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Artificial ground freezing of fully saturated mucky clay: Thawing problem by centrifuge modeling

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ABSTRACT

In the construction of cross passages in subway tunnels in soft soils having high water content and large void ratio, Artificial Ground Freezing (AGF) has been preferred due to its unique advantages as both a structural support and a water barrier. Compared to the freeze process, the thaw response is much more complicated and less research work has been documented, particularly in applicably predicting long-term settlement. It is mainly because of the variability in the redistribution of water released from melting ice crystals and the re-consolidation or over-consolidation circumstances during freeze. This paper is based on centrifuge modeling experiments to investigate the thaw settlement of the saturated mucky clay surrounding the subway tunnel. The experimental results demonstrated the significance of replicating the prototype self-weight stress condition in a model to evaluate the thaw settlement of Shanghai mucky clay after artificial ground freezing. The water content profiles of model soils presents that there was still serious water content re-distribution even after freeze–thaw. It indicates the potential reason of differential settlement along subway tunnel around AFG construction site. Great increase in permeability of mucky clay also makes clear sense for additional large thaw settlement after artificial ground freezing. More importantly, field self-weight stress condition extended the influence area of moisture migration and aggravated the pore size to be concentrated in coarser field. All the discussion revealed that the advantages of centrifugal modeling in thaw problem by providing field self-weight. Additionally in the further computation model development, large strain thaw consolidation theory should be applied to prognosticate the long-term settlement of thick soft mucky clay after artificial ground freezing construction. Finally the scaling laws generally used in thaw processes were also checked in this paper in consideration of lacking references on thaw problem in centrifuge models.

1. Introduction

The artificial ground freezing technology uses the freezing of pore water to stabilize and seal the ground for excavation. This method has its unique advantages especially for the cross passage construction in the subway tunnel under locally adverse hydro-geological conditions, such as excavation in saturated mucky clay with high water content, large void ratio and high compressibility, etc. (Dassargues et al., 1991; Xu et al., 2009). Because it can achieve a sufficiently thick frozen soil wall, which thereby enhances the strength of the soil and can also effectively seal the water to form a hydraulic barrier during the project construction. Until now, AGF is quite popular and commonly used in Germany, UK, USA, Sweden and France for a long period. It was firstly adopted in urban construction in Stockholm, Sweden as far back to 1886 in a 24 m pedestrian tunnel. Although it started relatively late in China, actually until the 1970s, the AGF method was firstly utilized on the subway tunnel in Beijing, a large number of successful experiences were accumulated and supported by the mature and consummate technology for the whole world (Chen et al., 2000).

Frost heave and subsequent thaw-induced settlement are the two main soil responses, directly relevant to AGF. Frost heave as a soil response to freezing is much more immediate and visible compared to thaw settlement in the AGF construction. During artificial ground freezing in subway cross passage, the freezing course is more likely under control compared to thawing. It stands to reason that all the excavation work can only be started after the frozen wall is completely achieved, which is also the core control technology and mainly concerned aspect in this method. While usually the onset of subways operation will not

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wait to resume until surrounding thawed soils are fully consolidated (it even takes many years due to the poor permeability and consolidation properties of Shanghai mucky clay), i.e. subway operation sometimes is conducted during the thaw consolidation, especially in those sites where natural thawing can only be applied. Presently in China, the long-term thaw settlement was briefly controlled just by pre-grouting or locally grouting based on daily field monitoring displacement data after thawing. Less effectiveness, higher cost could not be improved without more specific and precise thaw settlement predicting model for in-site soils.

Despite as early as around 1970s, thaw settlement has been observed in artificial ground freezing. Clays with higher plasticity are generally less susceptible to frost heave, while freezing can cause significant changes in soil structure and density which can lead to adverse settlement during thaw. Settlement of clayey soils after artificial ground freezing is the results of the suction forces that draw pore water to the freezing front and also the increase on permeability. These suction forces cause an over-consolidation effect on the clay and excess pore water pressures are generated during freezing, resulted larger additional settlement under larger soil permeability during thawing (Andersland and Ladanyi, 2004; Chamberlain, 1981). Jones and Brown (1978) briefly discussed thaw settlement related to ground freezing projects. Ehdo (1969)) observed thaw settlement for a subway construction project to be about 10% greater than the amount of heave occurring during the freezing period. The previous research was mostly concentrated on laboratory test for theory development (Morgenstern and Nixon, 1971; Morgenstern and Smith, 1973; Nixon and McRoberts, 1973; Nixon and Morgenstern, 1974; Pane and Schiffman, 1981). Subsequently a large amount of theoretically-based or empirically-based methods to predict final thaw settlement were proposed. Johansson (2009) summarized 14 published ones to prognosticate the thaw settlement. Field tests were conducted as well to check out that large dispersion of theoretical or empirical results emerged with field results. Many researchers focused on numerical simulation of thaw settlement in permafrost area. Yao et al. (2012) proposed a three dimensional large strain thaw consolidation theory and verified it through numerical calculation and laboratory sample thaw consolidation test. Qi et al. (2012) further considered the influence of several factors, including load, the effective consolidation time and drainage condition, for better analysis on roadway embankment settlement. Subsequently another model coupled phase change factor into Biot's consolidation theory was established by Qi et al. (2013) through numerical simulation as well, but the results indicate the method can only fit for the small strain with low water content. Recently, a novel method for estimating embankment settlement was published by introducing both thaw consolidation and creep (Wang et al., 2013). It is a pity that no any field test program or case study was involved for reference.

Self-weight compression alleviates the frost heave but it aggravates the thaw settlement. To precisely identify the amount or validate some prediction method into AGF, experiments that can best represent the field condition, or suffice it to say the field tests, are really important. While practical experience in many areas is still quite limited. Even field tests have been and are being undertaken, the costs are often prohibitive if the time scale are very long in the study (Taylor, 2005). Herein centrifuge modeling is an attractive proposition with its scale effects. Thus in this paper the thaw settlement of saturated mucky clay is investigated by centrifugal modeling and the experimental results are presented and discussed. The final water content and permeability of soil specimens from the model after freeze–thaw were measured as well for supplementary analysis on thaw settlement mechanism. Results indicate that self-weight prototype stress conditions play important role to evaluate thaw settlement of thick soft mucky clay. It turns out that the thaw front advances far swifter than predicted in conventional sample thaw consolidation. All the results presented in this paper can be a good reference for the prediction model of thaw settlement along subway tunnel around AFG construction site.

2. Experimental program

2.1. Engineering background

This artificial ground freezing project was applied in the cross passage of subway tunnel section from Jufeng Road Station to North Yanggao Road Station in Line 12, Shanghai Metro. The construction site is located in the area of Pudong New District, which lies on the alluvial plain in southeast edge of Yangtze River Delta. It belongs to plain-littoral deposit environment (Q_h^2). According to the geotechnical investigation, there are mucky silty clay, mucky clay and silty clay along this cross passage construction site, in which mucky clay has highest thickness of almost 7.8–9.0 m. The ground temperature is relatively stable at 16–18 °C beneath a depth of 4 m. The main design parameters of AGF construction are shown as Table 1. The project model is schematically presented in Fig. 1 (left).

Considering better simulation results, the simplified freezing mode is utilized in this research program (Fig. 1 right). Artificial ground freezing process encompasses both “conventional” geotechnical considerations and those encountered in heat transfer and pollution migration. The basic scaling laws concerning the modeling of stresses, strains, seepage, consolidation, and particle size effect, etc. are summarized in Table 2, as well as heat transfer by conduction and convection. In our research experiments, the specific scales were designed properly in all respects of model box, model soil and heat circulation system to get the best consistent scaling of all parameters concerned. Here note that the geometry scale of model box is strictly designed according to the acceleration value N (such as 1:50 mentioned in below parts). But due to the limit of the smallest size of 6 mm in freezing tubes, the diameter of freezing pipe could not be satisfied by 1:50 to simulate a size of 89–107 mm in prototype. Nevertheless this research program is still reasonably designed by ensuring same heat flux to acquire the convincible results according to the heat conduction theory. The specific explanation is well documented in our newly published paper (Tang et al., 2015). It is not necessary to repeatedly explain it here. Actually this same heat flux is controlled by specifically designed flow flux with a certain temperature based on a formula in heat conduction theory: $G=\frac{3.6Q}{c(t_1-t_2)}=\frac{3.6qA}{c(t_1-t_2)}=\frac{3.6q*4\pi dL}{c(t_1-t_2)}$, where Q is the heat; q is the heat flux; c is the specific heat capacity; A is the flank area of the freezing pipe; t_1-t_2 is the temperature difference between outlet and inlet temperature of freezing pipe; G is the flow flux; i.e. to ensure the same heat flux, specific flow flux should be under control according to corresponding ratio of $\frac{G_\mathrm{m}}{G_\mathrm{p}}=\frac{A_\mathrm{m}c_\mathrm{p}\Delta t_\mathrm{p}}{A_\mathrm{p}c_\mathrm{m}\Delta t_\mathrm{m}}=\frac{d_\mathrm{m}L_\mathrm{m}c_\mathrm{p}\Delta t_\mathrm{p}}{d_\mathrm{p}L_\mathrm{p}c_\mathrm{m}\Delta t_\mathrm{m}}$. In field site, the circulation fluid is brine solution ($CaCl_2$); the specific heat capacity in prototype c_p is 2.734 kJ/kg°C (DG/TJ08-902-2006, 2006) at temperature of −25 to −30 °C; In the model tests, 90% glycol is employed as circulation fluid to prevent frost during freeze; the specific heat capacity in model c_m is 2.177 kJ/kg°C (ASHRAE, 2005). The temperature difference in field Δt_p is controlled to be 1–2 °C (DG/TJ08-902-2006, 2006). In the model, Δt_m is almost 0.5–1 °C through several trial circulation. Herein the biggest flow flux is determined as 20 L/min in each freezing pipe (3 m^3/h in prototype in Table 1). According to the design parameter of AGF project in Table 1, the cross passage is between two adjacent up-down tunnels with center space of 15–20 m. The length of freezing pipe is designed into 400 mm in model (20 m in prototype under similarity of 1:50). The freezing pipe design is ϕ80mm@0.5 m. From the aspect of heat conduction area, the safest arrangement of freezing pipe system is proportionally chosen as ϕ6mm@40 mm. Limited by the model box size and the specifically designed freezing pipe space, this model experiment is just designed to simulate the 8 single-row freezing pipes.

2.2. Materials

To simulate cross passage construction site of the artificial ground freezing, the soil in this research program was all retrieved from the subsurface 11.0 m–13.0 m in field. The geotechnical and thermal