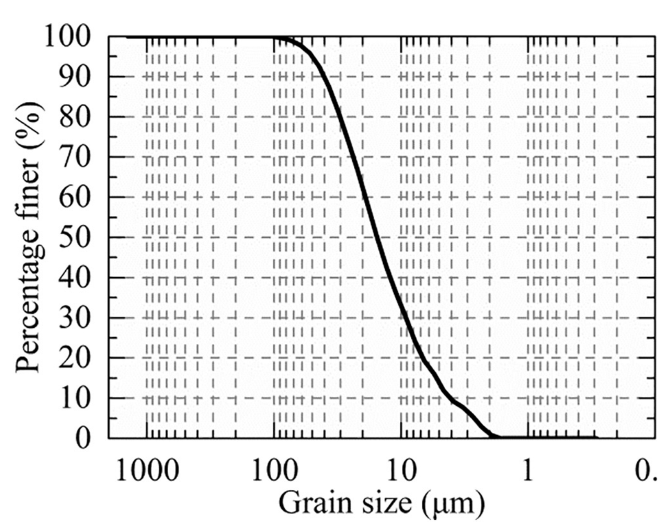

Fig. 2. Grain size distribution of clay used in testing.