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

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A R T I C L E   I N F O

Article history:
Received 29 November 2016
Received in revised form 14 February 2017
Accepted 17 March 2017
Available online 19 March 2017

Keywords:
Clay
Structural change
Volumetric shrinkage
Three-dimensional X-ray computed tomography (X-ray CT)
Freeze-thaw

A B S T R A C T

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.

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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 soils...
changes; thaw settlement was accumulative of both short-term volume
is needed. Most studies took a holistic approach to look at the property
during AGF is limited, and more accurate estimation of thaw settlement
monitoring after thawing (e.g. Zhou and Tang, 2015).
were mainly dealt with by pre-grouting or passively based on
deep clay deposits, particularly those related to long-term settlement,
(Chang and Lacy, 2008). In practice, the thaw settlement issues in
were the buried utility pipes and surface structure, which are typically
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

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

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

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above the freeze pipes (refer to Fig. 1), the cold plate is located at the bottom to promote a uniaxial freezing of the soil specimen from bottom to top. Thermal couples are used to gather the variation of the temperature field within the specimen, and displacement transducers are used to monitor vertical displacement at the warm plate. The temperature range of the environmental chamber is $-30^\circ C$ to $50^\circ C$ with a temperature control accuracy of $\pm 0.2^\circ C$. The top and bottom plates are connected to external cooling baths; the cooling medium is alcohol with a working temperature range of $-40^\circ C$ to $60^\circ C$. The specimen tube is made of double-layer acrylic glass with 79.8 mm inner diameter, 120 mm height, and a removable external insulation layer. Soil samples were carefully trimmed to make cylindrical soil specimens $100$ mm in height and a removable external insulation layer. Soil samples were carefully trimmed to make cylindrical soil specimens $100$ mm in height and a diameter of 79.8 mm to $120$ mm height, and a removable external insulation layer. Soil samples were made of double-layer acrylic glass with 79.8 mm inner diameter, 120 mm height, and a removable external insulation layer. Soil samples were carefully trimmed to make cylindrical soil specimens 100-mm high with a diameter of 79.8 mm to fit with the specimen tube snugly.

Freeze-thaw experiments were conducted under four scenarios with the cold plate set at freezing temperatures of $-5^\circ C$, $-7^\circ C$, $-10^\circ C$, or $-15^\circ C$ (referred to as Case I, II, III, or IV), and the warm plate at $1^\circ C$, resulting in temperature gradient of 0.6, 0.8, 1.1 and 1.6 °C/cm respectively. The thawing temperature was set at 20 °C. The specimen before and after freeze-thaw for all four cases. For each experiment involving non-uniform volumetric shrinkage, moisture content distribution and soil structural changes in terms of void ratio and dry density were tested by taking samples from five layers (labeled as A, B, C, D and E as shown in Fig. 3) after freeze-thaw. No surcharge was applied on the top plate to allow investigation of volumetric behavior due to pore water migration during AGF. Instead, subsequent oedometer tests of samples from Layers A through E were conducted for assessing long-term settlement due to dissipation of excess pore pressure, the results are reported in a separate paper.

### Table 1

<table>
<thead>
<tr>
<th>Engineering index</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content, $\omega$ (%)</td>
<td>38</td>
</tr>
<tr>
<td>Natural bulk density, $\rho$ (g/cm$^3$)</td>
<td>1.69</td>
</tr>
<tr>
<td>Void ratio, $e$</td>
<td>1.18</td>
</tr>
<tr>
<td>Specific gravity, $G_s$</td>
<td>2.73</td>
</tr>
<tr>
<td>Liquid limit, LL (%)</td>
<td>44</td>
</tr>
<tr>
<td>Plastic limit, PL (%)</td>
<td>19</td>
</tr>
<tr>
<td>Plastic index, PI</td>
<td>25</td>
</tr>
<tr>
<td>Natural bulk density, $\rho$ (g/cm$^3$)</td>
<td>1.69</td>
</tr>
</tbody>
</table>

#### 2.3. Three-dimensional X-ray CT

Computed tomography is a non-destructive imaging procedure that uses x-ray attenuation to produce cross-sectional images, or virtual slices, of specimens, allowing users to see inside the object without cutting. Two-dimensional CT has been extensively used in studying the internal structure and phase change of soil during freeze and thaw over the last three decades (e.g. Tollner and Verma, 1989; Qi et al., 2003). Three-dimensional (3D) X-ray is an imaging technique that can analyze and reconstruct 3D images of the sample to allow detailed examination of soil’s internal structure with high resolution and has gained popularity in the last decade. Fig. 4 shows a schematic diagram of 3D X-ray CT system consisting of four parts: X-ray source, mechanical scanning system, flat panel detector, and data acquisition and processing system. During scanning, a cone shaped X-ray beam passes through a specimen at a certain azimuth angle and the resultant decreases in intensities are measured on all detectors; multiple views must be acquired via the turntable at a different azimuth angle to allow 3D reconstruction of X-ray attenuation distribution within the specimen by a mathematical process involving filtered back projection algorithm (Birgul, 2008). The reconstruction or image consists of voxels with intensities representing X-ray attenuation for a specific soil volume. With available industrial X-ray CT equipment, the resolution can reach 0.0012 mm$^3$ soil volume per voxel. These reconstructions can be used to identify local changes in soil structure and relative density, and localization of shear strain development (e.g. Bésuelle et al., 2006; Lenoir et al., 2007; Hall et al., 2010; Tagliaferri et al., 2011). During this study, a CT scan was performed before and after the specimen was subjected to freeze-thaw process. Currently, it is impossible to perform scanning while the soil is at steady state due to sample size limitation of the CT equipment and the amount of time required finishing a round of scanning.

#### 3. Moisture redistribution, soil structural change, and volumetric shrinkage

This section reports freeze-thaw experiment results including maximum frozen height, time to achieve thermal equilibrium, observation of non-uniform volumetric shrinkage, moisture content distribution and soil structural changes in terms of void ratio and dry density within the specimen before and after freeze-thaw for all four cases. For each temperature gradient, the results from two specimens were averaged and reported. ASTM standards (i.e. ASTM D2216 – 10, and ASTM D7263 – 09) were used to measure the water content and dry density respectively. The volumetric shrinkage was assessed quantitatively by using a software tool that will be discussed later.
3.1 Freeze-thaw process and maximum frozen height

Fig. 5 presents a typical variation of temperatures at five locations and vertical displacement with time during a freeze-thaw experiment \( (T_f = -10 ^\circ C) \). It is clear from Fig. 5 that as the temperature within the specimen stabilized during the freezing process, the specimen heave reached a maximum value, and then quickly settled as the temperature was raised to \( 10 ^\circ C \) during the thawing process. The time to achieve thermal equilibrium within the clay specimen, referred to as freeze equilibrium time, is directly related to the temperature gradient, or the cold end temperature when the warm end temperature is fixed. At thermal equilibrium, the maximum frozen height was assessed based on temperature distribution and interpolation. Fig. 6 presents both the freeze equilibrium time and the maximum frozen height for all four cases. The freeze equilibrium time decreased from 43.4 h to 11.4 h, and the maximum frozen height increased from 72 mm to 99 mm, or the unfrozen zone at the warm end decreased from 28 mm to 1 mm, as \( T_f \) decreased from \(-5 ^\circ C\) to \(-15 ^\circ C\).

3.2 Observation of non-uniform volumetric change

Soil specimens before and after freeze-thaw for four cases were scanned by X-ray CT to render 3D images for examination of overall shape and void shape change, and accurate dimension measurement. Fig. 7a and b are longitudinal and horizontal sections of the specimen CT image before freeze-thaw, respectively. Fig. 7c and d show longitudinal and horizontal views of the specimen CT image after freeze-thaw for Case I. The darker gray outside the sample indicates the acrylic specimen tube. Within the soil specimen, brighter gray indicates soil minerals, and the darker gray indicates voids or low density material. It is interesting to note from Fig. 7a and b that the CT image is very effective in revealing tiny fissures within the clay specimen. These fissures may exist in the field, or formed due to rebounding after removal of confining pressure in the sampling process. By comparing the longitudinal and horizontal sectional views before and after freeze-thaw, one can observe a reduction in fissure volume. The fissures almost became invisible for the upper portion, indicating more compacted soil and increased density. Fig. 7 also presents views of enlarged fissure details with the image contrast adjusted for better visual observation. It is apparent that the somewhat randomly distributed fissures before freeze-thaw became mostly horizontal after, possibly due to formation of horizontal ice lenses due to moisture migration during the unidirectional freeze-thaw process. This structural change in void distribution helps explain the observed two orders of magnitude increase in the permeability coefficient of Ellsworth clay in the horizontal direction (Chamberlain, 1981).

While frost heave at the center of soil specimen was substantial during the freezing process, the focus of this study is on the specimen volumetric change after freeze-thaw. The overall vertical movement of the specimen in reference to the specimen tube after freeze-thaw is hardly visible from Fig. 7c, however, the diameter of the soil specimen at the warm end shrank after the freeze-thaw experiment for case 1. In fact, a similar observation was made for the other three cases. The final height, depth of shrinkage and radial shrinkage can be measured from the CT image using software tools, the results are presented in Fig. 8a, b, c and d for these four cases, respectively. The final height decreased by 0.4 mm to 0.7 mm for all cases, and the height reduction decreased with increasing temperature gradient. Interestingly, the warm end diameter also shrank for all four cases, and the shrinkage was non-uniform along the height of the specimen, as opposed to previous observations of compacted clay subject to freezing (Hamilton, 1966). Formation of this neck-shaped zone at the warm end is referred to as freeze-necking throughout this paper. The height of the shrinkage zone or “neck” varies from 16.1 mm to 38.8 mm in the four cases, with the higher temperature gradient inducing a shorter shrinkage zone. Careful examination of the diameter of the CT image at the warm end shown in Fig. 8 reveals that the shrinkage amount of the diameter also varies with the temperature gradient. Measurement with software tools indicates that the radial shrinkage varied from 1.2 mm to 1.7 mm, with the lower \( T_f \) or larger temperature gradient resulting in less shrinkage.

Radial shrinkage, or the formation of a “neck”, indicates that volumetric reduction occurred after freeze-thaw. As noted previously, a portion of the specimen at the warm end did not freeze during freeze-thaw experiments, even at the largest temperature gradient, therefore the freezing shrinkage theory proposed by Hamilton (1966) cannot explain the warm end shrinkage observed in this study. Instead, existing knowledge about the large suction at the freezing fringe (e.g. Konrad and Morgenstern, 1981; Fredlund et al., 1991), observation about pore pressure decrease in the soil beneath the freezing fringe during freezing (e.g. Tiedje and Guo, 2011; Zhang et al., 2016) and evidence on the fissure shape change due to ice lens formation hint that moisture migration from the warm end to the freezing fringe is most likely the cause of the shrinkage on the warm end. Similar observation was made when studying the ground settlement data observed during December, January and February of 1952 and 1953 in Winnipeg, Canada (Baracos and Bszozm, 1957).
The next subsection will present relevant results to confirm this assumption and assess the volumetric change quantitatively.

3.3. Moisture redistribution and soil structural change

The negative pore-water pressure or suction existing in the freezing fringe is anticipated to induce significant moisture migration and redistribution under the unidirectional freeze-thaw experiments in a closed system, and can render an originally uniform soil into a non-uniform soil. The water content, void ratio and dry density of the soil specimen were measured by sampling layers A, B, C, D and E (refer to Fig. 3), and the changes compared with their respective values before freeze-thaw are presented in Fig. 9 for the four cases. Note that the dry density and void ratio were obtained at three layers (i.e. A, C and E) due to the test procedure requirement of sample height. It is clear from Fig. 9a that the moisture content of the upper portion of the soil specimen decreased, and that of the lower portion increased after freeze-thaw for all four cases. The maximum decrement clearly occurred at the layer closest to the warm end and varied from 2% for Case IV (−15 °C) to 7% for Case I (−5 °C). The maximum increment occurred at varying depths, and ranged from 1% - 2% in a much larger lower portion of the soil specimen for different freezing temperatures. The moisture data indicates a consistent moisture migration from the warm end to the cold end.

Moisture migration in an undrained environment is expected to alter soil structural and this is confirmed by void ratio and dry density change after freeze-thaw experiments. Fig. 9b and c are plots of the distribution of void ratio and dry density change for four cases; they indicate that the top third of the specimen densified due to pore water flowing out, whereas the bottom two thirds loosened due to pore water flowing in during freezing. The void ratio decreased from 2% for cases III and IV to as much as 15% for case I, whereas the void ratio increased from 1% for Cases III and IV to 5% for case I. Similarly the dry density increased from 1% for cases III and IV to 9% for case I, the decreased from 0.5% for cases III and IV to 2.2% for case I.

3.4. Short-term volumetric shrinkage

Observations in Sec. 3.2 indicated that a volumetric shrinkage occurred immediately after freeze-thaw, and results including moisture content, void ratio and dry density changes before and after testing confirm that the moisture migration was responsible. With the 3D X-ray CT digital model of soil specimens, the outer boundary of the soil specimen can be accurately identified by using a threshold image intensity value that separates the soil specimen from the specimen tube and any air space existing in between the specimen and the tube. Therefore the overall change in volume can be evaluated by finding the difference between the soil specimen volume before and after the freeze-thaw experiments. As the shrinkage was due to moisture migration caused by suction in the freezing fringe, and it is reasonable to assume that the frozen volume of the specimen was responsible for the amount of shrinkage. Therefore, we normalized the shrinkage volume by the frozen volume to produce a non-dimensional volumetric shrinkage, or short-term volumetric shrinkage ratio:

\[
\alpha_{\text{VT}} = \frac{\Delta V_{\text{FT}}}{V_F}
\]

where \(V_F = H_F \times A\) and

\[
\Delta V_{\text{FT}} = V_{\text{FT}} - V_F
\]
where $\alpha_{F-T}$ is the short-term volumetric shrinkage ratio, $\Delta V_{F-T}$ is the volumetric reduction due to unidirectional freeze-thaw, $V_f$ is the volume of frozen soil, and $H_f$ is the maximum frozen height, and $A$ is the cross-sectional area of the original specimen. Fig. 10 presents the volumetric shrinkage result in relation to $T_f$ for the four cases. It can be observed from Fig. 10 that the volumetric shrinkage reduces quickly when the cold end temperature drops. The shrinkage reached 5.7% for case I, and dropped nonlinearly to 1.2% for case IV. An exponential equation can be used to fit the shrinkage vs. cold end temperature data, as shown in Fig. 10.
4. Discussion

4.1. Mechanisms of moisture migration and volumetric shrinkage

The results presented in the previous section indicate that the amount of moisture change clearly relates to the severity of overall structural change as reflected in void ratio and dry density change, and the short-term volumetric shrinkage in an undrained environment. The underlying reason for the different amount of moisture change has to do with the temperature gradient within the freezing fringe and the rate of freezing (Williams, 1981). The suction value just below the frost front (i.e. freezing fringe in this case) can be as high as 400 kPa in Leda clay (Williams, 1967), and this value in the frozen zone increases with decreasing temperature below 0 °C. Considering that the permeability of the frozen clay is in the order of $10^{-10}$ m/s and drops as temperature decreases (Nixon, 1991), the suction at the warm end of the freezing fringe will control the moisture migration rate. Given the uniformity of the soil before freeze-thaw, it is safe to assume the migration rate is relatively constant as the freezing fringe moves towards the warm end. Therefore the freezing rate or the freeze equilibrium time, both of which depend on the temperature gradient between the cold end and warm end, will be the main factors controlling the amount of moisture migration in the same type of soil.

Moisture migration alone does not explain the volumetric shrinkage, as no volume change is expected after freeze-thaw in a closed system if the clay soil is saturated. However, for unsaturated clay, the negative pore pressure developed at the freezing fringe acts as a vacuum that sucks pore fluid from overlying soil to the freezing fringe, as also evidenced in Tiedje and Guo (2011) and Zhang et al. (2016), and sweeps through the frozen soil volume as the freezing fringe moves upwards, causing contraction in the overlying soil due to decreased pore pressure and increased effective stress. In the freezing fringe, pore water freezes and expands due to phase change, and has the potential to enlarge the voids. However, this potential will be somewhat suppressed due to compression of air by pore ice pressure and confinement of lateral pressure from the container or, in the field, from the lateral confinement of adjacent soil. As the freezing fringe moves upward, the overall effects of freezing is to densify the overlying soil, particularly closer to the warm end, and loosen the soil in the freezing fringe by a reduced magnitude, resulting in a net volumetric shrinkage. If this mechanism holds true, one would suppose the volumetric shrinkage can be directly related to the freeze equilibrium time, as the freezing fringe stays stationary, and significant water migration and structural changes diminish when thermal equilibrium is achieved. The volumetric shrinkage vs. freeze equilibrium time, as presented in Fig. 11, exhibits a linear relationship, which confirms the hypothesis discussed above.

Fig. 12 illustrates the mechanism for short-term settlement observed in the overlying soil when AGF is used. As the coolant circulates in the freeze pipe, the soil surrounding the pipe will freeze first. As the freezing fringe in the surrounding soil moves upwards, the pore water migrates towards the freezing fringe due to the large suction generated at the freezing fringe. Due to the extremely low permeability of clay and the relative short freeze equilibrium time, the water supply to this local zone will be limited, resulting in possible volumetric shrinkage in soils overlying the frozen zone.

A smaller temperature gradient such as in Case 1 means a lower freezing rate, hence more moisture migration due to a longer freeze equilibrium time, and larger volumetric shrinkage, as observed in this experiment. The effective stress increase and the change in compression index as a result of soil structural alteration during the freezing process will also lead to additional long-term settlement due to consolidation, which will be discussed in a separate article.

4.2. Limitations and engineering implications

As indicated in the previous discussion, the degree of saturation will have a direct impact on the volumetric shrinkage ratio. The maximum shrinkage should not exceed the air volume percentage of the total soil volume (i.e. 6.5% for the soil tested), which is the theoretical limit of short-term volumetric shrinkage ratio. The shrinkage ratio as defined here is slightly amplified as the volume change was normalized by the frozen soil volume, which is smaller than the total specimen volume. Nonetheless, the maximum shrinkage ratio in this investigation, i.e. 5.7%, did not exceed the theoretical limit. What impact soil index properties such as degree of saturation, water content, liquid limit, and plasticity index may have on the maximum volumetric shrinkage after freeze-thaw remains unknown and should be investigated in future studies.

Soil specimen CT images obtained during freezing would be useful for understanding the volume change in the freeze process; however, no such image is available due to limitations of the current equipment setup. No overburden pressure was applied in this experiment for examining the structural change in an idealized condition. It is known that overburden pressure will certainly affect settlement due to consolidation after freeze-thaw. However, the overburden pressure effect on the short-term volumetric shrinkage will depend on its impact to the suction in the freezing fringe, and hence the moisture migration rate, and needs to be investigated.
5. Summary and conclusions

An apparatus was designed for conducting unidirectional freeze-thaw experiments to investigate the effects of artificial ground freezing on structural change of unsaturated clay specimens at different freezing temperatures. The soil specimens before and after freeze-thaw under different conditions were scanned by three-dimensional X-ray CT for examining the structural change and short-term volumetric shrinkage. Based on the results of this study, the following conclusions can be drawn:

1) Three-dimensional X-ray CT is shown to be an effective tool for examining detailed and overall structural change and volumetric variation due to freeze-thaw.

2) Non-uniform volumetric shrinkage, or freeze-necking phenomenon, was observed in an unsaturated clay specimen in a closed freeze-thaw experiment.

3) Significant change in water content, void ratio and dry density within the clay specimen was induced by the freeze-thaw process.

4) A short-term volumetric shrinkage was defined as the ratio of volume reduction and the volume of frozen clay, and the ratio was found to be related to freezing temperature.

5) A linear relationship exists between the short-term volumetric shrinkage ratio and the freeze equilibrium time. It is speculated that moisture migration was the main cause of structural change and volumetric shrinkage in unsaturated clay.

Limitations of this study include no application of overburden pressure and lack of CT images of the specimen during the freezing process. Future study is also needed to investigate the effect of degree of saturation and soil index properties such as water content and Atterberg limits on the short-term volumetric shrinkage. Despite these limitations, the results have important implications for engineering application and could be useful for estimation of potential short-term settlement due to artificial ground freezing and other applications when the freeze-thaw process is involved.

Acknowledgements

The research work herein was supported by the National Natural Science Foundation of China (Grant No. 51478226), the Priority Academic Program Development of Jiangsu Higher Education Institutions and Excellent Doctoral Dissertation innovation fund of Nanjing Forestry University, China (Grant No. 2014-12-5w). The authors are thankful to Dr. Ping Zhang of Southeast University, China for technical support and guidance on the CT scanning.

References
