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Freeze-thaw cycles-physical time analogy theory based method for predicting long-term shear strength of frozen soil

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Abstract: Freezing and thawing processes can change the structure of frozen soil and reduce the mechanical properties, thus affecting the stability of engineering infrastructures built in frozen soil. Due to the different settings of freeze-thaw cycles, a large number of experimental results cannot be effectively compared and analyzed. In addition, estimating the soil mechanical characteristics under freeze-thaw action has also become a research difficulty. In this paper, based on the frozen soil genetic creep theory, a spherical indenter is developed, and a freeze-thaw cycle–physical time analogy method is proposed. Using the number of cycles (numbers of freeze-thaw cycles) and the duration time (physical time–minutes), we can obtain the long-term strength curve family of the frozen soil and mapping the curve family into the same stress space to achieve the normalized strength curve, and thus we can predict the long-term deformation and shear strength. Finally, two soil samples are selected for testing, and the relevant equations for predicting the long-term shear strength are obtained. This method has important theoretical significance for the comparative study on the mechanical behavior of frozen soils under freeze-thaw actions. It also has value for engineering practice and stability analysis of infrastructures built in cold regions.

Keywords: freeze-thaw cycle; frozen soil mechanics; long-term frozen soil strength; time analogy method; spherical indenter

1 Introduction

The long-term shear strength of frozen soil is considered to be one of the important characteristics that determines the bearing capacity of foundation in permafrost regions. As permafrost has rheological property, the long-term shear strength and long-term creep deformation are usually used in the foundation design in permafrost regions[1−3]. However, the arrangement and connection of soil particles can be changed during the freeze−thaw cycles, which results in a drastic change of the soil structure. When a new structure is formed in the soil under the freeze−thaw cycle, the long-term shear strength and deformation will also change, thus affecting the physical−mechanical stability of the frozen soil and the performance of the engineering building structures [4−8]. In the permafrost region of Quebec, Canada, the roadbed should be paved 3−5 years after the completion of subgrade, because the roadbed can only be constructed after it has experienced enough freezing-thawing cycles to become stabilized [2,9]. The variation law of physical−mechanical properties of soil under freezing−thawing cycles has always been a popular research topic, and there are a lot of research results. However, there are two major difficulties in comparing the research results. One is the different physical times of the single freeze−thaw cycle in the freeze−thaw test, and the other is the different settings of the number of freeze-thaw cycles.

For frozen soil, the factors affecting its deformation and shear strength are not only the external freezing−thawing cycle, but also many other factors, such as temperature, stress, salinity, peat formation, ice content, etc. The induction, analogy and analysis of the influence of these factors on the frozen soil and the revealing of the relationship between stress, strain and time are known

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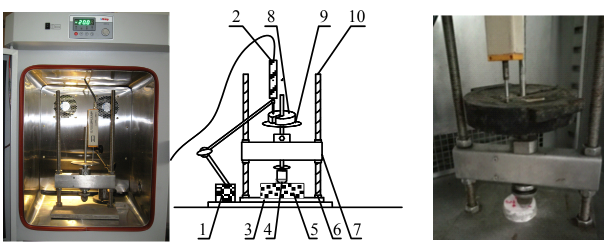
as the time analogy method [10]. The time analogy method can be divided into temperature−time analogy method, stress−time analogy method and other time analogy methods. In other words, the influence of the above factors on the deformation and strength of frozen soil is similar to that of time, and these methods are interchangeably[11−14].

Because freezing and thawing cycles have a direct impact on permafrost [15−17], and they are the important factors that affect the deformation and strength, this article tried to convert the number of freezing and thawing cycles into physical time, thus, established a freezing and thawing cycles–physical time analogy method to predict the long-term strength of permafrost under different number of freeze and thaw cycles.

2 Test principle of spherical indenter

The theory of the spherical indenter was established by Ishlinsky, an academician of the former Soviet Academy of Sciences, based on the principle of point load[18]. Subsequently, former Soviet union frozen soil mechanics professor Vyalov and Tsytovich improved the theory, experiment and calculation method, and applied it to the frozen soil mechanics testing[19]. Later, professor Roman, a Russian honorary geologist from Moscow State University, established theory and method for modulus calculation, and improved the method of predicting the long-term shear strength [11].

The structure of the spherical indenter is shown in Fig. 1, and has been reported in detail by some articles [7, 10−14, 17, 19−23].



1− Magnetic stone 2− LVDT 3− Sample plate 4− Spherical indenter 5− Soil sample 6− Nut knob 7− Horizontal support 8− Counterweight 9− Counterweight platform 10− Metal guide rod

Fig. 1 Schematic diagram of the spherical indenter testing apparatus and supporting equipment

The experimental principle of this instrument is established on the basis of the plastic theory of the ideal viscous unreinforced body. The main difference between the mechanical characteristics of frozen soil and conventional soil lies in the temperature and ice content, and its shear strength conforms to Coulomb's Law under certain conditions [7]:

$$\tau = c(\theta, W, t) + \sigma' \tan\varphi(\theta, W, t) \qquad (1)$$

where τ is the shear strength of frozen soil (kPa); c is the cohesion (kPa); σ' is the normal pressure (kPa); φ is the angle of internal friction (°); θ is the temperature (°C); W is the water (ice) content; and t is the time (s).

In a study of the shear strength of frozen silty soils using a triaxial compression test, Chamberlain et al.[4] found that the angle of internal friction was small (close to 0), possibly due to the presence of ice in the soil. This important conclusion shows that the assumption of frozen soil as an ideal viscoelastic body is reasonable. In this case, Eq. (1) can be simplified as

$$\tau = c(\theta, W, t) \qquad (2)$$

In other words, when the vertical load P acting on the spherical indenter which penetrates into the frozen silt, the shear strength of the soil is equivalent to its cohesion. When determining the cohesion of non-cohesive soil based on the spherical indention test, the measured c value includes the influence of internal friction. According to Tsytovich's suggestion, this c value can be regarded as equivalent cohesion c_e, which is expressed as c_e=c [19].

The theory of the spherical indenter test is similar to that of the Brinell hardness tester[19]. Brinell hardness was proposed by Swedish engineer Brinell in 1900[10]. It is widely used in engineering practice, especially in mechanical and metallurgical industries. The measurement method of Brinell hardness is to press the steel ball (diameter D) into the surface of the tested material with a specified load P, and unload the ball after a specified period of time. The hardness value is defined by the ratio of load P and indentation area S. The calculation formula of Brinell hardness HB is [24]

$$\mathrm{HB} = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})} \qquad (3)$$

where D is the ball head diameter; and d is the indentation diameter.

Brinell hardness tester is especially suitable for determining the hardness of materials with coarse crystal materials or coarse particulate materials. The indentation

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is large, thus it is not suitable for nondestructive testing, and cannot determine the hardness of thin-walled parts or hardened surface layer.

As shown in Fig. 2, the indentation radius Z in the spherical indentation is

$$Z = \sqrt{R_b^2 - \left(R_b^2 - h^2\right)^2} \tag{4}$$

where R_b is the radius of ball; h is the depth of spherical indentation varying with time（mm）.

The indentation area S is

$$S = Z^2\pi = \left(2Rh - h^2\right)\pi \tag{5}$$

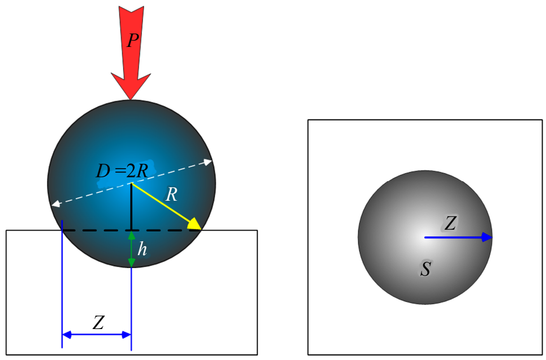


Fig. 2 Schematic diagram of indentation created by the spherical indenter

The average resistance (shear strength) of soil, that is, the equivalent cohesion c_e, can be calculated according to Eq.(6):

$$c_e = \frac{P}{S} = \frac{P}{\left(2R_b h - h^2\right)\pi} \tag{6}$$

Because of the radius of the ball $R \gg h$, therefore,

$$c_e = \frac{P}{2R_b h\pi} = \frac{P}{\pi dh} \tag{7}$$

Since the material of the ball differs from that of the soil, the hardness ratio of the two is taken as the correction factor K, and Eq. (7) is amended as [10]

$$c_e = K\frac{P}{\pi dh} \tag{8}$$

where K is the proportional coefficient, and the value is 0.18.

As shown in Fig. 3, the failure strength c_f is determined by the initial strength c_0 and the long-term strength c_∞ (the long-term strength c_∞ is the long-term shear strength, namely the long-term equivalent cohesion).

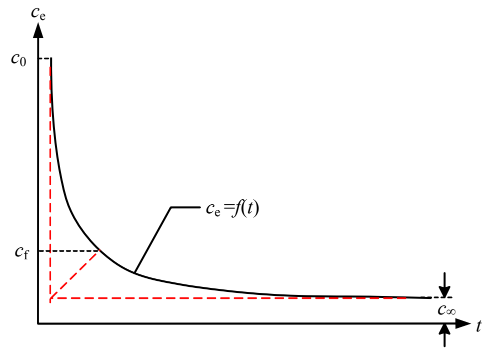


Fig. 3 Schematic diagram of strength curve measured by spherical indenter

3 Freeze and thaw cycles–physical time analogy theory

The physical properties of soil reflect its mechanical properties to a certain extent. The long-term strength of frozen soil is directly related to the soil structure, mineral composition and physical properties of soil. With the increase of the number of freeze-thaw cycles, these characteristics also change, which leads to the change of the mechanical properties of frozen soil. If the freezing and thawing cycles are converted into physical time, the characteristics of frozen soil that change with the increase of freezing and thawing cycles are actually changed with the advance of physical time. The conversion formula is given as follows:

$$t_i = tN_i \tag{9}$$

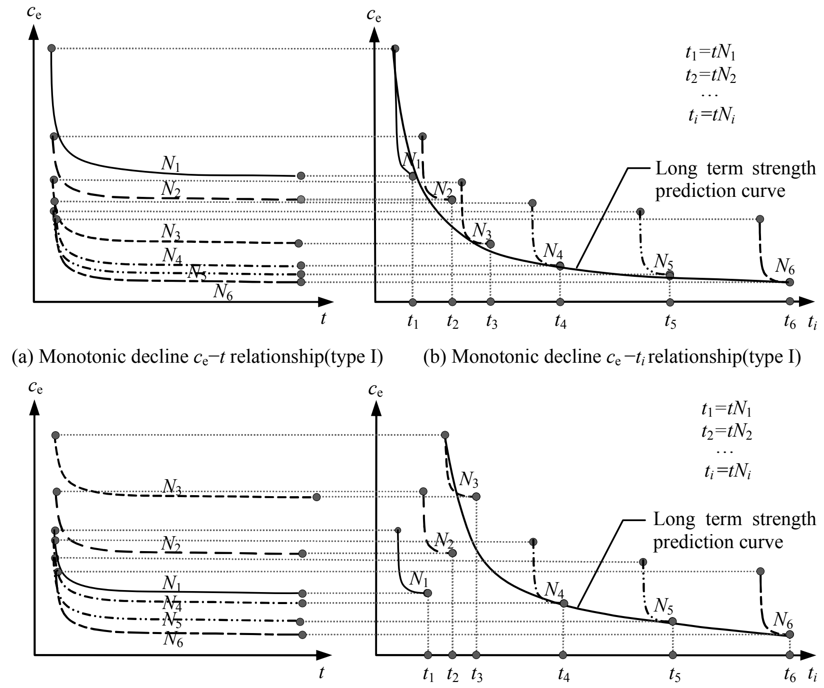
where t is the loading time required for soil sample deformation becomes stabilization; N_i is the number of freeze-thaw cycles; and t_i is the physical time after the conversion of the ith freez-thaw cycle.

Figure 4 shows the schematic diagram of the freeze and thawe cycles–time analogy method established based on the Eq. (9). With the increase of the number of freeze-thaw cycles, the trend of monotonic decline of the long-term strength curve is defined as type I (monotonic decline type). However, with the increase of the number of freeze-thaw cycles, the long-term strength curve fluctuates initially and then decreases gradually. This trend is defined as type II (fluctuating decline type).

4 Freeze and thaw cycles–physical time analogy theory and its application

4.1 Sample preparation and experimental testing

Moraine clay in the outskirts of Moscow, Russia and Fuping loess in Shaanxi, China were selected as the research soil samples. The soil samples were prepared in a ring with a diameter of 61.8 mm and a height of 20.0 mm, and parallel samples were prepared which subjected to different number of freeze-thaw cycles. The basic physical properties of the two prepared soil samples are provided in Table 1.



(a) Monotonic decline c_e–t relationship(type I) (b) Monotonic decline c_e–t_i relationship(type I)

(c) Fluctuating decline c_e–t relationship(type II) (d) Fluctuating decline c_e–t_i relationship(type II)

Fig. 4 Schematic diagrams of freeze-thaw cycle–time analogy method

Table 1 Basic physical properties of soil samples

Sample name	Water content /%	Density /(g • cm^{-3})	Void ratio	Liquid limit /%	Plastic limit /%	Plasticity index
Moraine clay	24	1.96	0.71	32	19	13
Fuping loess	22	1.89	0.74	29	18	11

4.2 Freeze-thaw test and spherical indenter test

The prepared samples were wrapped with plastic film (to prevent moisture content change) and put into a temperature controlled box for freezing and thawing test. The freezing and thawing temperatures were set at −20°C and +20°C, respectively. After the initial freezing temperature test, the freezing and thawing times of the samples were determined as 2 h, which refers to a single freezing−thawing cycle of 4 h. The samples of Russian moraine clay were subjected to freeze−thaw cycles of 3, 6, 20 and 40 times, and the samples of Fuping loess underwent freeze-thaw cycles of 6, 8, 50 and 100 times, respectively. After the freeze-thaw test, the frozen samples were put into a temperature-controlled box with a constant temperature of −20°C, and waiting for the sample temperature to stabilize at −20°C, then spherical indenter tests were started.

Adjust the height of the spherical indenter to just contact the surface of the soil sample and lock the pressing head with a fixing bolt. Apply a normal pressure of 10 kg on the upper part of the spherical indenter, and loosen the fixing bolts to start the indentation test. The spherical indenter test lasted for 24 h. At the 15 min of the test, the pressure displacement value was collected, and the pressure displacement met the following equation:

$$0.005D \leqslant S_{15\min} \leqslant 0.05D \tag{10}$$

where $S_{15\min}$ is the vertical displacement (mm) of the spherical indenter at 15 min.

4.3 Test results and model prediction

The experimental results of moraine clay are shown in Fig. 5. The indentation depth of the spherical indenter on the moraine soil increases with the increase of the number of freeze-thaw cycles (Fig. 5(a)), therefore, its equivalent cohesion decreases with the increase of the number of freeze-thaw cycles (Fig. 5(b)).

The freeze-thaw cycle has a profound effect on the long-term shear strength of soil. Overall, this effect finally tends to be stable with the increase of freezing−thawing cycles. In other words, when the soil is relatively dense, freeze−thaw action is equivalent to compaction (or den-

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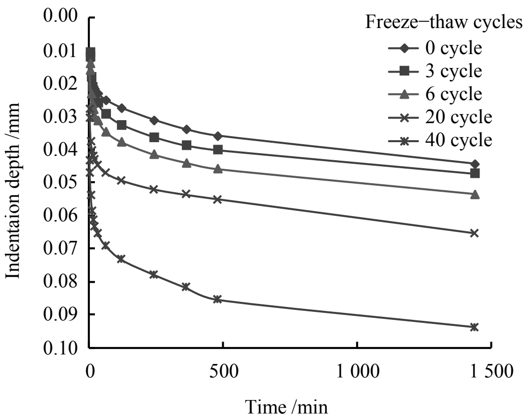
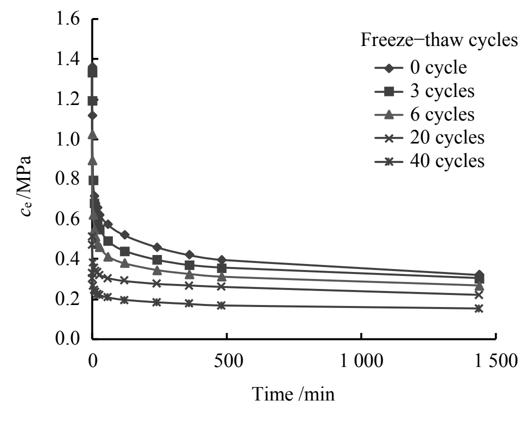
sification) effect on the soil. The opposite is true for loose soil, freeze–thaw effect reduces the pore ratio and increase the compactness of unconsolidated soils. This phenomenon is the concept of residual void ratio based on freeze–thaw action proposed by Viklander[25], that is, after several freeze–thaw cycles, dense soil and loose soil tend to have a common pore ratio. The common pore ratio is one of the important factors that determines the long-term stability and strength of frozen soil after many freezing–thawing cycles. During the freezing–thawing, the strength of soil presents a dynamic change process with the increase of the number of freezing–thawing cycles. When the long-term strength monotonically declines with the increase of the number of freezing–thawing cycles, the number of freezing–thawing cycles will be converted into physical time and calculated from the beginning, namely, type I in Figs. 4(a) and 4(b), whose strength monotonically reduces. The long-term strength curve cluster of the moraine clay shows a monotonic decline, namely type I.



(a) Indentaion depth–time relationship



(b) Long-term strength–time relationship

Fig. 5 Indentation depth and long-term strength of moraine clay

As shown in Fig. 6, after normalization of curve clusters, curve clusters of frozen soil show a trend of attenuation after different freeze–thaw cycles. As the number of freeze–thaw cycles grow, the difference between the initial strength and the long-term strength in the long-term strength curve decreases. It also proves that the influence of freezing and thawing on soil tends to be stable with the increase of freeze and thaw cycles. After the curve is normalized, the normalized long-term strength equation can be obtained: $y = 1.187\,8x^{-0.189}$, the long-term strength of soil undergoing different freeze-thaw cycles can be predicted by using this equation.

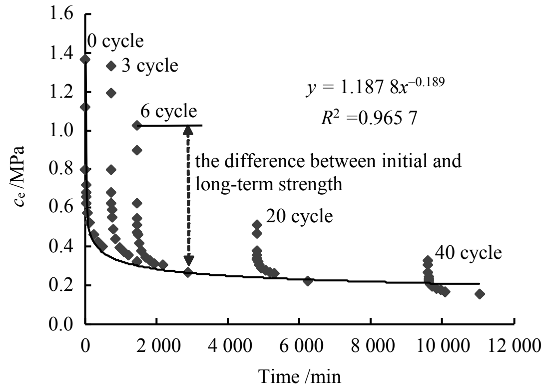
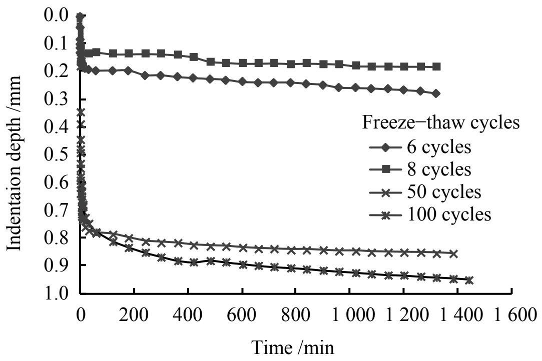
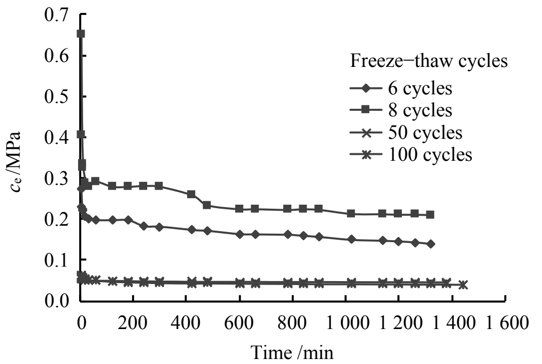


Fig. 6 Long-term strength curve cluster of frozen moraine clay obtained by freeze-thaw cycle-time analogy method

Figure 7 shows the test results of Fuping loess. It can be seen from the figure that the indentation depth of the spherical indenter head on the Fuping loess samples after the 6th freeze–thaw cycle is greater than that of the 8th cycle, and the indentation after the 8th freeze-thaw cycle becomes deeper and deeper after the 50th and the 100th freeze-thaw cycles. However, the corresponding long-term strength after 8th freeze–thaw cycles is greater than that of the 6th cycle, and the long-term strength still decreases after the 8th cycle. Due to the changes of soil particles (aggregation and fragmentation) caused by freezing and thawing, the structural change process is more complicated, and there is often strength fluctuations before the long-term strength reaches a stable trend. Then when the long-term strength fluctuates with the increase in the number of freeze–thaw cycles, converting the number of freeze-thaw cycles into physical time needs to be calculated from the number of freeze–thaw cycles at which the long-term strength begins to attenuate (the 8th freeze-thaw cycle), which is type II (Figs. 4(c), 4(d)).



(a) Indentaion depth−time relationship



(b) Long-term strength−time relationship

Fig. 7 Indentation depth and long-term strength of Fuping loess

After normalization of the clusters of long-term strength curves of the Fuping soil samples with different freeze-thaw cycles (as shown in Fig. 8), the normalized long-term strength equation is obtained as $y = 122.12x^{-0.799}$, which can be used to predict the long-term strength of the frozen Fuping soil.

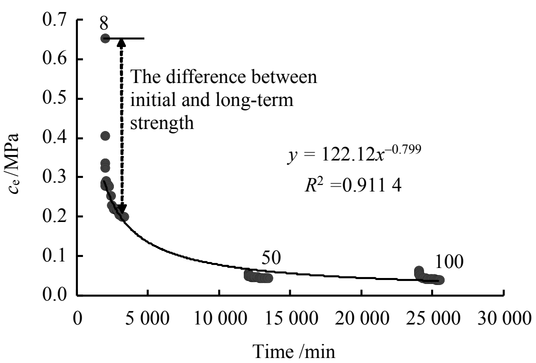


Fig. 8 Long-term strength curve cluster of frozen Fuping loess obtained by freeze-thaw cycle–time analogy method

The creep process of frozen soil has hereditary characteristics. According to the genetic creep theory, not only the stress-strain relationship at a known time can be obtained, but also the relationship between the strain at this time and the stress at the previous time, which is based on the iterative principle. These relations are all obtained based on the iterative principle. The strain produced at time t by the applied load is equivalent to the accumulation of the strain in the previous time period $0-t'$. When the number of freeze-thaw cycles is converted into physical time, the stress-strain relationship (curve cluster) during the whole period can be normalized and mapped into a curve. The stress and strain curves (clusters) after different freezing-thawing cycles only represent the deformation and stress performance, however, the structure and material composition changes of the soil during freezing-thawing process are also reflected in the stress and strain curves (clusters). Therefore, the freeze-thaw cycles - time analogy method has typical characteristics of the genetic creep theory.

5 Conclusions

The number of freezing−thawing cycle−time analogy method is a time comparison method based on the genetic creep theory of frozen soil. The number of freezing−thawing cycles is transformed into physical time, and the stress curves of different freezing−thawing cycles are mapped into the same time coordinate axis, and these curves are used to predict the long-term deformation and strength of frozen soil.

According to the physical−mechanical change during freeze−thaw cycles, the curve cluster of freeze−thaw cycles were converted into physical time and divided into monotonic decline type (type I) and fluctuating decline type (type II).

The moraine clay in the outskirts of Moscow, Russia, and the Fuping loess in Shaanxi, China were selected as the research soil samples. It was found that the two soil samples belong to the monotonic decline type (type I) and fluctuating decline type (type II), respectively. The number of freeze−thaw cycles−time analogy method provides an alternative approach for comparing the long-term strength test results of rock and soil under different freezing-thawing cycles.

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