Measurement 92 (2016) 483–488

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

The freeze-thaw cycles-time analogy method for forecasting long-term frozen soil strength

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ARTICLE INFO

Article history:
Received 22 May 2015
Received in revised form 21 April 2016
Accepted 22 June 2016
Available online 23 June 2016

Keywords:
Freeze-thaw cycle
Spherical template indenter
Long-term frozen soil strength
Time analogy method

ABSTRACT

To determine the stability of a frozen soil structure, the soil's long-term shear strength must first be determined. Freeze-thaw cycling is a weathering process in soil (i.e., a process of energy input and output). In cold climates, the freeze-thaw cycle (FTC) has a great influence on long-term strength and stability of soil, which are important considerations for frozen soil engineering. This paper offers a brief introduction to the spherical template indenter and introduces the FTC-time analogy method for forecasting long-term strength of frozen soil. Using the number of cycle repetitions (numbers of freeze-thaw cycles) and the cycle duration (minutes), we calculate the long-term strength of the curve family and their normalized curves, which allows us to predict the long-term frozen soil deformation and strength. Because of the soil transformation that occurs due to the number of repetitions and the duration of FTCs, the results of earlier research can be compared. The FTC-time analogy method can be used to solve problems of forecasting long-term frozen soil strength, as well as for research concerning frozen soil engineering.

1. Introduction

Shear strength is considered an essential property for determining foundation-bearing capacity. Because of the fierce rheological conditions in cold regions, practical frozen soil engineering usually uses calculations of long-term strength and long-term deformation to design foundations [13,5,23]. However, the freeze-thaw cycle (FTC) can change the arrangement and connection of soil particles so that the soil structure changes dramatically. In such cases, the soils form new structures, and the resulting changes in the long-term strength and the long-term deformation affect the stability of the frozen soil and require changes in engineering [4,3,30,20,12,2,21,24,42,37,41]. FTC is one of the geotechnical engineering hazards common to cold regions, so construction work in cold regions involving newly exposed soils must take freeze-thaw cycling into consideration [30]. For instance, in the permafrost regions in Quebec, Canada, it has been found that embankments constructed on soil that has never experienced freeze-thaw cycling are damaged in just one year due to the loss of bearing capacity [13]. Therefore, newly constructed highway embankments that are left unpaved for a few years are, to some extent, liable to be damaged by freeze-thaw cycling [5].

Freeze-thaw cycling is a process of energy input and output in soil [14]. The soil structure after freeze-thawing cycles can change significantly after an FTC because of fragmentation of coarse particles and aggregation of fine particles [41]. The variation in soil structure decreases after aggregation, and particle size eventually becomes homogeneous [38]. Transformations in soil structure may also cause variations in particle bonding. These kinds of soil changes impact soil engineering properties [8,15,36,39,40,43]. Freeze-thaw has a dual influence on soil density: loose soils tend to become denser, and dense soils become looser after FTCs [11]. According to this phenomenon, Viklander [34] proposed a residual void ratio, e^{res}, in terms of freeze-thaw, which means that both loose and dense soils reach the same void ratio after a number of FTCs. However, in both cases the hydraulic permeability increases regardless of the change in density [4,19,34].

Regarding the change in soils' mechanical properties after freeze-thaw cycling, different and sometimes even contradictory conclusions can be found. This may be because different researchers studied different soils and applied different conditions during FTCs [23]. Regarding strength parameters for example, Aoyama et al. [1] found that cohesion decreased while the friction angle changed very little, yet both Ogata et al. [18] and Qi and Ma [22] found that cohesion decreased while the friction angle increased.

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http://dx.doi.org/10.1016/j.measurement.2016.06.044

Nomenclature

STI	the spherical template indenter	τ	shear strength
FTC	freeze-thaw cycle	C	cohesive force
C_{equ}	equivalent cohesive force	φ	internal friction angle
C_0	initial relative instantaneous strength	θ	temperature of frozen soil
C_f	failure strength	W	water content
C_∞	long-term strength	K	proportion coefficient (0.18)
N	number of freeze-thaw cycle	d	diameter of the pressing plate
t	loading time required for a steady of soil deformation	S_t	depth pressed into sample
t_i	transformation time form FTCs to time	C_t	cohesive of the per unit area

Ground surfaces in cold areas may experience over 100 FTCs in one year [6]. As a result, much attention has been paid to the long-term influence of FTCs on the engineering properties of soil, especially long-term strength and deformation of the soil. However, the number of FTCs does not represent the actual time these cycles last, so the results of such experiments cannot be compared to each other.

Our time analogy is built on the basis of experiments. By inducing factors that affect the deformation process, our time analogy method reveals the relationship between stress, strain, and time. For frozen soil, the deformation factors are temperature, stress, salinity, peat formation, ice content, and so forth. Based on the given elements, the temperature-time analogy method, the stress-time analogy method, and other analogy methods are identified [26,27,25,28]. Although the number of FTCs directly influences frozen soil and most current studies focus on this point [1,11,29], linking the effect to the number of FTCs is not universally done. In this research, the number of FTCs was set as an important factor for predicting long-term soil strength.

2. The theoretical basis of the FTC-time analogy method

2.1. Apparatus description

A spherical template indenter (STI) is an instrument that can be used to quickly test and predict the long-term strength of frozen soil. The experimental principle of the STI is similar to the Brinnel hardness meter [33]. This principle was first proposed by Ishlinskiy, and it was based on the plasticity theory of ideal viscosity and non-strengthening body structure [10]. Tsytovich and Vyalov used the apparatus to determine soil mechanical properties, and established a theory on frozen soil strength, experimentation, calculation, and prediction methods. More recently, Roman [26] expanded on the application of the apparatus by building a method for calculating the modulus and improving the process for predicting long-term strength.

STI has three primary parts (see Fig. 1): the pressure system, the support member, and the displacement meter. The pressure system is used for loading the samples and includes components (4), (5), (6), (7), and (9). The support member binds the instrument together and includes components (3), (8), and (10). The displacement meter (components 1 and 2) measures the depth reached when the spherical indenter is pressed into a sample.

2.2. Theoretical basis

The shear strength of frozen soil is influenced by the soil skeleton, mineral composition, and structure, as well as the temperature of the frozen soil (θ), the soil water content (W), and the time of loading (t). As with thawed soil, the shear strength of frozen soil is determined by the cohesive force and the internal friction angle,

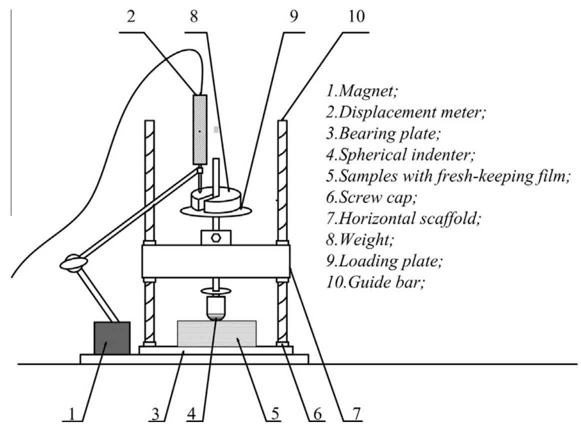

Fig. 1. Schematic of the spherical template indenter (STI).

while also accounting for the Coulomb-Mohr criterion under certain conditions. The shear strength can be calculated using the following equation [16]:

$$\tau = C(\theta, W, t) + \sigma tg\varphi(\theta, W, t) \quad (1)$$

In the shearing process, the relative sliding resistance, rolling resistance, and bite force between coarse soil particles forms friction force. The size of this force is reflected mainly in the friction angle (φ). Shear strength depends on the strength of the link between particles. Finer particles increase binding between particles, and include more hydrophilic minerals, so that links consist essentially of bound water (hydro-cementation) and physical or chemical cementation. Thus, the shear strength is mainly reflected in the cohesion force (C). In addition to the above physical or chemical cementation, for frozen soil, ice cementation also has a decisive impact on shear strength. As a result of ice cementation, the role of the cohesive force in soil strength is much greater in frozen soil than the role of friction between particles [35,33]. The rheology of ice and frozen heavily clayed soil make them an ideal viscoplastic body. So, given the internal friction angle $\varphi(\theta, W, t) \to 0$, then the above formula (1) can be simplified as:

$$\tau = C(\theta, W, t) \quad (2)$$

In other words, the shear strength will equal the cohesive force as measured by the pressing plate of the STI, which takes the soil sample in a circular groove. According to geometric parameters and normal pressure, the value of the cohesive force deduced from the theory of plasticity is expressed as [9,7]:

$$C_t = K\frac{P}{\pi d S_t} \quad (3)$$

where C_t is the cohesion of the per unit area, which changes with time, MPa; P is the vertical load on the ball presser, kg; the