

Experiment of freeze-thaw cycling effect on silty clay under different environmental freezing temperatures

HU Tian-fei, LIU Jian-kun, LIU Da-wei

(School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China)

Abstract: In order to study the influence of freezing temperature on freeze-thaw cycling of soil, a set of triaxial tests were conducted under different confining pressures (50, 100, 150 kPa) for samples based on silty clay from Qinghai-Tibet Plateau regarding different freeze-thaw cycle numbers (0, 1, 3, 6, 9, 12, 15 times) under different freezing temperatures (-5°C , -10°C , -15°C , -20°C , -25°C , -30°C). The results show that the level of freezing temperature considerably affects the soil freeze-thaw cycling. The failure strength decreases when freezing temperature changes from -5°C to -15°C , and increases when freezing temperature changes from -15°C to -30°C . Though volume of the surface increases under frozen condition, expansion and contraction coexist in freezing process. With the decrease of freezing temperature, it is earlier for expansion to reach the limit than contraction. Meanwhile, with the increase of freeze-thaw cycle number, the failure strength decreases dramatically, and then keeps constant. The failure strength achieves the relative stability index with less cycling times, when freezing temperature is lower. The migration rate inside samples becomes less when freezing temperature is lower, thus the amount of water migration correspondingly becomes less. Apparent shear strength parameters vary in the same regularity as failure strength, internal friction angle suffers a more significant effect on the freezing temperature than cohesion. 1 tab, 8 figs, 20 refs.

Key words: road engineering; permafrost; freeze-thaw cycling; freezing temperature; failure strength; shear strength; freezing contraction

CLC number: U416.168

Document code: A

冻结环境温度对粉质黏土冻融循环效应影响的试验

胡田飞, 刘建坤, 刘大伟

(北京交通大学 土木建筑工程学院, 北京 100044)

摘 要:为明确冻结过程中环境温度对土体冻融循环效应的影响规律,以青藏高原粉质黏土为对象,首先选择冻结环境温度(-5°C 、 -10°C 、 -15°C 、 -20°C 、 -25°C 、 -30°C)和冻融循环次数(0、1、3、6、9、12、15)为变量进行了一系列冻融循环试验,然后,以围压(50、100、150 kPa)为变量,对经历冻融循环试验后的试样进行三轴压缩试验。研究结果表明:冻结环境温度会显著影响土体经历冻融循环后的物理力学性质。冻融循环后试样的破坏强度整体上有所减小,并随冻结环境温度

的降低呈先减小、后增大的变化规律, $-15\text{ }^{\circ}\text{C}$ 时破坏强度达谷值。虽然土体冻结后的表观体积增大, 但膨胀变形分量和收缩变形分量在冻结过程中同时存在, 而且随着环境温度的降低, 冻胀先于冻缩达到极限状态, 因此表观体积呈先增大、后减小的变化规律, 相应地破坏强度呈相反的变化规律。此外, 随着冻融循环次数的增加, 破坏强度呈先减小、后逐渐稳定的变化规律。同时, 冻结环境温度越低, 破坏强度达到稳定值所需的冻融循环次数越少。试样冻结过程中的水分迁移速率和迁移量随环境温度的降低而减小, 水分迁移对土体结构的影响也随之减小。抗剪强度指标表现为与破坏强度一致的冻融循环效应, 其中内摩擦角对冻结环境温度变化的响应程度大于黏聚力的影响程度。

关键词: 道路工程; 冻土; 冻融循环; 冻结温度; 破坏强度; 抗剪强度; 冻缩

0 Introduction

In cold regions, periodic freezing and thawing process, which was caused by seasonal or diurnal variation of temperature in nature, always existed in subgrade filling materials and may lead to both additional deformation and deterioration of soil properties^[1-2]. Essentially, freeze and thaw phenomenon of soil is the migration and phase transition processes of water inside soil, among which the migration needs to be driven by temperature gradients and the phase transition occurs only at a certain critical temperature. Accordingly, only under the condition of temperature variation, soil aggregate then will present different freeze-thaw cycling effects due to the difference of original moisture content, original compaction degree, water supplement condition, particle size distribution, or mineral composition etc^[3-5]. So temperature is one of main reasons that affect the freeze-thaw cycling effect on soil physical and mechanical properties.

Previous studies showed that the variation of physical and mechanical properties of soil subjected to freeze-thaw cycle was certainly influenced by freezing temperature in freezing process. Bing, et al. mentioned that the reduction of soil strength after freeze-thaw cycles was enlarged when temperature in freezing process decreased. The strength would keep constant when temperature is below $-10\text{ }^{\circ}\text{C}$ ^[6]. Song, et al. conducted a set of direct shear tests on Lanzhou Loess and found that variation amount of pre-consolidation pressure was depended on freezing temperature gradients, i. e., it decreased with the increase of temperature gradi-

ent, and the value of cohesion kept decreasing in consistence with temperature gradient, whereas the friction angle varied little^[7]. Wang, et al. presented a set of uniaxial compression tests and triaxial compression tests on the samples subjected to freeze-thaw cycles, and noted that the lower the cold-end temperature, the larger the changes in compressibility and shear strength^[8]. Wang, et al. worked on the cement-, lime- and AS curing agent-treated clayed soil, and reported the same conclusion above. In addition, they found that the freeze-thaw cycle number for samples to enter a relatively stable state would be less when freezing temperature was lower^[9-10].

However, there still are some opposite conclusions compared with those above. Yu, et al. performed triaxial tests to investigate the effect of freeze-thaw cycles on saturated silty clay^[11]. The results indicated that the cohesion decreased and the friction angle increased after freeze-thaw cycles and their variation ranges became less when freezing temperature decreased. Liu, et al. investigated the effect of freeze-thaw cycle on the unconfined compression, and found that the strength increased with the decrease of freezing temperature when the positive temperature in thawing period was constant^[12]. Zhou, et al. suggested that the variation of shear strength caused by freeze-thaw cycles under different freezing temperatures were closely related to the original moisture content^[13]. The cohesion would exhibit opposite trends under different original moisture contents, i. e., there was a critical freezing temperature to make cohesion decrease or increase with the decrease of freezing

temperature whether freezing temperature was lower than the critical value or not. In addition, the conclusion, which showed that the freeze-thaw cycling effect on soil was not sensitive to freezing temperature, was drawn by a series of triaxial tests on the silty sand from Qinghai-Tibet Plateau^[14].

In fact, physical properties of soil, such as porosity, moisture content, capillary rise, and type of soil, all play important roles in deterioration degree induced by freeze-thaw cycles. To explain different trends, some studies had also been conducted. For samples with same soil and original state, water migration and ice forming method both changed with freezing temperature in freezing process, hence the influence levels, mainly caused by freezing to act on soil structure, responded to temperature levels^[15]. Zhang, et al. monitored the pore water pressure of soil subjected to freeze-thaw cycles, and found it varied periodically with the cyclic variation of temperature^[16]. In addition, the negative pore water pressure was detected in freezing process. Especially for the strength improvement phenomenon in freeze-thaw cycles, several reasons were put forward and verified by tests. Zhang, et al. conducted mercury intrusion porosimetry(MIP) tests and scanning electron microscopy(SEM) tests to investigate the microstructure before and after freeze-thaw cycles^[17]. Number of contact points between soil particles was found to keep increasing, because of the aggregated particles crushing. Furthermore, contraction phenomenon, which was always ignored in soil freezing, was found to appear in freezing process^[18-20]. Contraction could cause over-consolidation effect and increase the effective stress, thus reinforcing the soil structure.

The limitation of previous studies lies in the fact that freezing temperature was generally within $-20\text{ }^{\circ}\text{C}$, which was the limit temperature for most freezing test chambers, whereas the natural temperature is below $-30\text{ }^{\circ}\text{C}$. Lack of references reporting on mechanical properties of silty clay with all potential freezing temperatures, this paper analyzed the behaviors of silty clay that experienced

six freeze-thaw cycles from 1 to 15, under six different freezing temperatures from $-5\text{ }^{\circ}\text{C}$ to $-30\text{ }^{\circ}\text{C}$. The present study attempts to further understand the process of freeze-thaw deterioration under all possible temperatures in freezing phase by measuring the failure strength.

1 Materials and experiment

1.1 Materials properties

The soil used in this study was taken from a research and observation base in permafrost regions located at Qinghai-Tibet Plateau, the maximum dry density is 1.828 g/cm^3 and the optimum water content is 14.8% , as shown in Fig. 1. The particle size distribution is shown in Fig. 2. The liquid limit and plasticity limit of fine particles of the soil are 10.3% and 17.7% , respectively. Then the soil is defined as CL (silty clay) according to *The universal soil classification system*.

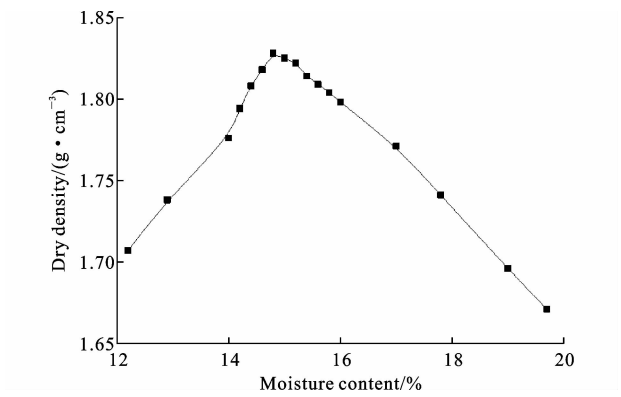


Fig. 1 Compaction curve of tested soil

图 1 土样压实曲线

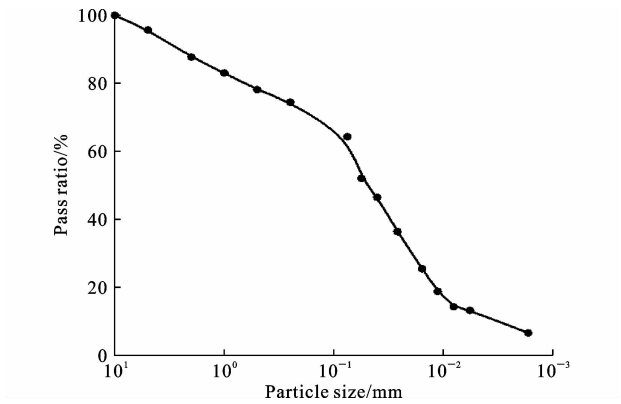


Fig. 2 Particle size distributions of silty clay

图 2 土样颗粒级配曲线

1.2 Samples preparation

In this study, soil materials are studied in an

unsaturated condition at the optimum water content and compaction degree of 95.0%, with the saturation degree of 78.1%. Procedures of sample preparation and triaxial test are conducted according to *Specification of soil test* (SL237—1999).

Thoroughly dry soil was first prepared by pre-determined quantities. Then the required amount of water, corresponding to the optimum moisture content of natural soils, was added and sample was remixed to obtain a uniform moisture distribution. The mixture was then placed in plastic bags and left for 1 h in a closed condition. Subsequently, the soil sample was compacted in four layers inside a cylindrical mold, until it reached 95% of the maximum dry unit weight of natural soil with a final dimension of 39.1 mm in diameter and 80 mm in height to serve for triaxial compression test. After compaction, the soil sample was immediately extracted from the mold and then wrapped with paraffin to prevent moisture loss.

1.3 Test scheme

In order to investigate the further influence of freezing temperature in freezing process on the freeze-thaw cycling effect of soils. Freeze-thaw cycle number and freezing temperature were chosen as main variables to conduct comprehensive tests. Soil samples were subjected to 1, 3, 6, 9, 12 and

15 freeze-thaw cycles under six different freezing temperatures including $-5\text{ }^{\circ}\text{C}$, $-10\text{ }^{\circ}\text{C}$, $-15\text{ }^{\circ}\text{C}$, $-20\text{ }^{\circ}\text{C}$, $-25\text{ }^{\circ}\text{C}$, $-30\text{ }^{\circ}\text{C}$.

In freeze-thaw cycling tests, soil samples wrapped in paraffin film were placed inside the freeze-thaw chamber, which was a three dimensional closed system without water supply in a range of $-40\text{ }^{\circ}\text{C}$ to $150\text{ }^{\circ}\text{C}$, with the constant freezing temperature for 12 h. After that, soil samples were subjected to thawing at $20\text{ }^{\circ}\text{C}$ for another 12 h, thus one freeze-thaw cycle was finished. The weight of soil samples was recorded at the end of each freeze-thaw cycle in order to ensure constant average water content. After each designed of freeze-thaw cycle number, triaxial tests of unconsolidated and undrained (UU) type were subsequently conducted on the freeze-thaw samples under three different confining pressures of 50, 100, 150 kPa with a conventional triaxial compression device, in order to obtain the stress-strain curves and failure strengths. Finally, values of apparent cohesion and internal friction angle were calculated, using the stress path method which was adopted in the standard of *Specification of soil test* (SL237—1999). Load was applied to soil samples with a constant strain rate of 0.4 mm/min. Totally 111 soil samples were used in the test as shown in Tab. 1.

Tab. 1 Experimental parameters of triaxial test

表 1 三轴试验参数

Parameter	Compaction degree/%	Moisture content/%	Confining pressure/kPa	Freeze-thaw cycle number	Freezing temperature/ $^{\circ}\text{C}$
Value	95	14.8	50,100,150	0,1,3,6,9,12,15	$-5,-10,-15,-20,-25,-30$

2 Results and analysis

2.1 Failure strength due to freezing temperatures

Failure strengths of freeze-thaw samples under different freezing temperatures ($-5\text{ }^{\circ}\text{C}$, $-10\text{ }^{\circ}\text{C}$, $-15\text{ }^{\circ}\text{C}$, $-20\text{ }^{\circ}\text{C}$, $-25\text{ }^{\circ}\text{C}$, $-30\text{ }^{\circ}\text{C}$) and confining pressures (50, 100, 150 kPa) are shown in Fig. 3. For the deviatoric stress-axial strain curves, if there are peak values of stress $\epsilon_1<15\%$, peak values of stress are taken as failure strengths of tested samples. And if no peak values exist in the stress-

strain curves in the range of $\epsilon_1<15\%$, values of $(\sigma_1-\sigma_3)$ at strain of 15% are taken as failure strengths. ϵ_1 , $(\sigma_1-\sigma_3)$ stands for axial strain and deviatoric stress, respectively. According to Fig. 3, all the freeze-thaw cycles under different freezing temperatures and confining pressures caused the deterioration of failure strength. Specifically, failure strengths decrease when freezing temperature changes from $-5\text{ }^{\circ}\text{C}$ to $-15\text{ }^{\circ}\text{C}$, and then increase when freezing temperature changes from $-15\text{ }^{\circ}\text{C}$ to $-30\text{ }^{\circ}\text{C}$.

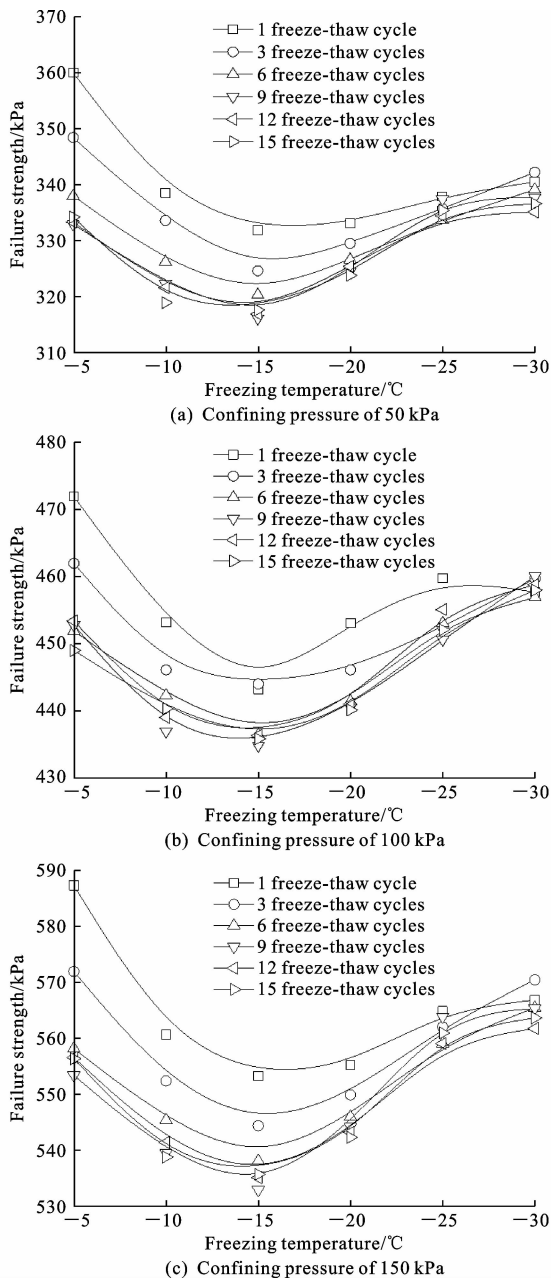


Fig. 3 Change of failure strength with freezing temperature

图 3 破坏强度随冻结温度的变化

2.2 Failure strength due to freeze-thaw cycle number

Fig. 4 shows the failure strengths of freeze-thaw samples with different freeze-thaw cycle numbers under confining pressure of 50, 100, 150 kPa. As can be seen from Fig. 4, for samples subjected to different freeze-thaw cycle numbers under any constant freezing temperature and confining pressure, failure strengths decrease to a large extent at the beginning compared with samples tested without application of freeze-thaw cycles, then decrease slightly with the increase of freeze-thaw cycle num-

ber, and finally reach a certain level, after which the variations tend to be stabilized, i. e., they remain constant without being influenced by additional freeze-thaw cycles. As a whole, the increasing freeze-thaw cycle has a negative effect on mechanical strength of compacted soil. In addition, number of freeze-thaw cycle, by which the failure strengths reach a relatively stable state, reduce with the decrease of freezing temperature. As for Fig. 4(b), when freezing temperature is -5°C , -15°C and -30°C , the mentioned number is 12, 6, 3, respectively.

2.3 Shear strength parameters

According to the failure strengths of samples under three different confining pressures as shown in Fig. 3, the apparent cohesions and internal friction angles of samples tested by different conditions were generated from the Mohr Coulomb failure criteria with the envelope drawn by a linear line. Fig. 5 and Fig. 6 show the apparent cohesions and internal friction angles of freeze-thaw samples under different freezing temperatures and numbers of freeze-thaw cycles, respectively. As shown in Fig. 5 and Fig. 6, shear strength parameters both vary with the decrease of temperature in the same regularity with failure strength, i. e., they both decrease with the decrease of temperature within -15°C and then the variations present an increase when freezing temperature changes from -15°C to -30°C . In addition, the results show that internal friction angle has a more significant response to freezing temperature than cohesion when freezing temperature is below -25°C , i. e., the internal friction angles of freeze-thaw samples with freezing temperatures of -25°C and -30°C are obviously larger than those under higher ones, but this phenomenon does not occur on cohesion.

The cohesion mainly represents cohesive strength between soil particles, including the cement strength of compound in soils, attraction of adjacent electric charges and molecules. Hence, the cohesion mainly depends on the connection mode and arrangement mode of soil particles. The frost-heave force of ice crystals in freezing process

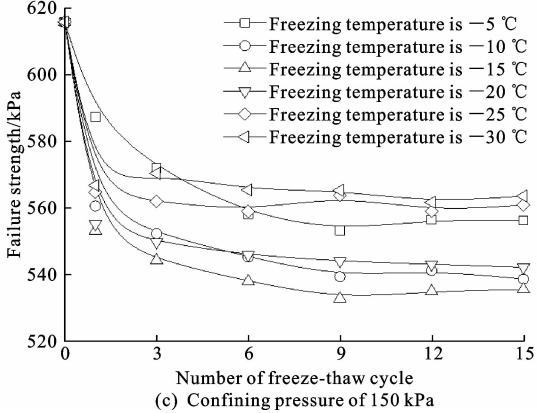
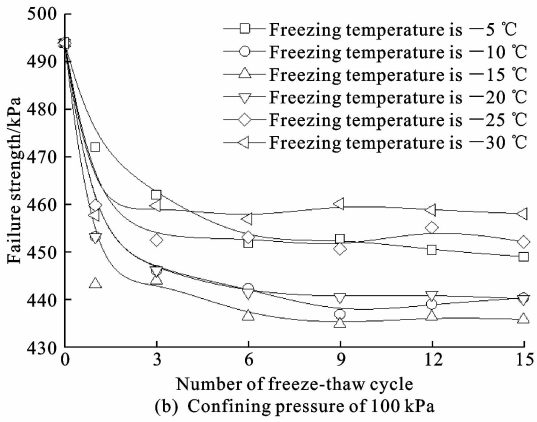
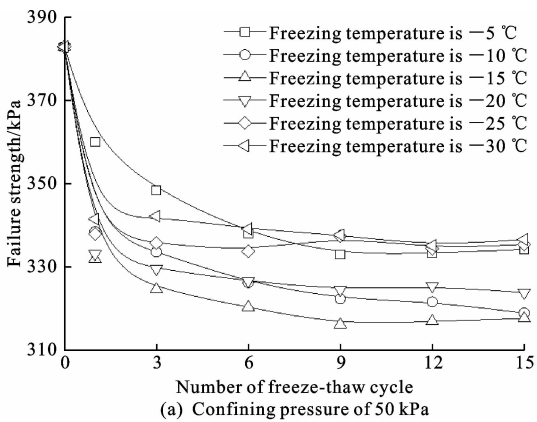


Fig. 4 Change of failure strength with freeze-thaw cycle number
图 4 破坏强度随冻融循环次数的变化

can destroy the cement strength of compound, and increase the spacing between soil particles, i. e., reducing the interaction force among molecules, thus causing a reduction on cohesion. With the increase of temperature gradient, the major freezing mode inside soils will gradually change from segregating freeze to in-situ freeze, with a growing damage on cohesion with temperature reducing within $-15\text{ }^{\circ}\text{C}$. Below $-15\text{ }^{\circ}\text{C}$, the cement strength tends to remain a minimum value and keeps constant because of the ice content reaching the peak

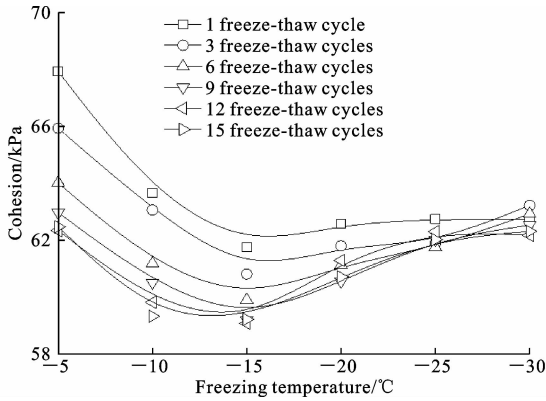


Fig. 5 Cohesion of freeze-thaw samples under different freezing temperatures
图 5 冻融循环试件黏聚力随冷却温度的变化特征

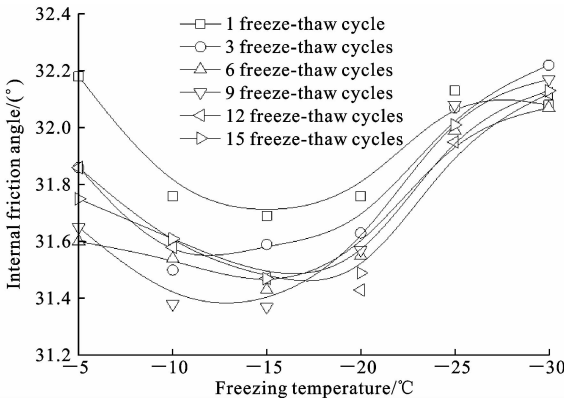


Fig. 6 Change of internal friction angle with freezing temperature
图 6 内摩擦角随冻结温度的变化

value, whereas the attraction of electric charges and molecules turn to increase, because of the reduction of particle spacing, which is reflected by the converse increase of sample volumes. These two different tendencies of cohesion components comprehensively lead to the cohesion switch to increase when freezing temperature changes from $-15\text{ }^{\circ}\text{C}$ to $-30\text{ }^{\circ}\text{C}$.

The internal friction angle mainly represents sliding friction, the sliding friction is caused by the rough contact surface between particles depending on the particle shape and size distribution, and occlusal friction caused by the constraint effect on relative motion between adjacent particles depends on the occlusal state of particles. The freezing effect on internal friction angle lies primarily in the damage of occlusal friction, which is closely related to the spacing of particles. Hence, internal friction angle presents an opposite variation rule compared

with the volume increment of freeze-thaw samples under different freezing temperatures. Furthermore, the effect of freezing temperature on internal friction angle is more significant than cohesion, which lies in the low degree of cementation of re-constituted samples.

3 Influencing mechanism of freezing temperature

The increase in sample volumes during freezing process is known to lie in the volume increment of 9% caused by the conversion from water into ice. Meanwhile, heat-expansion and cold-contraction are the basic properties of most objects. Hence, the increase of volume caused by water-ice conversion and the decrease of volume caused by cold-contraction exist inside of soils during the freezing phase, and they have opposite effects on total change in volume. In addition, their effects both keep increasing with the decrease of freezing temperature. Furthermore, what plays the leading role between two phenomena mentioned above may cause different changes in soil volumes. Fig. 7 shows the volume increment of sample after one freeze-thaw cycle under different freezing temperatures. It is clear from Fig. 7 that the volume increments keeps increasing when freezing temperature changes from -5°C to -15°C , and then decrease conversely when freezing temperature changes from -15°C to -30°C , with a peak value of 4.286 cm^3 . Volume increment caused by water-ice conversion plays a leading role for all tested samples because of the existence of pore water. Remarkably, a part of pore water remains unfrozen during the freezing process, and its content decreases with the decrease of freezing temperature, corresponding to the increase in soil volume. Whereas, the expansion is earlier to reach the maximum state than the contraction accompanied by the decrease of freezing temperature, so the contraction keeps increasing even after the expansion reaches the maximum state, thus the volume increment, on the whole, is shown as a V-shape curve.

The reason for strength variation during

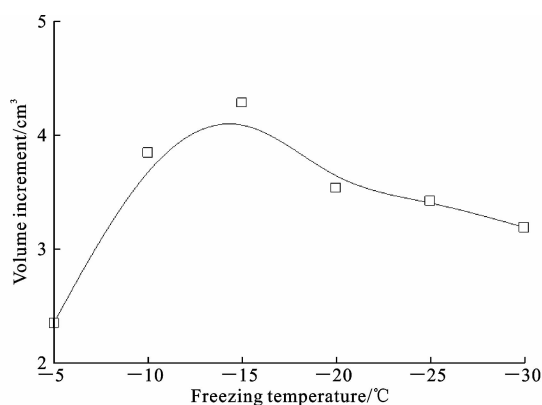


Fig. 7 Volume increment of sample after one freeze-thaw cycle under different freezing temperatures

图 7 不同冻结温度下试样冻融循环 1 次后的体积增加量

freeze-thaw cycles devotes to the fact that before freezing, the soil samples can be assumed to be tightly packed and have high strength. During the development of ice crystals in freezing process, soil particles are separated from adjacent particles by ice, and a dispersed packing is consequently formed. During the thawing process, although the volume increment during freezing process decreases because the ice melts, soil structure can not return back to the initial state. Therefore, the dispersed packing subsists after freeze-thaw cycles and the number of voids increase compared with the original state. In addition, the changing point of volume variation, accompanied by the decrease of freezing temperature, is consistent with that of the failure strength. Thus, the segregation of particles and reduction of average dry density cause the decrease of failure strength, and the deterioration effect is deteriorated with the decrease of freezing temperatures above -15°C , within which the amount of ice keeps increasing in freezing process. After the changing point corresponding to the maximum volume increment, the unfrozen water content in freezing may tend to be constant, and then the contraction can be reflected. By dint of the contraction, both the effective stress and average dry density of soil increase. Hence, the failure strength increases conversely below -15°C .

The reason for different cumulative effects of number of freeze-thaw cycle, acting on failure strength under different freezing temperatures as

illustrated in Fig. 4, lies in the redistribution characteristics of moisture content inside samples after freeze-thaw cycles. It varies with the amount of water migration, which mainly depends on the freezing rate. The freezing rate is essential for the moving speed of freezing front, and it changes in a monotonous regularity with freezing temperature when the original properties and storage environment of soil samples are coincident, i. e., the lower the temperature is, the higher the freezing rate will be. Meanwhile, the water inside unfrozen area of samples mainly migrates to the freezing front and then becomes ice. Fig. 8 shows the water redistribution characteristics of samples after one freeze-thaw cycle under different freezing temperatures. It can be seen from Fig. 8 that the amount of water migration and its additive effect caused by freeze-thaw cycles keep decreasing with the decrease of freezing temperature.

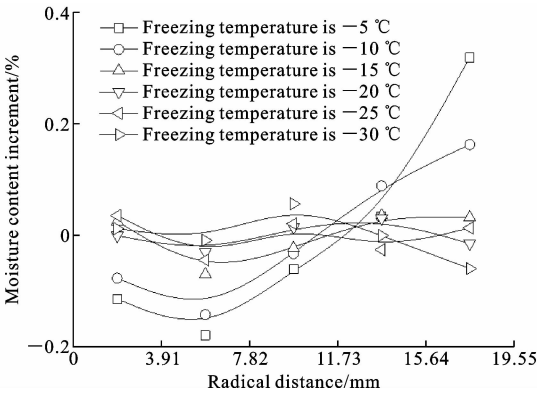


Fig. 8 Water redistribution characteristics of samples after one freeze-thaw cycle under different freezing temperatures
图 8 不同冻结温度下试样冻融循环 1 次后的水分重分布特征

4 Conclusions

(1)Expansion and contraction exist simultaneously inside the soils during freezing process, the former one is caused by the volume increment when a certain amount of water turns into ice, and the latter one is mainly caused by both the cold-contraction property of most solid matters and the squeezing effect of frost heaving force. The effect of freeze-thaw cycle on volume variation of samples depends on the relative influence degree between these two above factors with opposite effects. In

general, freezing expansion plays a leading role, i. e., sample volumes always increase. Expansion phenomenon is earlier to reach the maximum state than contraction with the decrease of freezing temperature, so the volume increment of soils in closed system keeps increasing to a certain extent, and then presents an increase conversely with the decrease of freezing temperature. The changing point represents the critical temperature with minimum unfrozen water content.

(2)Freezing temperature is a key factor that influences the soil mechanical properties under freeze-thaw cycles. Failure strength, which is closely related to dry density, varies in a contrary regularity compared with the volume increment with the decrease of freezing temperature. Failure strength decreases gradually when freezing temperature changes from $-5\text{ }^{\circ}\text{C}$ to $-15\text{ }^{\circ}\text{C}$, and then increases when freezing temperature changes from $-15\text{ }^{\circ}\text{C}$ to $-30\text{ }^{\circ}\text{C}$. Under any certain freezing temperature, the failure strength of freeze-thaw samples decreases to a large extent upon the first few freeze-thaw cycles, and then the strength decrement induces by every additional cycle gradually decreases to be stabilized, i. e., the failure strength becomes constant, no matter the number of freeze-thaw cycle keeps increasing or not. Meanwhile, when the freezing temperature is lower, the number of freeze-thaw cycle, after which the failure strength keeps constant, may be less. Apparent cohesion and internal friction angle vary in the same regularity as the failure strength with the decrease of freezing temperature, and also with the increase of freeze-thaw cycle number. In addition, due to the remodeling of soil samples, internal friction angle has a more significant response to freezing temperature than cohesion.

(3)In this study, the integral volume change of specimens were tested, while the variation characteristics of pore volume caused by both freezing expansion and contraction still need further study, so as the corresponding pore water pressure properties. In the following work, pore volume change and pore water pressure properties will be tested by scanning electron

microscope (SEM) and consolidated undrained (CU) triaxial test, respectively.

Acknowledgements

This research is funded by the Applied Basic Research Project (Key Platform) by Ministry of Transport (No. 2014319363200), and the National Natural Science Foundation (No. 51378057 & 41371081).

References:

- [1] XU Xue-zu, WANG Jia-cheng, ZHANG Li-xin. Frozen soil physics[M]. Beijing: Science Press, 2001.
- [2] CHEN Xiao-bai, LIU Jian-kun, LIU Hong-xu, et al. Frost action of soil and foundation engineering[M]. Beijing: Science Press, 2006.
- [3] SIMONSEN E, ISACSSON U. Soil behavior during freezing and thawing using variable and constant confining pressure triaxial tests[J]. Canadian Geotechnical Journal, 2001, 38(4): 863-875.
- [4] QI Ji-lin, MA Wei. State-of-art of research on mechanical properties of frozen soils[J]. Rock and Soil Mechanics, 2010, 31(1): 133-143.
- [5] MA Wei, WANG Da-yan. Mechanics of frozen soil [M]. Beijing: Science Press, 2014.
- [6] BING Wen-shan. Road frost damage and prevention translation (collection)[M]. Harbin: Harbin Institute of Technology Press, 1994.
- [7] SONG Chun-xia, QI Ji-lin, LIU Feng-yin. Influence of freeze-thaw on mechanical properties of Lanzhou loess[J]. Rock and Soil Mechanics, 2008, 29(4): 1077-1080, 1086.
- [8] WANG Xiao-bin, YANG Ping, WANG Hai-bo, et al. Experimental study on effects of freezing and thawing on mechanical properties of clay[J]. Chinese Journal of Geotechnical Engineering, 2009, 31(11): 1768-1772.
- [9] WANG Tian-liang, LIU Jian-kun, TIAN Ya-hu. Static properties of cement- and lime-modified soil subjected to freeze-thaw cycles[J]. Rock and Soil Mechanics, 2011, 32(1): 193-198.
- [10] WANG Tian-liang, ZHANG Li-ling, LIU Yao-jun, et al. Influences on engineering properties of AS firming agent modified soil by freeze-thaw cycles[J]. Journal of Civil, Architectural & Environmental Engineering, 2012, 34(5): 109-115.
- [11] YU Lin-lin, XU Xue-yan, QIU Ming-guo, et al. Influence of freeze-thaw on shear strength properties of saturated silty clay[J]. Rock and Soil Mechanics, 2010, 31(8): 2248-2252.
- [12] LIU Jian-kun, PENG Li-yun. Experimental study on the unconfined compression of a thawing soil[J]. Cold Regions Science and Technology, 2009, 58(1/2): 92-96.
- [13] ZHOU Zhi-jun, LU Da-wei, SONG Wei, et al. Experiment on loess characteristics after freeze-thaw circle based on changes of moisture content and temperature[J]. China Journal of Highway and Transport, 2013, 26(3): 44-49.
- [14] CHANG Dan, LIU Jian-kun, LI Xu, et al. Experiment study of effects of freezing-thawing cycles on mechanical properties of Qinghai-Tibet silty sand[J]. Chinese Journal of Rock Mechanics and Engineering, 2014, 33(7): 1496-1502.
- [15] PENG Li-yun, LIU Jian-kun, TIAN Ya-hu. Study on frost heaving property of silty caly[J]. Hydrogeology and Engineering Geology, 2009, 36(6): 62-67.
- [16] ZHANG Lian-hai, MA Wei, YANG Cheng-song. Pore water pressure measurement for soil subjected to freeze-thaw cycles[J]. Rock and Soil Mechanics, 2015, 36(7): 1856-1864.
- [17] ZHANG Ze, MA Wei, QI Ji-lin. Structure evolution and mechanism of engineering properties change of soils under effect of freeze-thaw cycle[J]. Journal of Jilin University: Earth Science Edition, 2013, 43(6): 1904-1914.
- [18] VIKLANDER P. Permeability and volume changes in till due to cyclic freeze-thaw[J]. Canadian Geotechnical Journal, 1998, 35(3): 471-477.
- [19] QI Ji-lin, MA Wei. Influence of freezing-thawing on strength of overconsolidated soils[J]. Chinese Journal of Geotechnical Engineering, 2006, 28(12): 2082-2086.
- [20] TANG Yi-qun, HONG Jun, YANG Ping, et al. Frost-heaving behaviors of mucky clay by artificial horizontal freezing method[J]. Chinese Journal of Geotechnical Engineering, 2009, 31(5): 772-776.