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# Practical model of deformation prediction in soft clay after artificial ground freezing under subway low-level cyclic loading

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ABSTRACT

Settlement was investigated after the long-term operation of a subway system, particularly at segments where the artificial ground freezing (AGF) method was applied in the soft clay area. In this paper, five group soil samples under different freezing temperatures (−5 °C, −10 °C, −15 °C, −20 °C, and −30 °C, respectively) were prepared to simulate different locations perpendicular to freeze tubes during one AGF circulation. Including one group of undisturbed soils, cyclic tri-axial tests were conducted on all samples, and the dynamic strains were measured and analyzed. The results show that the residual cumulative plastic strain of soft clay after artificial freeze-thaw under subway low-level repeated cyclic loading behaves quite differently from the typical Monismith's power function development. A hyperbolic model of cumulative plastic strain of soft clay after artificial freeze-thaw is established and the relevant model parameters has been discussed for practical prediction. A critical cyclic stress ratio (CSR) of soft soil can be empirically calculated out by this practical model, only based on soil stress and soil physical state parameters without numerous cyclic tri-axial tests. All the results could provide significant reference for the safe control and environmental protection during AGF construction and subsequent subway operation.

## 1. Introduction

The artificial ground freezing (AGF) method has unique advantages in providing good performance as both a structural support and a water barrier during tunneling (Fig. 1). It serves as one of the main construction methods in subway tunnels and cross passages in soft clay areas, due to the presence of some crucial adverse soil properties, such as high water-content, low strength, and high compressibility. 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 technology. While usually the onset of subways operation will not wait to resume until surrounding thawed soils are fully consolidated (it even takes many years in naturally thawing due to the poor permeability and consolidation properties of Shanghai mucky clay), i.e. subway operation sometimes or rather mostly is conducted during the thaw consolidation, since artificially thawing is hard to control and damage potential is large. Up to now artificially thawing cases are rarely documented. 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.

In past decades, self-weight and external static loading were the main concerns with respect to the thaw deformation study. With the development of the AGF applied to subway tunnel construction, it is evident that research on static loading is insufficient for the engineering practice. The influence of dynamic loading could not be ignored when repeatedly subjected to soft clay over long-term duration, especially after the influence of freeze-thaw. Repeated cyclic loading is a kind of special long-term low-level vibration induced by subways or other high-speed traffic systems. As a result, the accumulative residual strain under long-term low-level repeated cyclic vibration loading may exceed the durable limit and serviceability of infrastructure, increasing the probability of loss of safe control.

A substantial amount of knowledge in the field of soil dynamics has been well documented over the past decades, particularly in the area of

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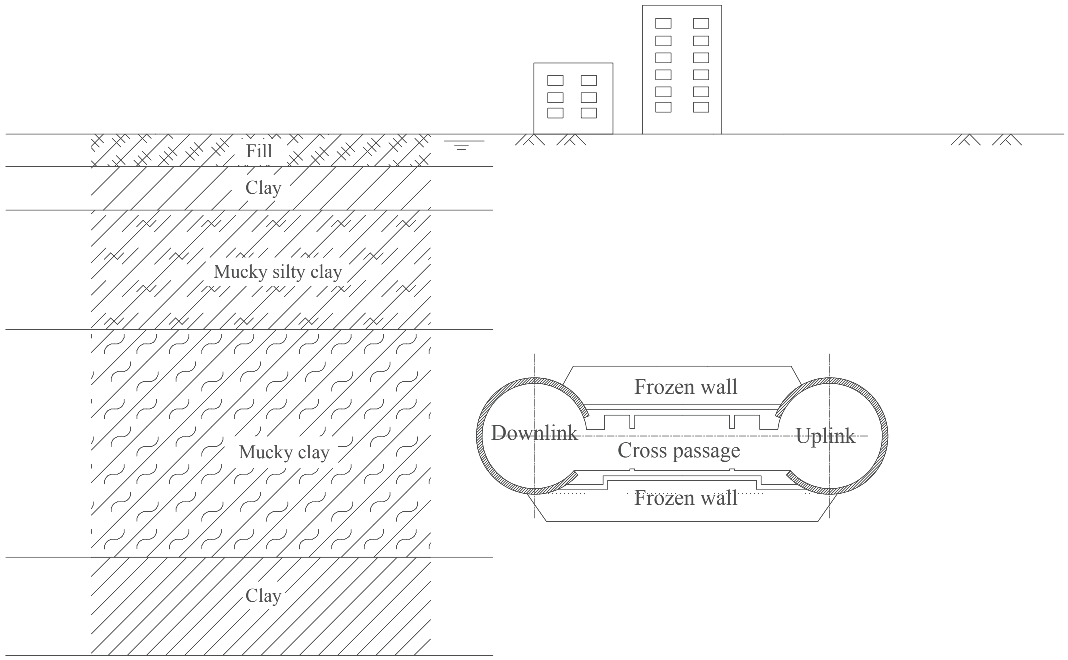


**Fig. 1.** Typical schematic diaphragm of artificial ground freezing method applied in subway cross passage construction.

residual deformation under cyclic loading. A famous empirical model was proposed by Monismith et al. (1975) as an exponential function as far back as 1970s. Later Li and Selig (1996) amended relevant parameters to broaden the application, in which they provided the connection of model parameters, soil basic properties, and loading conditions. Chai and Miura (2002) considered the influence of the initial stress condition and revised the Monismith model for a more specific expression form. In addition, in China, Zhou et al. (1996), Huang et al. (2006), Wei and Huang (2009), and Tang et al. (2011) all discussed long-term cyclic deformation behavior. Recently, Shahin et al. (2011), Guo et al. (2013), and Wang et al. (2013) observed the deformation characteristics of soft clay under different cyclic loading conditions and proposed their own deformation models, respectively. However, whether the cyclic deformation behavior of soil after the freeze-thaw action is similar to undisturbed soil is uncertain. Studies regarding the effects of the freeze-thaw process on soils have been done by many scholars and researchers. General conclusions are that not only physical characteristics such as moisture content, hydraulic conductivity, and void ratio are affected by the freeze-thaw process, but also mechanical properties, such as the stress-strain behavior, failure strength, and elastic modulus (Chamberlain and Gow, 1979; Chamberlain et al., 1990; Konrad and Samson, 2000; Qi et al., 2006; Ghazavi and Roustaie, 2010; Wei et al., 2015). These studies have mainly concentrated on the static loading condition. Even though recently some researchers have become aware of cyclic loading condition, their focuses are mostly on frozen soil, indifferent to whether it was natural or artificial frozen soil. For example, Ling et al. (2013) discussed the dynamic properties of stiffness and damping ratio of frozen clay under long-term low-level repeated cyclic loading through experiments. Ling et al. (2015) also conducted cryogenic cyclic triaxial tests of frozen compacted sand subjected to the freeze-thaw cycles and discussed different freeze-thaw cycles, temperatures, initial water contents, loading frequencies and confining pressures for the empirical expression to estimate dynamic shear modulus and damping ratio. Interestingly, Zhang and Hulsey (2015) focused on influence of near-freezing temperature in fine-grained soil on dynamic properties and concluded that thermal conditioning paths with the same target near-freezing temperature impacted dynamic properties much. Yang et al. (2010) and Zhang et al. (2017) investigated the deformation and strength behavior of artificial frozen soil and seasonally frozen soil. However, relevant studies on the cyclic behavior of soft clay after artificial freeze-thaw have been rare.

Therefore, in this paper, the accumulative strain characteristics of soft clay after an artificial freeze-thaw process under subway low-level cyclic loading has been the focus. Our main aim is to establish a practical model of deformation prediction in soft clay after artificial ground freezing under subway low-level cyclic loading, for improved engineering utilization simply based on the soil physical state and loading condition. This model could be of great significance in optimizing the less effectiveness, higher costs caused by conventional entire pre-grouting or locally grouting based on daily field monitoring displacement data after AGF. It can also provide reference to address the geotechnical and environmental problems involved applying the artificial ground freezing method in subway tunnel construction.

## 2. Materials and methods

### 2.1. Materials

The soil used in this research program was grey mucky clay of Shanghai fourth layer in Quaternary coastal-shallow marine deposition, which was formed during latest transgression ten thousand years ago (Xu et al., 2009). Testing soil were retrieved from a typical foundation pit near South Sungkiang Station of Line 9 in Shanghai Metro. The basic physical and mechanical properties are presented in Table 1. It shows that Shanghai mucky clay is characterized by high water content, a large void ratio, high compressibility, and low strength. All the soils in this research program were sampled from the field in the subsurface 11.0–13.0 m, where the cross passages are mostly located in Shanghai. Once penetrated by a thin-wall sampler, all the samples were sealed in a 300-mm height and 100-mm diameter sampling tube and maintained at constant temperature and humidity in a sample storage room. Influenced by a large amount of clay particles (over 80% as Fig. 2(a)), Shanghai mucky clay is labeled as CH according to Atterberg limits (Table 1). The grain-size distribution (GSD) is shown in Fig. 2(a), using sieving analysis and the hydrometer method in the laboratory. The percent passing the #200 sieve (0.075 mm) is as high as 84%. Fig. 2(b) presented the soil-water characteristic curve (SWCC) of the undisturbed soil, measured by the vapor method in the high suction part