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Influence of freeze-thaw cycles in the presence of a supplementary water supply on mechanical properties of compacted soil

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Abstract

In seasonal frozen regions where the groundwater is relatively shallow, the upward migration of groundwater during the freezing process will change the moisture content of the subgrade soil after freeze-thaw (F-T) cycles. This study attempted to investigate the deterioration effect of F-T cycles in combination with available groundwater migration on the mechanical properties of compacted clayey soil. For this purpose, the compacted clay specimens were frozen and thawed from the top to bottom and external water was supplied from the bottom of the samples. Specimens with different initial states (i.e. different initial dry densities and initial moisture contents) were subjected to different number of F-T cycles. The changes in moisture content and frost heave after the F-T cycles were measured. The failure strength and elastic modulus of the soil then were determined using unconsolidated and undrained triaxial compression tests. The results of the study demonstrated that water replenishment of the soil during the freezing process had considerable influence on the mechanical properties of soil, and the availability of a supplementary water supply could accelerate the development of stable state in the failure strength and the elastic modulus of soil. Moreover, the reduction rates of failure strength and elastic modulus reached 85% and 92% after 7 F-T cycles, respectively. The degradation effect of the F-T cycles on the mechanical property of soil can be reduced by enhancing the dry density or by moderately raising the moisture content of soil. Finally, the fitted models describing the combining effects of F-T cycles, initial dry density, initial moisture content and confining pressure on the failure strength and elastic modulus of soil were developed and verified by the experimental data to be rational and reliable.

Keywords: freeze-thaw cycles; water supply; mechanical properties; triaxial test; compacted soil.

1. Introduction

In recent years, the construction of high-speed traffic in China has been developing rapidly. A large number of such roads pass through regions that are subject to seasonal freezing, and freeze-thaw (F-T) cycles cause degradation in the service performance of the subgrade (Lee et al., 2017; Niu et al., 2016). Especially in areas where the underground water level is high (i.e. the over-cover of soil is limited), capillary water can move to the base of the subgrade during the freezing process under the action of cryogenic suction (Aldaood et al., 2016; Thomas et al., 2009), and ice lenses form in the compacted soil, leading to a change in the macro- and micro-structure of the soil (Hohmann-Porebska, 2002; Konrad & Morgenstern, 1980). Furthermore, when the ice lenses melt in spring, the water may not dissipate immediately, so the moisture content in compacted soil of subgrade will increase. Under the action of traffic load, some degradation effects such as pavement depressions and cracks are induced.

The influence of F-T cycles on the mechanical properties of compacted soils is a research hotspot that has attracted the attention of many researchers. The most common method to study the mechanical properties of freeze-thawed soils is to place wrapped specimens in a thermo-tank that can be controlled by manually adjusting the temperature and the number of F-T cycles, and the samples undergo F-T cycles without any supplementary water supply (Wang et al., 2007). After that, the mechanical parameters of soil are studied using triaxial tests (Liu et al., 2016; Roustaei, Eslami, & Ghazavi, 2015; Tang et al., 2017), unconfined compression tests (Eskisar, Altun, & Kalipcilar, 2015; G. Li et al., 2018) and direct shear tests (Xu et al., 2018). In addition, some researchers cut large-sized samples after F-T cycles into standard-sized specimens for further mechanical tests (Cui, He, & Yang, 2014; Qi, Wei, & Song, 2008). For the factors influencing the strength of soil after F-T cycles, Liu et al. (2016) investigated the effects of number of F-T cycles and cooling temperatures on soil failure strength and elastic modulus, and concluded that the number of F-T cycles had a significant effect on the mechanical properties of soil, but the influence of cooling temperature was not obvious. Hu et al. (2017) found that after the soil was exposed to F-T cycles, the failure strength mainly decreased for the soils with a high initial degree of compaction, while the opposite was observed for soils with a low initial degree of compaction. Wang et al. (2010) believed that F-T cycles seriously affected the mechanical properties of undisturbed loess when the moisture content was high.

In these earlier studies, most of the F-T cycles tests were carried out without an external water supply, and relatively few reports are available in the literature that have examined mechanical properties of soils when a water supply was present during the F-T cycles. Aldaood et al. (2016) investigated the unconfined compressive strength of lime stabilized soil after F-T cycles with a water supply during thawing. In fact, when the depth of soil above the groundwater level is shallow, the water may seep upward during the freezing process, after the water absorption and F-T cycles, the soil structure is extremely unstable, which results in the observed strength degradation (Andersland et al., 2003). It is important, therefore, to study the mechanical properties of the soil in conjunction with an available water supply during the F-T cycles.

In consequence, the present study investigated the influence of F-T cycles in conjunction with an available water supply during the freezing process on the mechanical properties of compacted clayey soil. Unconsolidated and undrained triaxial compression tests were conducted to evaluate the effects of number of F-T cycles, initial dry density, initial moisture content, confining pressure, and cooling temperature, on the failure strength and elastic modulus of the soil after F-T cycles. Fitted models for failure strength and elastic modulus were proposed and verified by the test results.

2. Materials and testing method

2.1. Materials

The sample soil was taken from a seasonally frozen soil area 5-10m below the ground surface in Harbin, Heilongjiang province, China. The basic physical properties of the soil are shown in Table 1 and the particle size distribution is shown in Fig. 1. According to the liquid plastic and plastic limit values of the soil, referring to the Specification of soil test (SL237-1999), the soil was defined as low liquid limit clay (CL). The soil sample was air-dried and crushed, then was sieved through a standard 2-mm sieve. According to the moisture content required, known quantities of water were mixed into the soil, then the sample was placed in a closed container for 24h. After that, the moisture content of soil sample was measured again, and the variability in moisture content was controlled within 0.5%, ensuring that the moisture content of soil sample was qualified. The prepared soil sample was put into a specimen-making device in five layers, and the sample was compacted into cylinders with a diameter of 38mm and a height of 76mm. Then the specimens were wrapped with preservative plastic film in readiness for use in the subsequent tests. In order to study the effect of initial moisture content and initial dry density on the mechanical properties of the soil after the F-T cycles, specimens were prepared with the initial moisture contents of

18.2%, 20.2%, and 22.2%, and initial dry densities of 1.50g/cm^3, 1.57 g/cm^3, and 1.63 g/cm^3, respectively.

Table 1 Basic physical properties of soil sample

Parameters	Value
Liquid limit/%	38.4
Plastic limit/%	23.5
Plastic index	14.9
Maximum dry density/(g/cm^3)	1.65
Optimum moisture content/%	20.2
Specific gravity	2.71

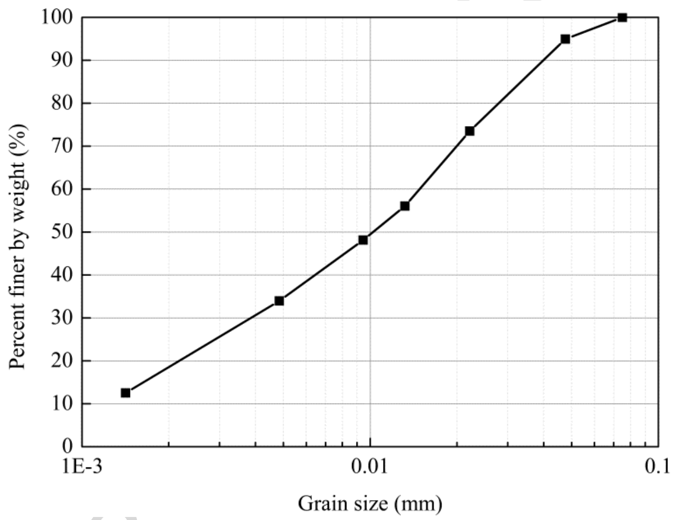
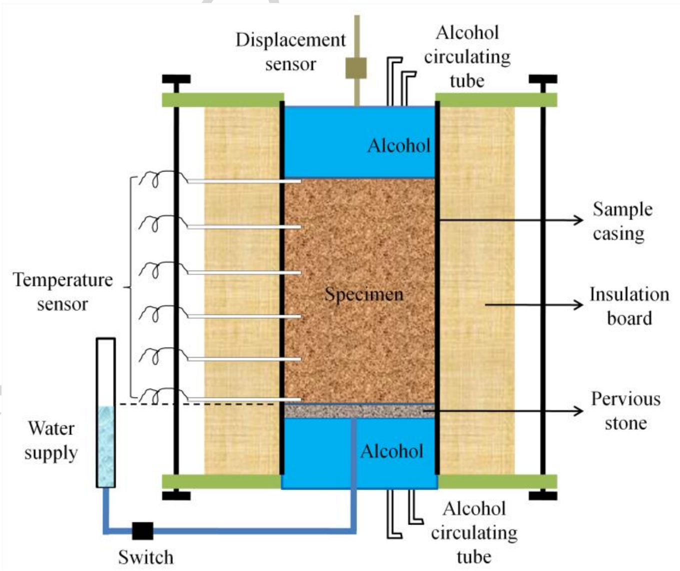


Fig. 1. Grain size distribution

2.2. Freeze-thaw cycle tests

After weighing the specimens, the tops and sides of the specimens were sealed with plastic film, and the bottoms were exposed to the water supply. The specimens then were installed in a nylon cylinder that was installed in the F-T equipment. Rubber and plastic foam board was wrapped around the outer wall of the sample casing to minimize heat transfer. A schematic diagram of the F-T equipment is shown in Fig. 2 (a). The specimens were frozen and thawed from top to bottom by adjusting the temperature (the range of temperature was from -40°C to

+40°C) of the circulating alcohol in a steel container at the top of the specimens. Meanwhile, the alcohol in the steel container at the bottom of the sample was kept at a constant temperature of about 1°C，ensuring that the water in the bottle can be transferred to the soil through the bottom of the specimens during the freezing process. The water level in the bottle was at the same height as the bottom of the specimens which was designed to meet the requirement of water replenishing without pressure. But during the thawing process, the water supply valve was closed, so there was no water replenishment. The frost heave and thaw settlement of the specimens was monitored constantly during the F-T test by the displacement sensors. Additionally, the temperature inside the specimen also was monitored by the temperature sensors (at intervals of about 15 mm) in real time during the test. The 4 F-T devices were integrated and were placed into an environmental chamber, as shown in Fig. 2 (b), and the temperature of the environmental chamber was maintained at 1°C-2°C.



(a) Schematic diagram

(b) Environmental chamber

Fig. 2. Apparatus for the freeze-thaw test

2.3. Test schemes

In Harbin City, the average temperature of the highest temperature month (July) is 23°C, and the average temperature of the coldest month (January) is -18.3°C (Tan et al., 2011). By using the finite element simulation method, the distribution law of the temperature field in the subgrade under the above-mentioned temperature change was obtained and the threshold value of the freezing and thawing temperatures in different regions of the soil was ascertained. According to the results of F-T cycles test at the beginning stage, the temperature change at different heights inside the specimen with one F-T cycle when the freezing temperature is -30°C and the melting temperature is 30°C is shown in Fig. 3. It can be seen that the internal temperatures of the specimen all reached below 0°C and gradually stabilized after freezing for 300 minutes, and the internal temperatures all increased to above 0°C and then gradually stabilized after thawing for 120 minutes. The stable temperatures at the top of the specimen were -25°C and 30°C, respectively. Accordingly, in the present study, and as per the basic procedures of the F-T experiment, the specimens were frozen unidirectionally at -30°C for 8 hours and thawed at 30°C for 4 hours. According to the literature (Ghazavi & Roustaie, 2010; Roustaei et al., 2015), the number of freeze-thaw cycles *N* was set to be 0, 1, 3, 5, and 7, respectively. For the specimen with an initial moisture content of 20.2% and initial dry density of 1.57g/cm^3, the number of cycles was set to be 0, 1, 2, 3, 4, 5, 6, 7, and 8. The influence of different cooling temperatures (-5°C, -10°C, -20°C, and -30°C) on the mechanical properties of the soil also was evaluated by choosing the specimens with an initial moisture content of 20.2% and an initial dry density of 1.57g/cm^3. These specimens were frozen for 8 hours and thawed at 30°C for 4 hours for 3 F-T cycles. After the F-T cycle tests, the specimens were taken out and the mass was weighed, and the average moisture content was calculated. Then the mechanical parameters of the specimens were measured using unconsolidated and undrained triaxial compression tests with an axial strain rate of 0.5%/min at three levels of confining pressure (50, 100, and 150kPa). The test scheme is shown in Table 2.

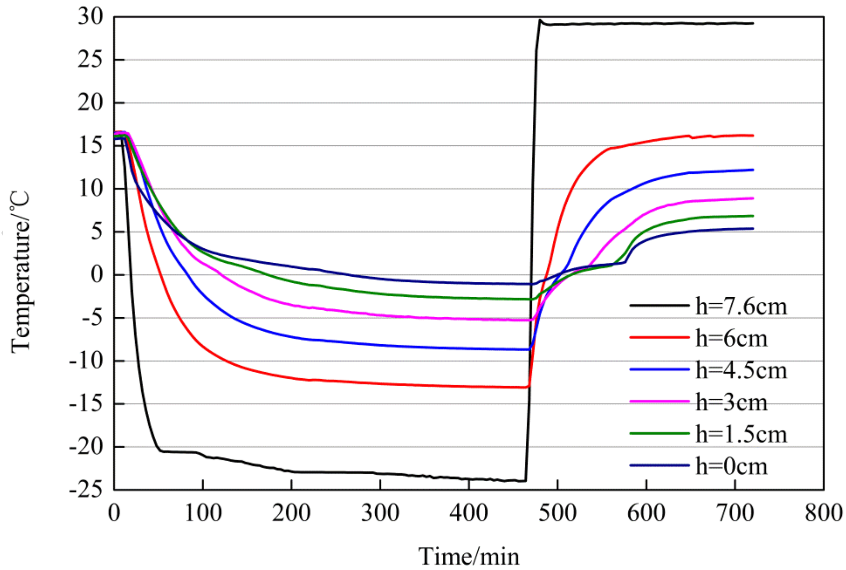


Fig. 3. Variations of temperature inside the sample during one freeze-thaw cycle

Table 2 Experimental scheme of the triaxial compression tests

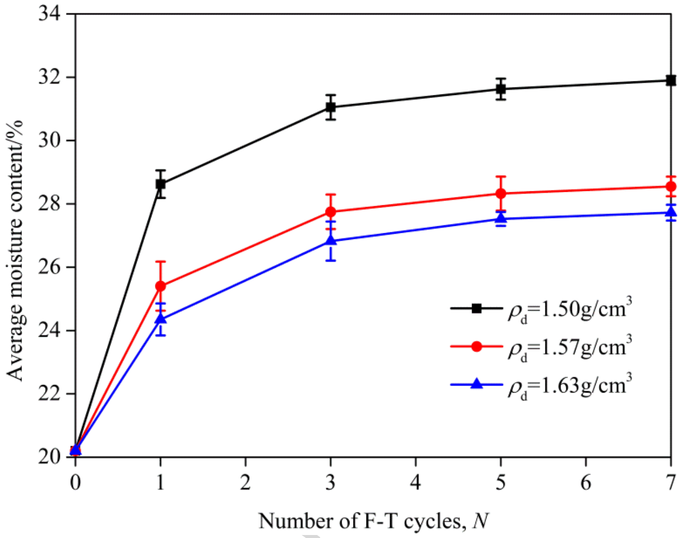
Initial dry density, ρ_d /(g/cm^3)	Initial moisture content, *w*/%	Confining pressure, σ_3 / kPa	Cooling temperature/°C	Number of F-T cycles, *N*	Dataset usage
1.50	18.2, 20.2, 22.2	50, 100, 150	-30	0, 1, 3, 5, 7	Fitting models
1.57	18.2	50, 100, 150	-30	0, 1, 3, 5, 7	Fitting models
	20.2	50, 100, 150	-30	0, 1, 3, 5, 7	Fitting models
			-30	2, 4, 6, 8	Verifying models
			-5, -10, -20	3	-
	22.2	50, 100, 150	-30	0, 1, 3, 5, 7	Fitting models
1.63	18.2, 20.2, 22.2	50, 100, 150	-30	0, 1, 3, 5, 7	Fitting models

Note: - = dataset not used for fitting or verifying the models

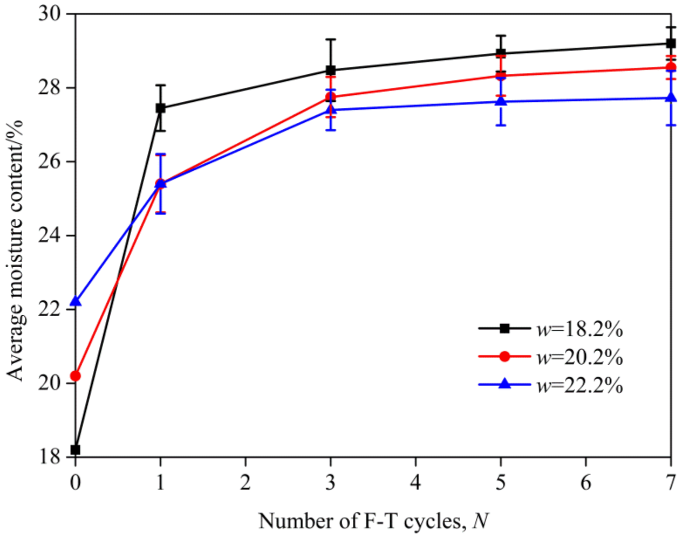
3. Results and discussion

3.1. Effect of F-T cycles on the moisture content and frost heave of compacted soil

In the present study, the effects of F-T cycles on the frost heave and moisture content of the soil samples were studied. Because of the large volume of data, specimens with an initial moisture content of 20.2% and specimens with an initial dry density of 1.57g/cm^3 were selected to evaluate the influence of different sample dry density and different sample moisture content, respectively. The recorded frost heave and moisture content values were the average of four parallel specimens. The moisture content and frost heave of specimens with different initial states after exposing to the F-T cycles are shown in Figs. 4 and 5, respectively. According to Fig. 4(a), with increasing the number of F-T cycles, the moisture content of specimens with different dry density increased rapidly at first, then stabilized gradually after the number of F-T cycles exceeded 3. The calculated saturated moisture contents of the specimens with initial dry densities of 1.50g/cm^3, 1.57g/cm^3, and 1.63g/cm^3 were 29.8%, 26.8%, and 24.4%, respectively. Therefore, the moisture content of the specimens almost reached or exceeded the value of the saturated moisture content after 3 F-T cycles. With an increase in the moisture content of the specimens, the free water in the voids of soil is frozen during the freezing process, and the ice lenses are formed which results in the structure change in the soil during frost heave (Hohmann-Porebska, 2002). The deformation caused by frost heave cannot be fully recovered after the F-T cycles, as shown in Fig. 5(a). The frost heave is caused mainly by water migration and aggregation (Hermansson & Guthrie, 2005), and therefore the variation in frost heave with increasing numbers of F-T cycles is consistent with that of change in the moisture content of the soil. In addition, the moisture content and frost heave of the specimens after the F-T cycles both decreased with an increase in the initial dry density of the sample, due to the reduction in permeability of the soil. Figs. 4(b) and 5(b) illustrate the variation of moisture content and frost heave for specimens with various initial moisture contents that were subjected to different numbers of F-T cycles, respectively. As shown in these figures, the moisture content and frost heave of the specimens after F-T cycles both decreased with an increase in the initial moisture content. In general, the freezing of water in the soil includes in-situ freezing and water migration freezing (Michalowski and Zhu, 2006). Taber (1929, 1930) demonstrated experimentally that external water migration was the fundamental cause of frost heave. When the initial water content was relatively low, at constant dry density (i.e. constant porosity), the soil mass will absorb more migration water when it reaches saturation, this then results in larger frost heave. In addition, there is more free water in soils with higher moisture contents. According to study of Konrad (1989), and Spaans and Baker (1996), free water freezes easily while the adsorbed water freezes only at very low temperatures. During the freezing process, the free water in soils with higher moisture contents will be frozen first. Then, the formation of the cold structure leads to a smaller permeability coefficient (McCauley et al., 2002), which causes a reduction in the degree of migration water from outside. Therefore, the frost heave of soil with higher moisture contents becomes smaller [Fig. 5(b)], and the moisture content after the F-T cycle decreases [Fig. 4(b)].

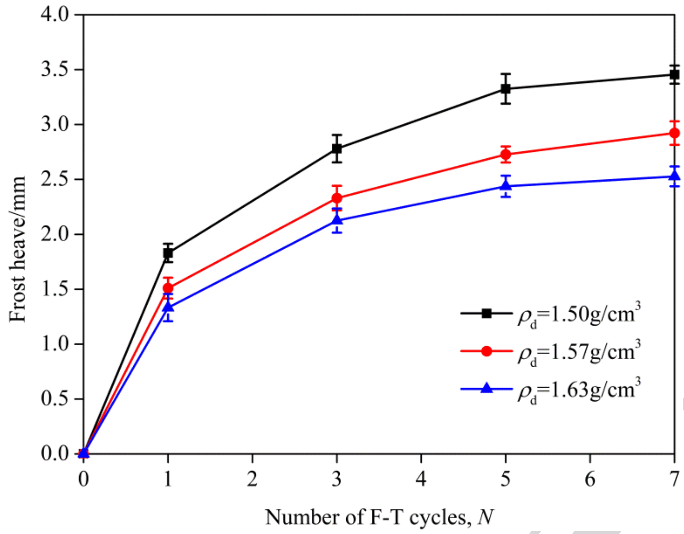


(a) Moisture content of 20.2% with different dry densities

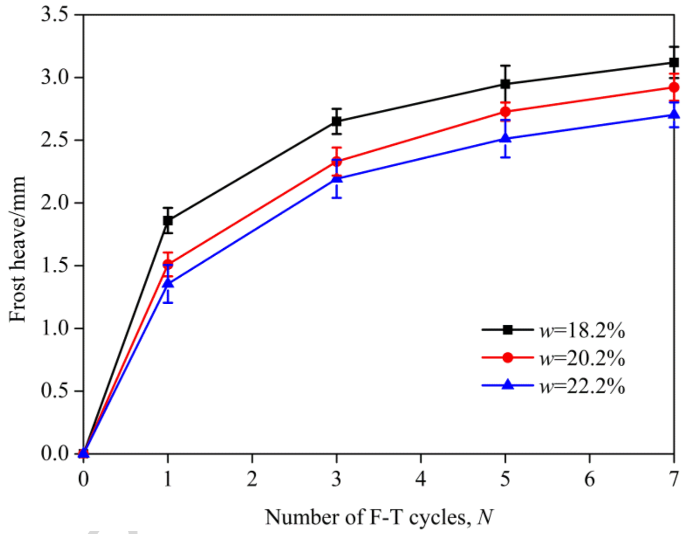


(b) Dry density of 1.57g/cm^3 with different moisture contents

Fig. 4 Moisture content versus the number of F-T cycles



(a) Moisture content of 20.2% with different dry densities



(b) Dry density of 1.57g/cm^3 with different moisture contents

Fig. 5 Frost heave versus the number of F-T cycles

3.2 Effect of F-T cycles on the mechanical properties of compacted soil

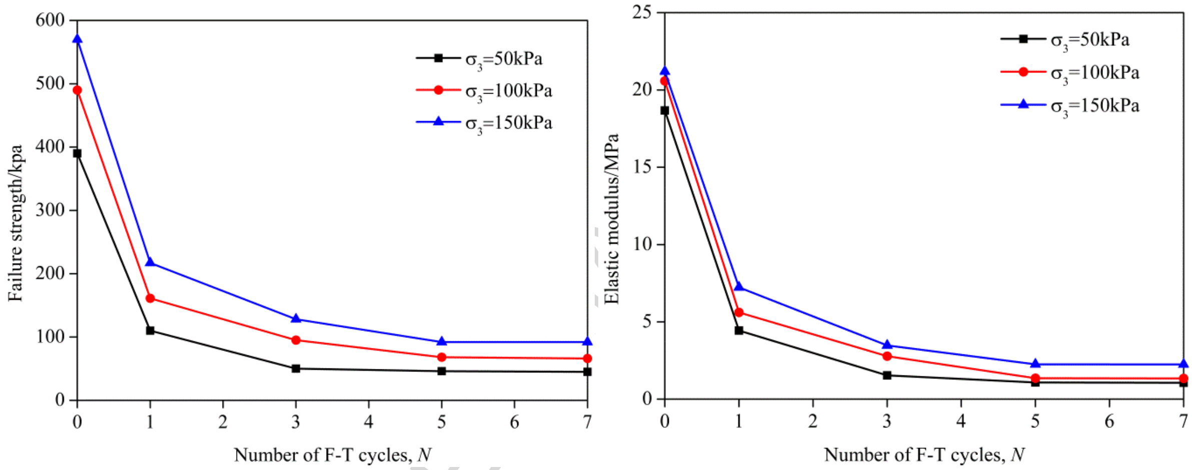
In the present investigation, the influence of various factors (such as the number of F-T cycles, the initial dry density, the initial moisture content and the cooling temperature) on the failure strength and elastic modulus of the compacted soil after F-T cycles was evaluated. The failure strength is the peak deviator stress of the strain-softening curve or the corresponding deviator stress at the strain of 15% for the strain-hardening curve in a stress-strain plot. The elastic modulus is defined as the ratio of the increment of deviator stress to the increment of axial strain when the axial strain is 1% (Kumar & Singh, 2008; Li et al., 2015), which can be expressed as:

$$E = \frac{\Delta \sigma}{\Delta \varepsilon} = \frac{\sigma_{1.0\%} - \sigma_0}{\varepsilon_{1.0\%} - \varepsilon_0} \quad (1)$$

where $\Delta\sigma$ is the increment of deviator stress, $\Delta\varepsilon$ is increment of axial strain, $\sigma_{1.0\%}$ is the corresponding deviator stress at the axial strain of 1.0%, and σ_0 and ε_0 are the initial stress and strain, respectively.

3.2.1. Effect of number of F-T cycles on the mechanical properties of compacted soil

The test results of specimens with an initial moisture content of 20.2% and an initial dry density of 1.57g/cm^3 were taken as examples for discussion. The variations in failure strength and elastic modulus with F-T cycles under different confining pressures (50kPa, 100kPa and 150kPa) are shown in Figs. 6 (a) and 6 (b), respectively. As can be observed from Fig. 6, both the failure strength and the elastic modulus decreased dramatically after the specimens were exposed to the first F-T cycle, but gradually stabilized after 3 F-T cycles. For specimens without supplemented water, the mechanical indices become relatively constant after 7 F-T cycles (Ghazavi & Roustaie, 2010; Roustaei et al., 2015), which indicates that the replenishment of water can reduce the time taken for specimens to achieve a stable mechanical state. Moreover, both the average reduction rate of failure strength and elastic modulus were more than 60% after the first F-T cycle, and the average decrease rates of these two indexes reached 85% and 92% after 7 F-T cycles, respectively. From these results, it was evident that the deterioration effect of F-T cycles on the mechanical properties of soil with water supply was caused mainly by the first F-T cycle. This finding was in accord with the conclusion of tests by others that were conducted without water replenishment (Roustaei et al., 2015; Wang et al., 2007). By comparing Fig. 6 with Figs. 4 and 5, it can be observed that the variation tendency of the mechanical properties of the specimen with the number of F-T cycles was consistent with the change trend of the moisture content and frost heave. These findings verified that the significant degradation on soil strength resulted from capillary water migration and soil structure change during the freezing-thawing process (Aldaood et al., 2016).

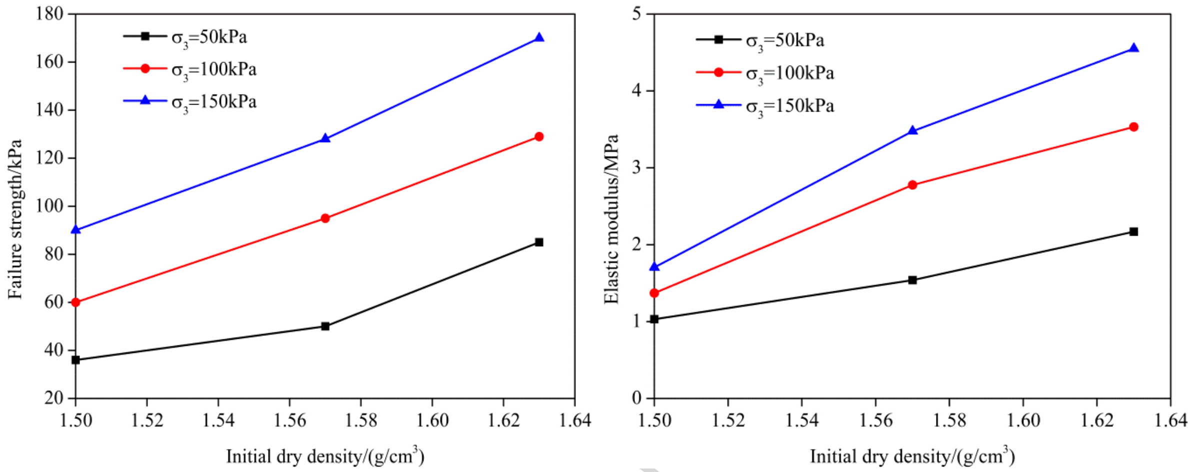


(a) Failure strength (b) Elastic modulus

Fig. 6 Variation in mechanical parameters versus number of F-T cycles

3.2.2. Effect of initial dry density on the mechanical properties of compacted soil

The test results of specimens with an initial moisture content of 20.2% that had been subjected to 3 F-T cycles were taken as examples for evaluation. The variations of failure strength and elastic modulus with initial dry density under different confining pressures are shown in Figs. 7 (a) and 7 (b), respectively. It is apparent from Fig. 7 that the failure strength and elastic modulus increased with the increase in the initial dry density of the specimens under different confining pressures. The increase in the initial dry density caused the decrease in the moisture content and the frost heave of soil samples after F-T cycles (see Figs. 4(a) and 5(a)), and the degree of softening and structural disturbance due to F-T cycles were smaller, so the soil mechanical properties were better. Confining pressure tended to decrease the degree of impact of F-T cycles on failure strength and elastic modulus.

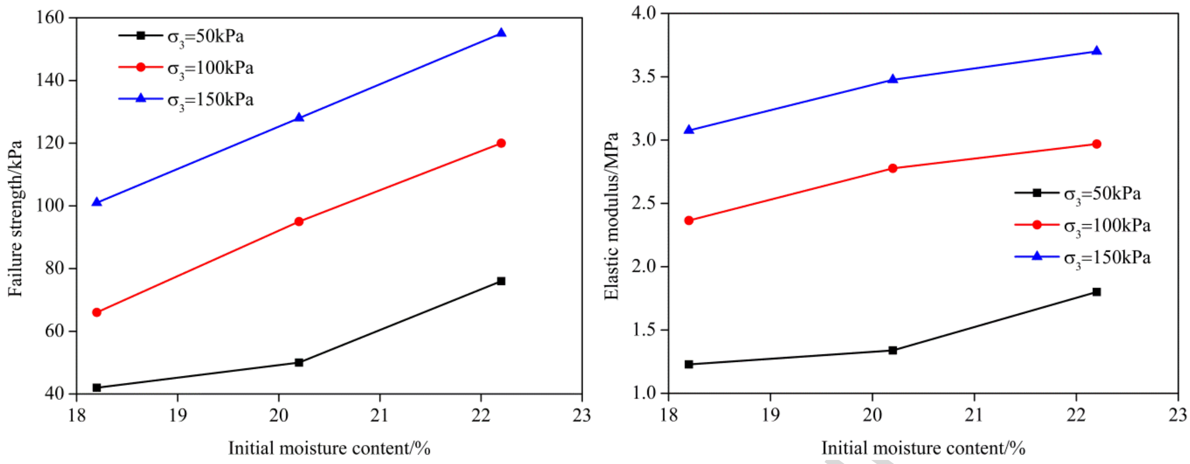


(a) Failure strength (b) Elastic modulus

Fig. 7 Variation in mechanical parameters versus initial dry density

3.2.3. Effect of initial moisture content on the mechanical properties of compacted soil

The test results of specimens with an initial dry density of 1.57g/cm^3 subjected to 3 F-T cycles were taken as examples. Fig. 8 illustrates the variation in failure strength and elastic modulus with respect to the initial moisture content under three confining pressures. As shown in this figure, the failure strength and elastic modulus increased with the increase in the initial moisture content of the specimens. The reason for this phenomenon was that when the initial moisture content of the specimen is high, the moisture content and frost heave of the specimen exposed to F-T cycles are lower than that of the specimen with low initial moisture content, so the mechanical properties of specimens with high initial moisture content will be enhanced to a certain extent.

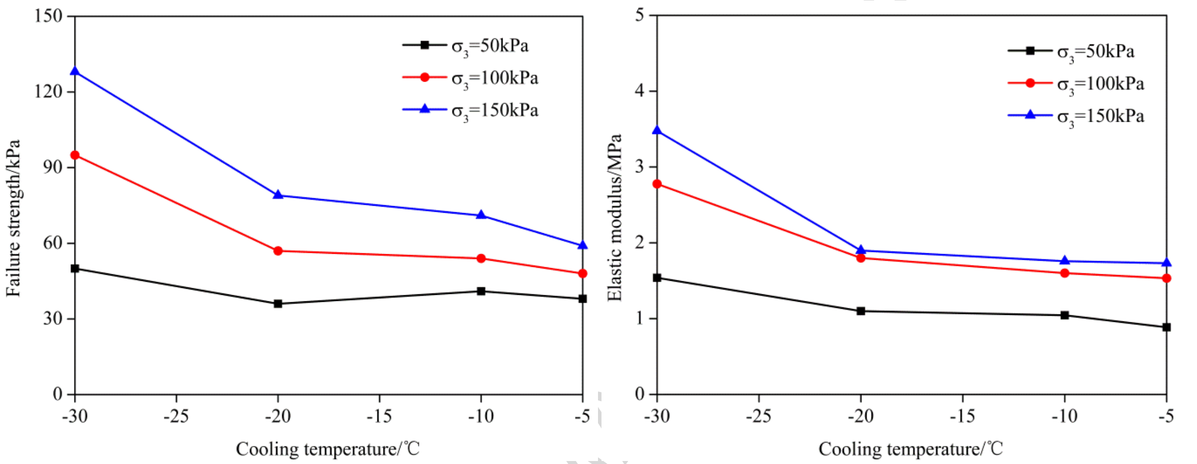


(a) Failure strength (b) Elastic modulus

Fig. 8 Variation in mechanical parameters versus initial moisture content

3.2.4. Effect of cooling temperature on the mechanical properties of compacted soil

The effect of different cooling temperatures on the failure strength and elastic modulus of soil is shown in Fig. 9. The specimens used for this evaluation had an initial moisture content of 20.2% and initial dry density of 1.57g/cm^3 and underwent 3 F-T cycles. As shown in Fig. 9, when the cooling temperature dropped from -5°C to -20°C, the failure strength and elastic modulus changed very little, whereas the failure strength and elastic modulus increased significantly when the temperature fell to -30°C. When the cooling temperature is higher (i.e. -5°C, -10°C and -20°C), the freezing rate is low and so is the temperature gradient within the specimen. In this condition, the cryogenic structure forms thick segregated ice inclusions and intervals (Bronfenbrener & Bronfenbrener, 2010), which cause considerable disruption to the structure of the soil specimen and this leads to a substantial decrease of the strength after melting. Conversely, when the cooling temperature is very low (-30°C), the freezing rate is high, and so is the temperature gradient in the specimen. In this case, the soil is frozen in-situ, which results in the formation of thinner ice lenses and a finer cryogenic structure, which cause little disturbance to the specimen structure and less deterioration in the strength of the soil sample (Liu & Peng, 2009). Therefore, a slow fall of temperature in winter has a great influence on the strength of soil. Furthermore, it can be observed from Fig. 9 that the effect of cooling temperature on soil strength under high confining pressures (100kPa and 150kPa) was larger than that under low confining pressure (50kPa).



(a) Failure strength (b) Elastic modulus

Fig. 9 Variation of mechanical parameters versus cooling temperature

3.3 Establishment of models considering factors affecting the mechanical properties of compacted soil

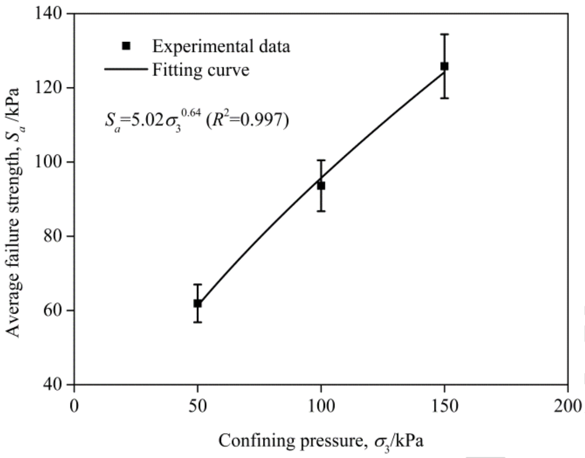
The failure strength and elastic modulus of soil both are important parameters in geotechnical engineering. By contrasting the influence of various factors (number of F-T cycles, initial dry density, initial moisture content, confining pressure, and cooling temperature) on the failure strength and elastic modulus of freeze-thawed soil, it was found that, under a confining pressure of 50kPa with 3 F-T cycles, the variations in failure strength caused by the changes of F-T cycles, initial dry density, initial moisture content and cooling temperature were 88%, 136%, 81% and 32%, respectively; and the variations in the elastic modulus were 94%, 110%, 47% and 45%, respectively. When the confining pressure increased from 50kPa to 150kPa, the failure strength and elastic modulus both more than doubled. The above comparisons show that, while the effects of number of F-T cycles, initial dry density, initial moisture content and confining pressure are notable (comparatively speaking), the effect of cooling temperature apparently is not significant. Therefore, the fitted models of failure strength and elastic modulus considering four factors were established, ignoring the influence of cooling temperature. Furthermore, in consideration of the difference between the influence factors on soil mechanical properties before and after F-T cycles, the mechanical indices of soil exposed to freezing and thawing were investigated.

In the present study, the fitted models for failure strength and elastic modulus were established using data obtained from the tests for soil samples with three initial dry densities, three initial moisture contents and for 1, 3, 5 and 7 F-T cycles at a cooling temperature of -30°C. These mathematical models were used to forecast the failure strength and elastic modulus of soil with an initial moisture content of 20.2% and an initial dry density of 1.57 g/cm^3 after 2, 4, 6 and 8 F-T cycles at a freezing temperature of -30°C. It can be seen from Figs. 6-8 that both the failure strength and elastic modulus have the same variation tendencies which is consistent with the findings of Zhang et al. (2015). Besides, two formulas of the same form were adopted to fit standard failure strength and standard modulus by Zhang et al. (2015). Recently, Tang et al. (2017) simplified the formula of standard modulus to fit the relationship between average elastic modulus and confining pressure. Through the comparative analysis mentioned above, the relationship between the average failure strength and the confining pressure, the average elastic modulus and the confining pressure can be expressed as:

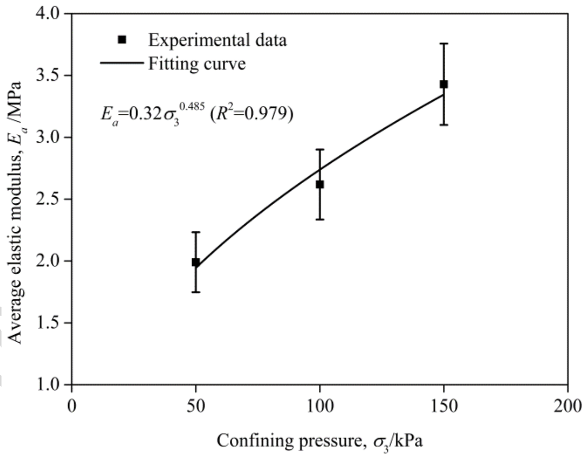
$$S_a = a\sigma_3^{\ b} \tag{2}$$

$$E_a = \alpha\sigma_3^{\ \beta} \tag{3}$$

Where S_a is the average failure strength under three confining pressures, E_a is the average elastic modulus under three confining pressures, a, b, α and β are experiment constants, a = 5.02, b = 0.640, α = 0.320, and β = 0.485 (see Fig. 10).



(a) Average failure strength



(b) Average elastic modulus

Fig. 10 Fitting curves for average failure strength and average elastic modulus

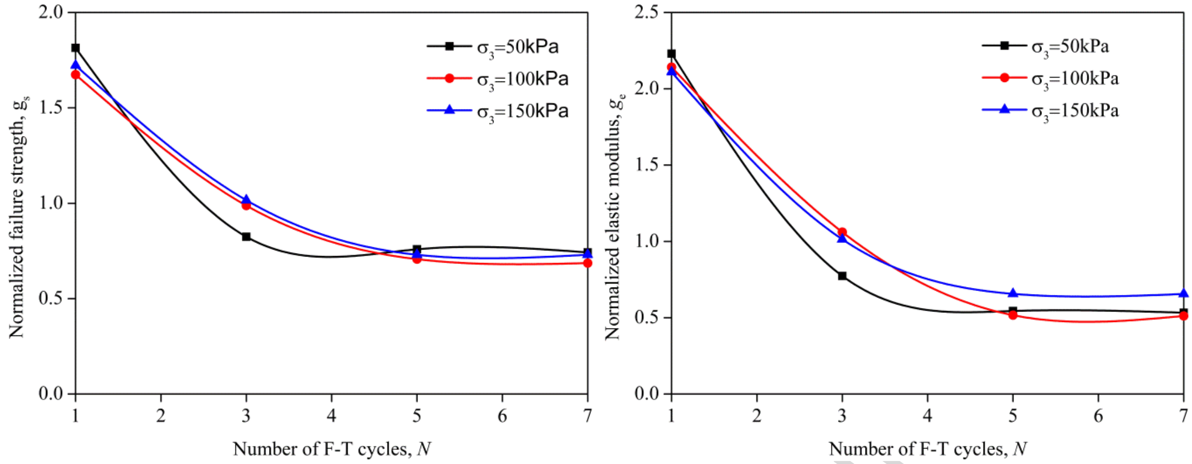
The failure strength and elastic modulus are normalized as follows:

$$g_s = S/S_a \tag{4}$$

$$g_e = E/E_a \tag{5}$$

where g_s is the normalized failure strength, S is the failure strength of soil subjected to F-T cycles, g_e is the normalized elastic modulus, and E is the elastic modulus after F-T cycles.

Adopting the specimens with an initial moisture content of 20.2% and an initial dry density of 1.57 g/cm^3 as an example, the variation curves for normalized failure strength and normalized elastic modulus can be obtained, as shown in Fig. 11.



(a) Normalized failure strength

(b) Normalized elastic modulus

Fig.11 Variation curves for normalized failure strength and normalized elastic modulus

The effects of the number of F-T cycles and the initial dry density on failure strength were considered. According to the variation trends of failure strength and elastic modulus shown in Figs. 7 and 11, the influence of number of F-T cycles and initial dry density on normalized failure strength and normalized elastic modulus can be expressed by:

$$g_s = \left(Ae^{-BN} + C\right)\rho_d{}^{D} \tag{6}$$

$$g_e = \left(Fe^{-GN} + H\right)\rho_d{}^{K} \tag{7}$$

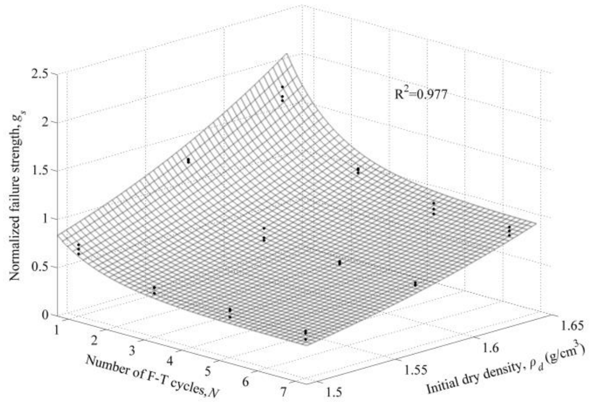
where N is the number of F-T cycles, ρ_d is the initial dry density, and A, B, C, D, F, G, H and K are all dimensionless regression coefficients affected by initial moisture content, as listed in Tables 3 and 4. The values of A, B, C, D, F, G, H and K are obtained by fitting the normalized failure strength g_s (Eq. (6)) and normalized elastic modulus g_e (Eq. (7)), adopting the experimental data for 1, 3, 5 and 7 F-T cycles. Figs. 12 and 13 show the comparison between the experimental results and the fitting surfaces obtained by using Eqs. (6) and (7), respectively. It can be noted that the fitting degrees in Figs. 12 and 13 all exceeded 0.9, which indicates that the fitting results were in good agreement with the experimental results.

Table 3 Fitting parameters of normalized failure strength with different moisture contents

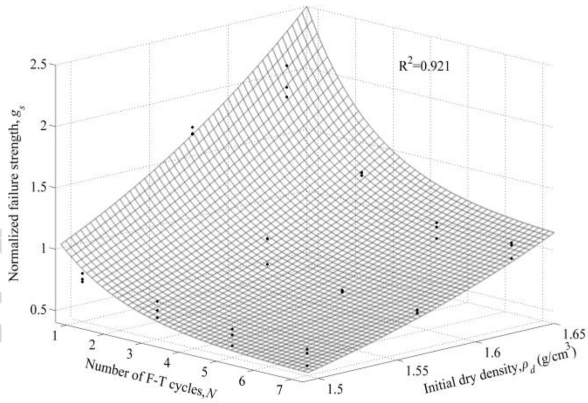
Initial moisture content/%	*A*	*B*	*C*	*D*	R^2
18.2	0.0156	0.774	0.00841	9.63	0.977
20.2	0.0239	0.567	0.0128	8.91	0.921
22.2	0.0306	0.452	0.0180	8.36	0.940

Table 4 Fitting parameters of normalized elastic modulus with different moisture contents

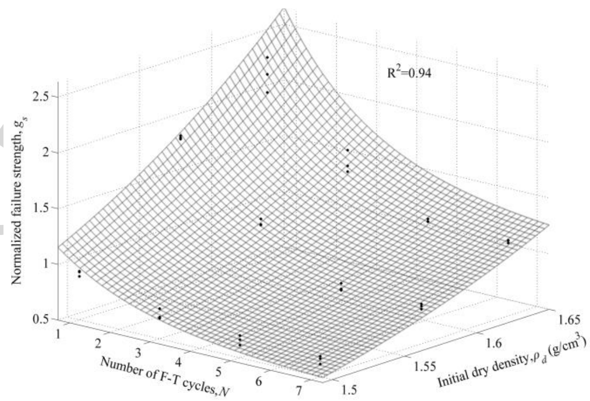
Initial moisture content/%	*F*	*G*	*H*	*K*	R^2
18.2	0.00530	0.585	0.00158	12.6	0.946
20.2	0.0180	0.696	0.00420	10.9	0.911
22.2	0.0237	0.909	0.00600	10.8	0.914



(a) *w* = 18.2%

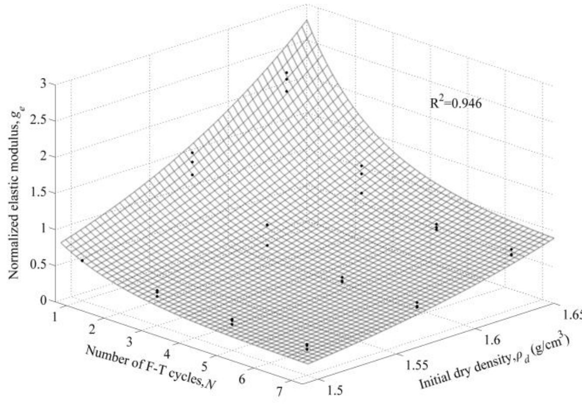


(b) *w* = 20.2%

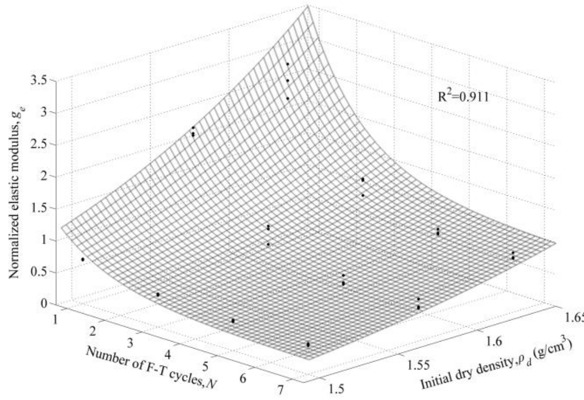


(c) *w* = 22.2%

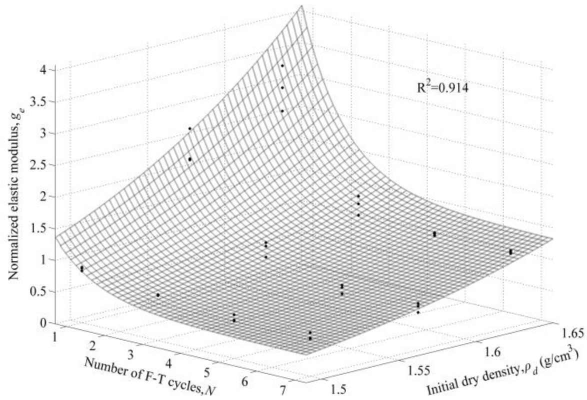
Fig. 12 Fitting surfaces of normalized failure strength with different moisture contents



(a) w = 18.2%



(b) w = 20.2%



(c) w = 22.2%

Fig. 13 Fitting surfaces of normalized elastic modulus with different moisture contents

The quotients: A, B, C, D, F, G, H and K, can be fitted as the function of moisture content, respectively. Then the following equations can be obtained:

$A = 0.375w - 0.0524$ ($R^2 = 0.996$) (8)

$B = -8.05w + 2.22$ ($R^2 = 0.974$) (9)

$C = 0.24w - 0.0354$ ($R^2 = 0.998$) (10)

$D = -31.8w + 15.4$ ($R^2 = 0.994$) (11)

$F = 0.46w - 0.0773$ ($R^2 = 0.954$) (12)

$G = 8.1w - 0.906$ ($R^2 = 0.968$) (13)

$H = 0.111w - 0.0184$ ($R^2 = 0.989$) (14)

$K = -45w + 20.5 \qquad (R^2 = 0.792) \qquad (15)$

where w is the initial moisture content.

Substituting Eqs. (8)-(11) to Eq. (6), and combining with Eqs. (2) and (4), the failure strength can be written as:

$$S = a((A_1 w + A_2)e^{-(B_1 w + B_2)N} + C_1 w + C_2)\rho_d^{D_1 w + D_2}\sigma_3^{\ b} \tag{16}$$

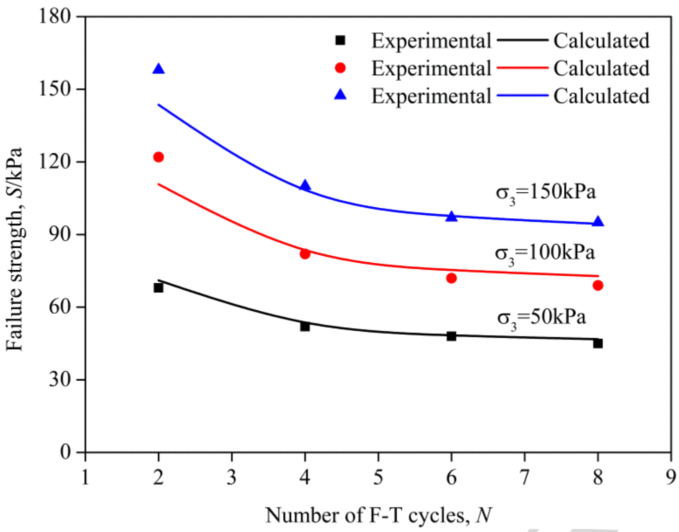
where $A_1 = 0.375$, $A_2 = -0.0524$, $B_1 = -8.05$, $B_2 = 2.22$, $C_1 = 0.240$, $C_2 = -0.0354$, $D_1 = -31.8$, $D_2 = 15.4$.

Through the similar operation, the equation of elastic modulus is obtained:

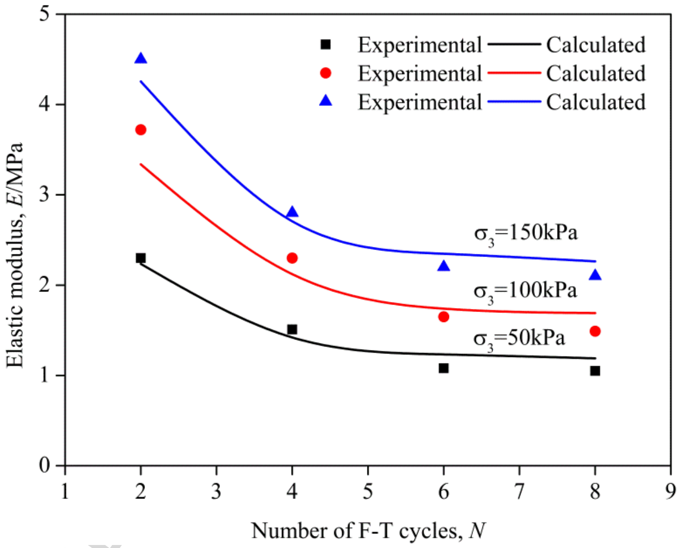
$$E = \alpha((F_1 w + F_2)e^{-(G_1 w + G_2)N} + H_1 w + H_2)\rho_d^{K_1 w + K_2}\sigma_3^{\ \beta} \tag{17}$$

where $F_1 = 0.460$, $F_2 = -0.0773$, $G_1 = 8.10$, $G_2 = -0.906$, $H_1 = 0.111$, $H_2 = -0.0184$, $K_1 = -45.0$, $K_2 = 20.5$.

Eqs. (16) and (17) were adopted to calculate the failure strength and elastic modulus of specimens with an initial moisture content of 20.2% and an initial dry density of 1.57g/cm^3 exposed to 2, 4, 6 and 8 F-T cycles, respectively. Fig. 14 illustrates the comparison between the experimental results and the calculated results. As can be observed in Fig. 14, the calculated data were consistent with the experimental data, which verified the rationality and reliability of the proposed models for the failure strength and elastic modulus of compacted soil under different numbers of F-T cycles.



(a) Failure strength



(b) Elastic modulus

Fig.14. Comparison between the experimental data and calculated results for N=2, 4, 6 and 8

4. Conclusions

In this study, unconsolidated and undrained triaxial compression tests were conducted after compacted clayey soil samples were subjected to freeze-thaw cycles in the presence of a supplemental water supply. The influence of the initial state of samples and of freezing and thawing on the mechanical properties of the soil was investigated. The results can be summarized as follows:

(1) With an increase in the number of F-T cycles, the moisture content and the frost heave of soil at first increased rapidly, then gradually stabilized after 3 F-T cycles. Both the moisture content and the frost heave decreased with an increase in the initial dry density and initial moisture content. This is the underlying cause of the deterioration in the mechanical properties of soil due to the effects of freezing and thawing.

(2) The failure strength and the elastic modulus of samples decreased dramatically after the first F-T cycle, then stabilized gradually after 3 F-T cycles. This indicates that the availability of a supplementary water supply can accelerate the development of the stable (reduced strength) state of the specimens. The average reduction rate of failure strength and elastic modulus both were more than 60% after the first F-T cycle, and the average rates of decrease of these two indices reached 85% and 92% respectively, after 7 F-T cycles.

(3) The variation tendency of the mechanical properties of the soil specimens with the number of F-T cycles was in good agreement with the change trend of the moisture content and the frost heave. The significant degradation in soil strength was the result of capillary water migration and soil structure change during freezing-thawing process.

(4) An increase in the dry density or a moderate improvement in the moisture content of a soil can reduce the water migration in the soil, and then weaken the degradation effect of the F-T cycles on the mechanical properties, but the effect of soil moisture content on soil compaction quality should be considered. The confining pressure has an

inhibitory effect on the deterioration of failure strength and elastic modulus.

(5) A high cooling temperature leads to a decrease in the strength of a soil after subsequent melting of the ice, and a low cooling temperature results in a decrease in the strength deterioration of a soil. A slower fall in temperature during winter can have a great influence on the strength of a soil. The effect of cooling temperature on soil strength under high confining pressure is larger than that in the case under low confining pressure.

(6) Fitted models for the failure strength and elastic modulus of compacted soil that consider the effects of the number of F-T cycles, the initial dry density, the initial moisture content and the confining pressure were proposed. Their rationality and reliability were verified by the comparison of test data with calculated results.

Acknowledgements

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Highlights

- The effect of water supply on the geotechnical properties of freezed-thawed soil during freezing was investigated.
- Influnce of the number of F-T cycles, the initial dry density, the initial moisture content, the confining pressure and the cooling temperature on freezed-thawed soil was analyzed, respectively.
- Fitted models for mechanical properties of freezed-thawed soil considering the initial conditions of soil and environmental conditions were proposed and verified.