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Jing SUN
School of Civil Engineering, Heilongjiang University, Harbin, Heilongjiang 150080, China

Mao-sheng GONG
Institute of Engineering Mechanics, China Earthquake Administration, Harbin, Heilongjiang 150080, China, gmshiem@163.com

Hong-qiang XIONG
School of Civil Engineering, Heilongjiang University, Harbin, Heilongjiang 150080, China

Lin-rui GAN
School of Civil Engineering, Heilongjiang University, Harbin, Heilongjiang 150080, China

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Experimental study of the effect of freeze-thaw cycles on dynamic characteristics of silty sand

SUN Jing[1], GONG Mao-sheng[2], XIONG Hong-qiang[1], GAN Lin-rui[1]

1. School of Civil Engineering, Heilongjiang University, Harbin, Heilongjiang 150080, China
2. Institute of Engineering Mechanics, China Earthquake Administration, Harbin, Heilongjiang 150080, China

Abstract: By using the GDS dynamic triaxial apparatus tests, the effect of freeze-thaw cycles on dynamic stress, dynamic modulus, dynamic modulus ratio and damping ratio of silty sand under different negative temperatures has been investigated in this study. It is found that under the same dynamic strain, the freeze-thaw cycles are negatively correlated with dynamic stress and dynamic modulus, but positively correlated with dynamic modulus ratio and damping ratio. With the increasing of freeze-thaw cyclic numbers, the dynamic stress and dynamic modulus decrease while the dynamic modulus ratio and damping ratio increase. The normalized fitting models for the dynamic modulus ratio versus the shear strain and the damping ratio versus the shear strain have been presented by regression analysis. The freeze-thaw cycles have a significant effect on the initial dynamic modulus and the maximum damping ratio. With the increasing of freeze-thaw cyclic numbers, the initial dynamic modulus decreases and the maximum damping ratio increases. The effects of freeze-thaw cycles on the initial dynamic modulus and the maximum damping ratio under different negative temperatures have also been analyzed, and the calculation formulae of the number of freeze-thaw cycles correlation coefficients have been given. The results indicate that the effect of freeze-thaw cycles on dynamic characteristics of silty sand is obvious with decreasing of the temperature, and the dynamic characteristics after five freeze-thaw cycles are relatively stable. It is suggested that the dynamic parameters after five freeze-thaw cycles can be used as the basic parameters for the dynamic response analysis.

Keywords: freeze-thaw cycles; silty sand; dynamic characteristics; dynamic modulus; damping ratio

1 Introduction

Subgrades in seasonally frozen ground areas are subjected to repeated freezing and thawing, which changes the original structure and particle composition of the soil due to cryogenic course, thereby changing the mechanical properties of the soil[1]. The repeated freezing and thawing results in frost heave and thaw settlement, causing road grouting and collapse, causing cracking and settlement of houses, instability of dam slopes, etc. Freezing and thawing is one of the main factors that affect the safety and stability of projects in cold regions, and directly affects the safety and operation of geotechnical structures in cold regions. Therefore, the mechanical characteristics of the thawed soil under the repeated freezing and thawing of the roadbed in seasonally frozen ground need special attention and are worthy of in-depth study.

The dynamic modulus and damping ratio of soil are the two basic parameters in soil dynamics, which are the necessary dynamic parameters in the seismic safety evaluation of the engineering site, and are also essential parameters in the seismic calculation of major engineering structures[2]. Many scholars have conducted extensive researches on the dynamic modulus and damping ratio of soil, and have obtained many valuable research results[2]. For instance, Christ et al.[3] studied the variation law of dynamic modulus and damping ratio of frozen soil under different frequency and moisture content conditions. Yan et al.[4] studied the variation law of silty sand dynamic parameters under repeated freeze-thaw conditions. Wang et al.[5] studied the influence of freeze-thaw cycles on the dynamic properties of subgrade soils with different plastic indices. Wang et al.[6] studied the deformation characteristics of Qinghai-Tibet frozen silty clay under train loads. Yu et al.[7] studied the influence of the low temperature on the dynamic shear modulus and damping ratio of soil. Ma et al.[8] studied the dynamic friction angle and dynamic cohesion of subgrade silty clay under different freezing and thawing times. Yu et al.[9] studied the effect of freeze-thaw on the shear performance of saturated silty clay. He et al.[10] used the low-temperature dynamic triaxial test to study the relationship between the dynamic elastic modulus, damping ratio and vibration frequency, confining pressure, and negative temperature of the test on the Qinghai-Tibet Railway.

Other scholars[11−16] have also studied the dynamic modulus and damping ratio of seasonally frozen soils to varying degrees. However, due to the development level of the test equipment and technology, the research on the seasonal frozen soils still has the following deficiencies: (i) Most of the research results are based on the dynamic characteristics of the frozen soil, and

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First author: SUN Jing, female, born in 1973, PhD, Professor, Research interests: earthquake engineering and soil dynamics. E-mail: iemsunj@163.com
Corresponding author: GONG Mao-sheng, male, PhD, born in 1976, Professor, Research interests: earthquake engineering and earthquake disaster assessment. E-mail: gmshiem@163.com

few studies focus on the dynamics characteristics of the frozen soil after multiple freeze-thaw cycles. (ii) In the past, the confining pressure used in the dynamic triaxial test is too large, while the actual maximum depth of frozen soil is less than 10 m, which results in the in-situ ground pressure of about 100 kPa. (iii) At present, most dynamic triaxial devices need to complete the freeze-thaw cycle with the help of an external high-low temperature freeze-thaw cycle box, which has two obvious deficiencies. First, the freeze-thaw process has no confining pressure, which cannot characterize the actual soil conditions. Second, it is difficult to precisely control the impact of soil disturbance on the test results.

In this paper, the low-temperature dynamic triaxial test method is used to study the relationship between dynamic parameters of silty sand roadbed in the seasonally frozen area, such as dynamic modulus and damping ratio, and multiple freeze-thaw cycles. The normalized fitting model of dynamic modulus ratio and damping ratio is proposed, which includes a formula for calculating the correction coefficient of freezing and thawing times of initial dynamic modulus and maximum damping ratio. Part of the basic data provides a more reasonable and reliable theoretical basis for the analysis and calculation of dynamic response in actual projects in the future.

2 Test method

2.1 Test equipment

This study uses the dynamic triaxial instrument developed by the British GDS company, which is composed of a control system, a test system, and a cold bath circulation system, as shown in Fig.1. The cold bath circulation system uses Thermo Fisher's water bath circulator, which communicates with the cooling tube in the spiral pressure chamber to increase or decrease temperature. The temperature can vary within the range of −40 ℃–50 ℃, and the accuracy is 0.01 ℃. The temperature sensor arranged in the pressure chamber and the variable differential pressure sensor at the top of the soil sample can monitor and collect data in real time. The GDS dynamic triaxial instrument adopts the method of dynamic servo motor loading from below the pressure chamber to overcome the shortcomings of other products that need to complete the freeze-thaw test with the help of high and low temperature freeze-thaw boxes. Saturation, consolidation, freeze-thaw and test integration can be completed in the triaxial pressure chamber, which is more in line with the actual soil conditions, and reduces the impact of soil disturbance. The main parameters are shown in Table 1.

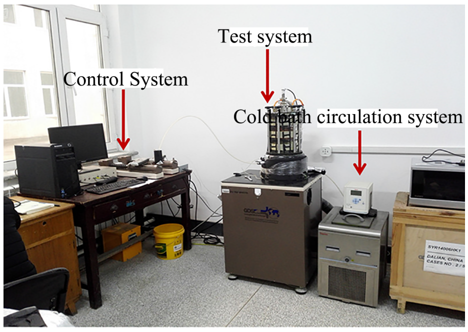


Fig.1 The adopted GDS dynamic triaxial apparatus

Table 1 Main performance parameters of the adopted GDS dynamic triaxial apparatus

Load frequency range	Control range and accuracy of pressure chamber temperature	Range and accuracy of axial force	Sample size / mm	Range and accuracy of confining pressure	Range and accuracy of displacement
0.01–2.00 , 0.01–5.00 Hz	>−30 ℃, 0.01 ℃	0–16 kN , 1 N	Φ39.1×80.0，Φ60.0×80.0	0–2 MPa , <1 kPa	100 mm , 35 μm

2.2 Sample preparation

The tested silty sand was taken from the Bacha area of Heilongjiang Province, with a natural water content of 9.88%, a compacted dry density of 1.74 g/cm^3, a maximum dry density of 1.84 g/cm^3, an uniformity coefficient of 4.66, a curvature coefficient of 1.30. It has a poorly-graded particle size distribution, shown in Fig.2.

The dried soil sample was evenly mixed with distilled water to achieve a water content of 5%. In order to ensure that the soil water content is uniform, the soil sample was infiltrated for 24 h before measuring the real-time water content. Triaxial specimens were prepared with 95% compaction degree to control dry density. After calculation, the three-valve saturation mold was used to compact it in 4 layers. Each layer has 47.55 g soil samples, and each layer was hit 30 times. The layers were shaved at the top to prevent delamination. The resulting triaxial specimen has a height of H = 80.0 mm and a diameter of D = 39.1 mm.

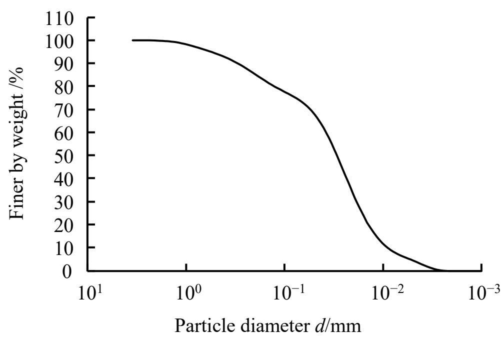


Fig.2 Particle size distribution of the tested soil

The prepared sample is filled in the triaxial pressure chamber to overcome back pressure saturation, so that the saturation reaches 90% or more. Then the confining pressure is applied and the sample is consolidated for 8 h. After the consolidation is completed, freeze at negative temperature for 12 h and melt at standard room temperature for 12 h, which is a freeze-thaw cycle. After the consolidation test is completed, the back pressure water supply valve is closed and the freeze-thaw cycle is started. During the freeze-thaw cycle, it is in a completely closed environment, that is, there is no external water supply during the freeze-thaw process. The confining pressure σ_3 of the test is 100 kPa, the frequency f is 1 Hz, and the moisture content ω is 5%. Three kinds of negative temperatures of −5, −10, and −15 ℃ are chosen, and five freeze-thaw cycles (FT) are set to be 0, 1, 3, 5, and 7. In this test, the stress-controlled stepped cyclic loading method is used to pre-add a partial stress of 10 kPa. The dynamic stress is increased by 5 kPa each level, and each level is applied for 5 cycles, 50 data points are collected in each cycle. The data collection, which is completed using the GDS automatic data collection system, stops once the sample is completely destroyed.

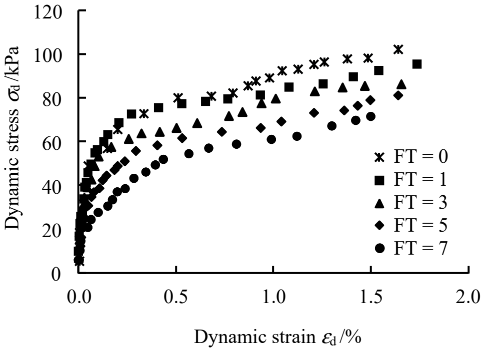
3 Analysis of test results

3.1 Dynamic stress

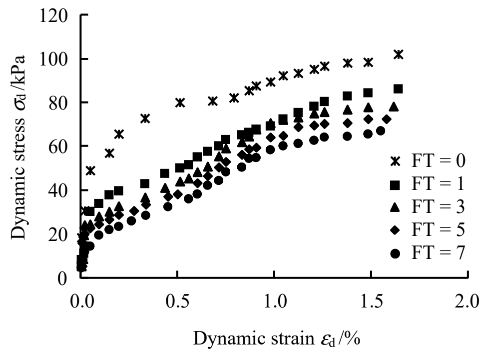
At temperatures of −5, −10, and −15 ℃, and different freezing and thawing cycles, the curves of dynamic stress σ_d versus dynamic strain ε_d after thawing are shown in Fig.3. It can be seen from the figure that at the initial of the loading, the dynamic stress at different negative temperatures increases approximately linearly with dynamic strain. In this case, the soil has obvious elastic characteristics. As the dynamic strain increases, the dynamic stress continues to increase, but the growth rate slows down, which indicates that the soil enters elastoplastic deformation stage. With the same dynamic strain, when the temperature is same, the dynamic stress is negatively correlated with the number of freeze-thaw cycles. As the number of cycles increases, the dynamic stress decreases. When the number of freeze-thaw cycles is same, the dynamic stress decreases with temperature.

3.2 Dynamic elastic modulus

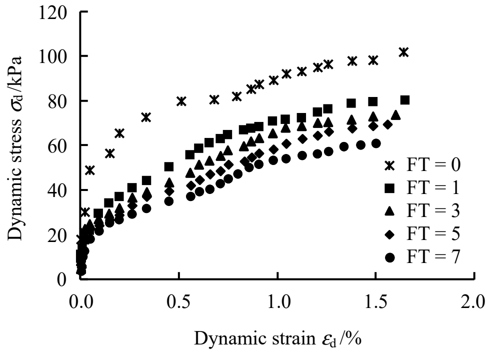
At the temperatures of −5, −10, and −15 ℃, and different freezing and thawing cycles, the relationship between the dynamic elastic modulus (hereinafter referred to as the dynamic



(a) T = −5 ℃



(b) T = −10 ℃



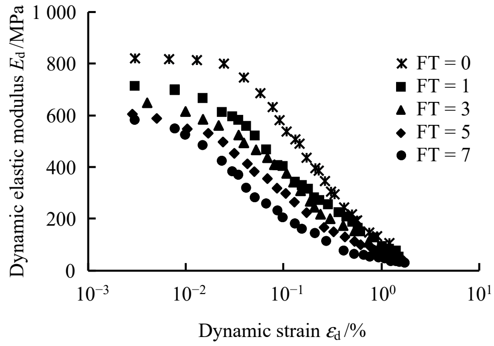
(c) T = −15 ℃

Fig.3 Curves of dynamic stress σ_d versus dynamic strain ε_d

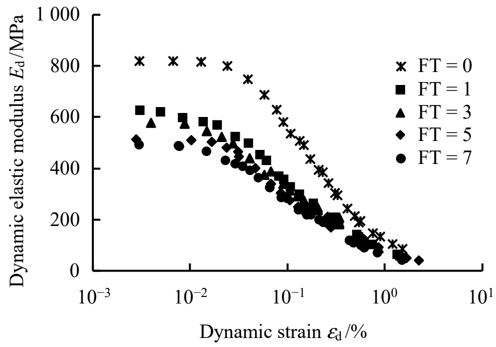
modulus) E_d and dynamic strain ε_d of the silty sand after thawing is shown in Fig.4. It can be seen from the figure that the dynamic modulus decreases slowly when the strain is small. With the continuous increase of the dynamic strain, the soil damage is intensified. The dynamic modulus decreases quasi-linearly with dynamic strain and tends to be consistent. The dynamic modulus in the test without freeze-thaw cycles is significantly higher than that in the tests with cycles. Due to the freeze-thaw effect, the pores of the soil are loosened and the microstructures are destroyed, which reduces the strength of the soil. And the effect of multiple cycles on the particle structure of the soil is gradually weakened. After 5 freeze-thaw cycles, the decrease of dynamic modulus is small, and is finally stabilized. With the same dynamic strain, when the temperature is same, the dynamic modulus is negatively correlated with the number of freeze-thaw cycles. As the number of cycles increases, the dynamic modulus decreases. When the number of freeze-thaw cycles is same, the dynamic modulus decreases with temperature.

3.3 Dynamic elastic modulus ratio

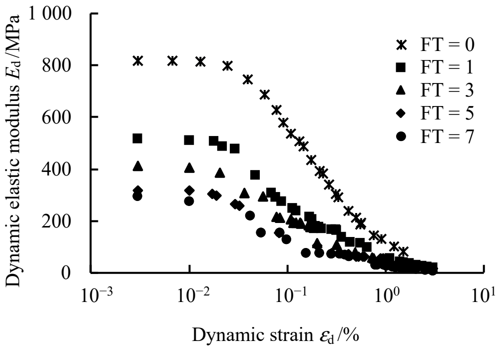
The nonlinear characteristics of the soil adopts the traditional equivalent linearization method. With different negative temperatures and different freeze-thaw cycles, the relationship between the dynamic elastic modulus ratio (hereinafter referred to as the dynamic modulus ratio) $E_d / E_{d\max}$ and the dynamic strain ε_d of the silty sand after thawing is shown in Fig.5. It can be seen that the dynamic modulus ratio decreases slowly with dynamic strain when the



(a) T = −5 ℃

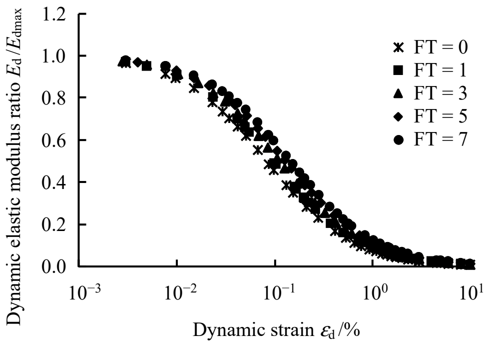


(b) T = −10 ℃

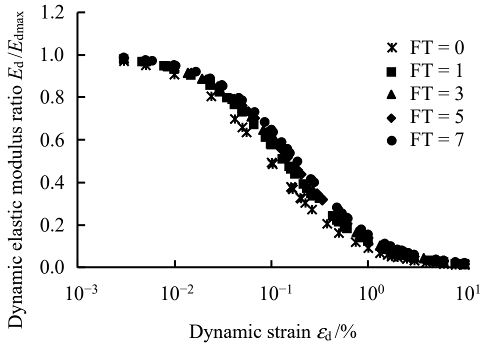


(c) T = −15 ℃

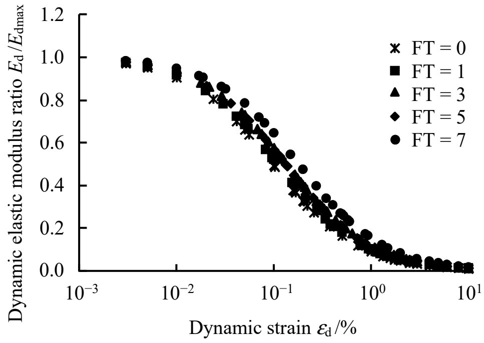
Fig.4 Curves of dynamic elastic modulus E_d versus dynamic strain in logarithmic scale lnε_d



(a) T = −5 ℃



(b) T = −10 ℃



(c) T = −15 ℃

Fig.5 Curves of dynamic modulus ratio E_d/E_{dmax} versus dynamic strain in logarithmic scale lnε_d

dynamic strain is small. As the dynamic strain continues to increase, the dynamic modulus ratio decreases significantly. When the dynamic strain reaches 10^{-2}, the dynamic modulus ratio becomes stable. With the same dynamic strain and the same negative temperature, the dynamic modulus ratio is positively correlated with the number of freeze-thaw cycles. As the number of freeze-thaw cycles increases, the dynamic modulus ratio increases.

In response to the above observations, many scholars have explored the attenuation relationship of the dynamic modulus, and obtained many equivalent calculation, such as linear viscoelastic model, elastoplastic model, nonlinear equivalent viscous model. Among them, the hyperbolic model, bilinear model, Hardin-Drnevich model and some other combined models are widely used in engineering practice. In this paper, the $E_d / E_{d\max}$ –ln ε_d curves and the test data points show good agreement, and the dispersion is small, indicating that the freeze-thaw effect has slight effect on the dynamic modulus ratio. The hyperbolic model is used to normalize the relationship between dynamic modulus ratio and dynamic strain attenuation at different negative temperatures. The fitted model is

$$\frac{E_d}{E_{d\max}} = \frac{1}{1+(\varepsilon_d / \bar{\varepsilon})^b} \tag{1}$$

where $E_{d\max}$ is the initial dynamic modulus; b is the fitting coefficient; and $\bar{\varepsilon}$ is the reference dynamic strain.

Using Equation (1) to fit the experimental data, the $\bar{\varepsilon}$ is 0.1288 and b is 0.9885. The fitting result is shown in Fig.6, with a correlation coefficient of R^2 = 0.999. It can be seen that the hyperbolic model is more suitable with better fitting result.

The normalized $E_d/E_{d\max}-\ln\varepsilon_d$ relationship is not affected by temperature and freeze-thaw cycles within this range, and has better representative and practical significance. The relationship between dynamic elastic modulus and dynamic strain can be well approximated by the formulas.

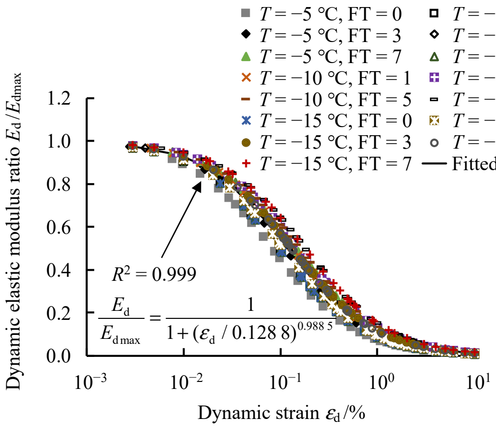


Fig.6 Normalized curves of dynamic modulus ratio $E_d/E_{d\max}$ versus dynamic strain in logarithmic scale $\ln\varepsilon_d$

3.4 Damping ratio

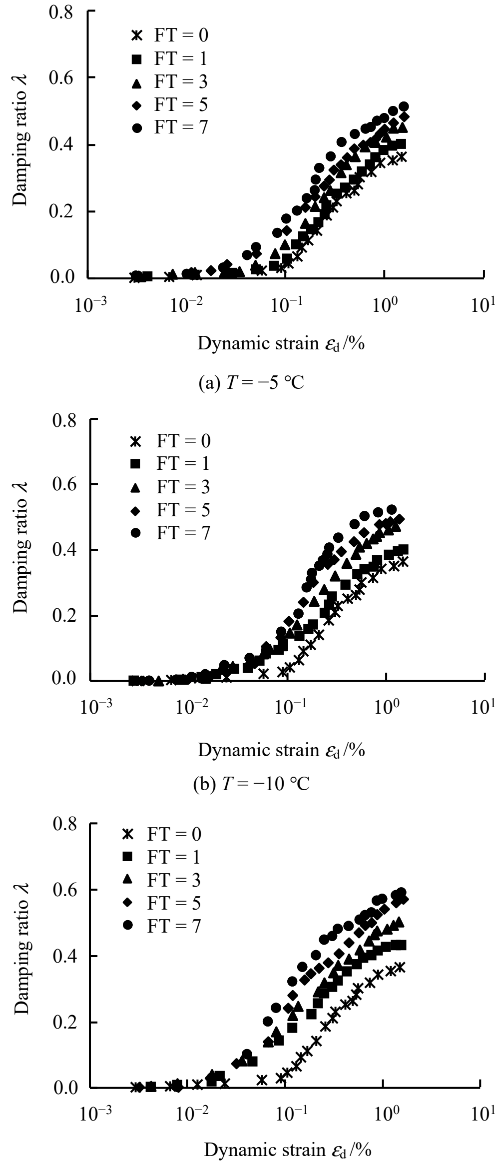
With different negative temperatures and different freeze-thaw cycles, the semi-logarithmic relationship curve between the damping ratio λ of the silty soil after thawing and the dynamic strain ε_d is shown in Fig.7. It can be seen that the damping ratio grows slowly when the dynamic strain is small, and the damping ratio increases rapidly as the dynamic strain develops. When the dynamic strain reaches 10^{-2}, the damping ratio tends to stabilize. As temperature decreases, the divergence of each curve increases, and the tests with T = −15 ℃ show the most prominent divergence, indicating that the effect of freeze-thaw on the damping ration is more significant when the temperature is low. After 5 cycles, the damping ratio does not change much and become stable. With the same dynamic strain and the same negative temperature, the damping ratio is positively correlated with the number of freeze-thaw cycles. As the number of freeze-thaw cycles increases, the damping ratio increases.

Because the damping ratio obtained by the experiment is relatively divergent and the changing characteristics are complex, the fitting with the Davidenkov model and the Hardin-Drnevich model is not satisfactory. Therefore, the exponential function is used for normalized fitting, which yields better results than the hyperbolic model. The fitted model is

$$\lambda = \eta\,\mathrm{e}^{(-\varepsilon_d/\bar{\varepsilon}_\lambda)} + \lambda_0 \tag{2}$$

where $\bar{\varepsilon}_\lambda$ is the reference dynamic strain; η and λ_0 are the fitting coefficients.

Fit the experimental data with the help of formula (2), and the parameters $\eta = -0.4914$, $\bar{\varepsilon}_\lambda = 0.3512$, $\lambda_0 = 0.4993$ can be obtained. The fitting results are shown in Fig.8, with a correlation coefficient of R^2 = 0.999. It can be seen from the figure that the data points of the damping ratio are evenly



(a) T = −5 ℃

(b) T = −10 ℃

(c) T = −15 ℃

Fig.7 Curves of damping ratio λ versus dynamic strain in logarithmic scale $\ln\varepsilon_d$

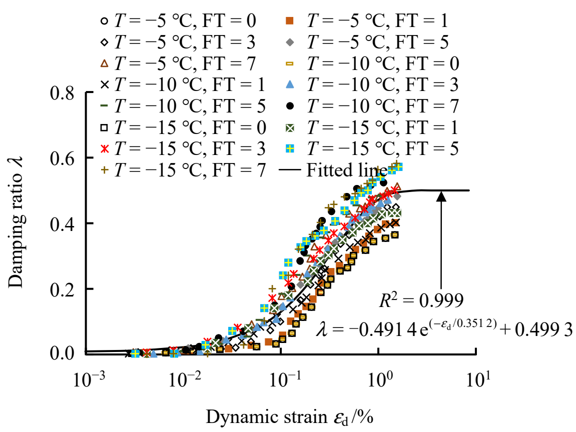


Fig.8 Normalized curves of damping ratio λ versus dynamic strain in logarithmic scale $\ln\varepsilon_d$

distributed on both sides of the fitting curve There is no clear boundary between different temperatures, but the upper and lower boundaries are the damping ratio curves of temperature −15 ℃, The damping ratio increases with the dynamic strain. After normalization the relationship is within this range, which is not affected by negative temperature and freeze-thaw cycles. This relationship is more general and easy to use. The damping ratio corresponding to any dynamic strain can be approximated by the formula.

4 Freeze-thaw times correction curve

In order to study the influence of freezing and thawing times on the initial dynamic elastic modulus (hereinafter referred to as initial dynamic modulus) of melted soil and the maximum damping ratio, the concept of the correction coefficient of freezing and thawing times is proposed. In this paper, soils completely melt to room temperature after freeze-thaw cycles. By multiplying the dynamic modulus and damping ratio at room temperature by a correction factor, the initial dynamic modulus and maximum damping ratio can be obtained with given freeze-thaw cycles and temperatures:

$$E'_{\mathrm{d\,max}} = \beta E_{\mathrm{d\,max\,0}} \tag{3}$$

$$\lambda'_{\max} = \alpha \lambda_{\max 0} \tag{4}$$

where β and α are the correction coefficients of freeze-thaw cycles for initial dynamic modulus and maximum damping ratio, respectively; $E'_{\mathrm{d\,max}}$ and $\lambda'_{\max}$ are the initial dynamic modulus and maximum damping ratio for different freeze-thaw cycles, respectively; $E_{\mathrm{d\,max\,0}}$ and $\lambda_{\max 0}$ are the initial dynamic modulus and maximum damping ratio for zero freeze-thaw cycles, respectively.

4.1 Initial dynamic elastic modulus

According to the test data, the initial dynamic modulus is derived using the $1/E_{\mathrm{d}}$– ε_{d} curve. Because of the linear relationship, when $\varepsilon_{\mathrm{d}} = 0$, the ordinate axis intercept is $1/E_{\mathrm{d\,max}}$. Therefore, $E_{\mathrm{d\,max}}$ under different freezing and thawing times are obtained. At the same time, under negative temperature, the initial dynamic modulus is slowly extended by increasing the number of freeze-thaw cycles, and it is basically stable after 5 cycles; with the same number of freeze-thaw cycles, the initial dynamic modulus decreases with temperature. When the temperature is −5 ℃, −10 ℃ and −15 ℃, the initial dynamic modulus of 7 cycles is reduced by 28.23%, 38.99% and 63.03%, respectively compared with zero cycles, indicating that the freeze-thaw cycle has more significant effect on modulus at low temperature.

Through the comparative analysis of the models, the hyperbolic model is used to fit the regression coefficients of the freezing and thawing times of the initial dynamic modulus for the three groups. The fitting degree is relatively high. The fitting model is expressed by

$$\beta = \frac{1}{1+\left(n/\gamma_n\right)^{\chi}} \tag{5}$$

where n is the number of freeze-thaw cycles; γ_n and χ are the parameters related to the number of freeze-thaw cycles.

Through data fitting, the relationship between the number of freeze-thaw cycles n and the correction coefficient β of the initial dynamic modulus at different negative temperatures is obtained, as shown in Fig.9. It can be seen from the figure that at the same temperature, as the number of freeze-thaw cycles increases, the correction coefficient β decreases. The decrease from 0 to 5 cycles is rapid, but it tends to be gentle after 5 times. With the same number freeze-thaw cycles, as the temperature decreases, the correction coefficient β becomes small. It shows that the lower the temperature, the more significant the effect of freeze-thaw cycles on the correction coefficient, and the correction coefficient β at T = −15 ℃ decreases most rapidly.

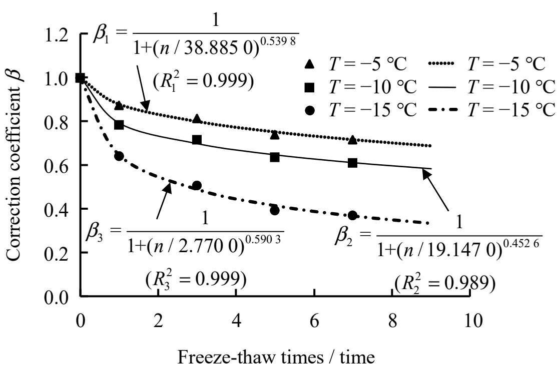


Fig.9 Correction curves of n–β for initial dynamic elastic modulus

When the temperature is constant, the freezing will cause the soil to freeze and expand. The particles will be redistributed, and the microstructure will change. Melting increases the porosity of the soil, weakens the adhesion between the soil particles, destroys the microstructure, increases the local moisture content, and reduces the strength. As a result, the soil mass macroscopically exhibits to be soft and thawed, and the dynamic modulus decreases. As the number of freeze-thaw cycles increases to 5, the soil forms a new balance. So the curve first falls and then stabilizes. When the number of freeze-thaw cycles is fixed, the lower the negative temperature is, the higher the ice content of the soil has, and the greater the ice binding force between the particles is. Macroscopically, the larger the soil frost heave volume is, the higher the strength is. Therefore, after the melting, the porosity ratio of the soil is also larger, and the original skeleton structure is also damaged more seriously, causing the curve to decline significantly.

4.2 The maximum damping ratio

Based on the test data, the measured damping ratios at different negative temperatures and freezing and thawing times are exponentially fitted and regressed to obtain the corresponding maximum damping ratio $\lambda_{\max}$. The comparison results show that at the same temperature, as the number of freeze-thaw cycles increases, the maximum damping ratio increases slowly; with the same freeze-thaw cycles, the lower the temperature is, the greater the maximum damping ratio is. When the temperature is −5 ℃, −10 ℃, and −15 ℃, the maximum damping ratios of 7 cycles increase by 34.82%, 40.12%, and 55.21%, respectively compared with zero cycles, indicating that the lower the temperature is, the more obvious effect of freeze-thaw cycles on the maximum damping ratio has.

After analysis and comparison, it is found that the maximum damping ratio obtained under different freezing and thawing times is regressed with an exponential function, and the fitting degree is the highest. The fitted model is

$$\alpha = \eta_n \mathrm{e}^{(n/\gamma_n)} + \mu_0 \tag{6}$$

where η_n and μ_n are the parameters related to the number of freeze-thaw cycles.

Through data fitting, the relationship between the number of freeze-thaw cycles n and the correction coefficient α with the maximum damping ratio at different temperatures is obtained, as shown in Fig.10. As can be seen from the figure, at the same negative temperature, as the number of freeze-thaw cycles increases, the correction coefficient α gradually increases. After 5 cycles, the effect of freeze-thaw weakens and α eventually stabilizes. With the same number of freeze-thaw cycles, as the temperature decreases, the correction coefficient α becomes larger. It shows that the lower the temperature is, the more significant the effect of the freeze-thaw cycle on the correction coefficient α has. The increase of the correction coefficient α is more significant when $T = -15$ ℃.

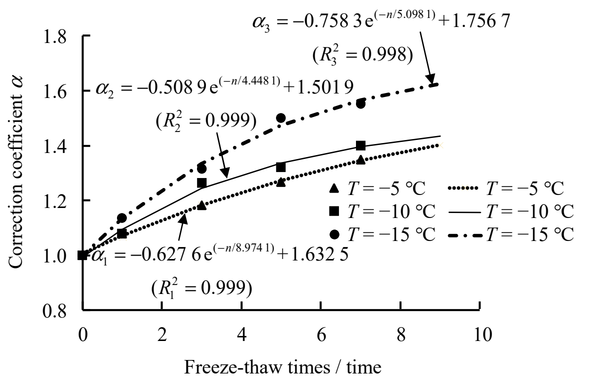


Fig.10 Correction curves of n–α for maximum damping ratio

The damping ratio is a parameter that characterizes the energy consumption of the soil. The difference between before and after freezing and thawing at different temperatures is due to the changes of microstructure and pore channels of the soil. The number of freezing and thawing increases, the soil structure becomes loose, the porosity ratio increases, and the dynamic wave propagation path decreases and the energy consumption increases, so the maximum damping ratio increases. It shows that the dual effects of the periodic cycle of freezing and thawing and the continuous decrease of temperature cause the microstructure of melted silty sand to be destroyed, which results in a reduction in the rigidity, an increase in the plasticity, the soil becoming soft. As a result, the energy consumption of the dynamic wave generated by the cyclic dynamic load is increased, so that the damping ratio of the soil is increased. But after more than 5 cycles, the effect is slight.

5 Comparison of results

With the action of freezing and thawing, there are few experimental studies on the dynamic triaxial thawing of frozen soil when it is melted to room temperature. Yan et al.[4] used dynamic triaxial tests to study the effect of repeated freeze-thaw on the dynamic parameters of silty sand in the Qinghai-Tibet region. Compared with the results of the freeze-thaw cycle test at −15 ℃ in this paper, it is found that under the same dynamic strain, as the number of freeze-thaw cycles increases, the dynamic stress and dynamic modulus decrease, the damping ratio increases, and the curve change trend is similar to the results in this paper. Qualitative results are consistent. Due to different soil properties, the overall dynamic stress is slightly higher than the dynamic stress in this paper. In Yan et al. paper, an in-vitro high and low temperature test chamber was used for the freeze-thaw cycle. Only the effects of the freeze-thaw cycle on the dynamic modulus and damping ratio were studied, and no quantitative analysis results were given.

Wang et al.[5] conducted a triaxial test on the dynamic characteristics of roadbed soils with three types of plastic index in seasonal frozen areas. The test results show that the dynamic modulus decreases with the increase of the number of freeze-thaw cycles. The dynamic modulus tends to stabilize after 6–7 freeze-thaw cycles, which is similar to the result of basic stability after 5 cycles in this paper. Due to the different plastic indexes and types of soil, the dynamic modulus of melted soil is slightly smaller than the experimental results in this paper. In the experiment in Wang et al. paper, an in-vitro high and low temperature test chamber was also used for freezing and thawing cycles, and no study was made on the dynamic modulus ratio, initial dynamic modulus and maximum damping ratio.

6 Conclusions

The freeze-thaw cycle has a great influence on dynamic stress and dynamic modulus. With the same dynamic strain, the dynamic stress and dynamic modulus are negatively correlated with the freeze-thaw cycle. As the number of freeze-thaw cycles increases, both the dynamic stress and the dynamic modulus decrease. The first 5 freeze-thaw cycles show a significant decrease, and after 5 times it becomes relatively stable.

The freeze-thaw cycles only have slight influence on the dynamic modulus ratio and damping ratio. With the same dynamic strain, the dynamic modulus ratio and damping ratio are positively correlated with the freeze-thaw cycle. As the number of freeze-thaw cycles increases, both the dynamic modulus ratio and damping ratio increase. Through regression analysis, normalized fitting models for the relationship between dynamic modulus ratio and dynamic strain, and the relationship between damping ratio and dynamic strain are proposed.

The freeze-thaw cycle has a significant effect on the initial dynamic modulus. With the same dynamic strain, as the number of freeze-thaw cycles increases, the initial dynamic modulus first decreases and then becomes stable after 5 cycles. The equation of the correction coefficient of the initial dynamic modulus freezing and thawing times under different temperatures is proposed. The results show that the correction coefficient decreases as the temperature decreases and the freezing and thawing times increase, and the correction coefficient finally stabilizes.

The freeze-thaw cycle has a significant effect on the maximum damping ratio. With the same dynamic strain, as the number of freeze-thaw cycles increases, the maximum damping ratio increases. The equation for calculating the correction coefficient of the number of freeze-thaw cycles for maximum damping ratio at different temperatures is proposed. The results show that the correction coefficient increases slowly as the temperature decreases and the number of freeze-thaw cycles increases, and then gradually stabilizes.

The lower the temperature is, the more obvious the effect of freeze-thaw cycles on the dynamic characteristics of silty soil is. The dynamic parameters after 5 freeze-thaw cycles are relatively stable. It is recommended to use the dynamic parameters after 5 freeze-thaw cycles as basic parameters for dynamic response analysis and calculation.

References

[1] ZHOU You-wu, GUO Dong-xin, QIU Guo-qing, et al. Chinese frozen soil[M]. Seismic Zoning, Beijing Science Press, 2000.

[2] SUN Jing, XIONG Hong-qiang, GONG Mao-sheng, et al. Study on the influence of nonlinear characteristics of dynamic shear modulus of soil on surface ground motion[J]. Earthquake Engineering and Engineering Vibration, 2018, 28(2): 28–34.

[3] CHRIST M, KIM Y C, PARK J B. The influence of temperature and cycles on acoustic and mechanical properties of frozen soils[J]. KSCE Journal of Civil Engineering, 2009, 13(3): 153–159.

[4] YAN Han, WANG Tian-liang, LIU Jian-kun, et al. Experimental study of dynamic parameters of silty soil subjected to repeated freeze-thaw[J]. Rock and Soil Mechanics, 2014, 35(3): 863–688.

[5] WANG Jing, LIU Han-bing, WU Chun-li, et al. Influence of freeze-thaw cycles on dynamic characteristics of subgrade soils with different plasticity indices[J]. Chinese Journal of Geotechnical Engineering, 2014(4): 633–639.

[6] WANG li-na, LING Xian-zhang, LI Qiong-lin, et al. Experimental analyses of train induced deformation behavior of frozen silt clay[J]. China Civil Engineering Journal, 2012, 45(Suppl.1): 42–47.

[7] YU Xiao-bo, SUN Rui, YUAN Xiao-ming, et al. Influence of negative temperature on dynamic shear modulus and damping ratio of soil[J]. Chinese Journal of Rock Mechanics and Engineering, 2016, 35(7): 1452–1465.

[8] MA Yu-tao, CUI Hong-huan, LIU Jian-kun, et al. Study on dynamic behavior of subgrade silty clays under freeze-thaw cycles[J]. Low temperature architecture technology, 2017, 39(1): 81–85.

[9] YU Lin-lin, XU Xue-yan, QIU Ming-guo, et al. Influnce of freeze-thaw on shear strength properties of saturated silty clay[J]. Rock and Soil Mechanics, 2010, 31(8): 2448–2452.

[10] HE Fei, WANG Xu, LIU De-ren, et al. Experimental study on dynamic characteristic parameters of undisturbed frozen sandy soil of modulus of remolded frozen silty clay for Qinghai-Tibet Rawilay[J]. Journal of the china railway society, 2017, 39(6): 112−117.

[11] LING Xian-zhang, WANG Zi-yu, ZHANG Feng, et al. Experimental investigation on dynamic shear modulus of frozen clay from subgrade of Beijing-Harbin Railway[J]. Chinese Journal of Geotechnical Engineering, 2013, 35(Suppl.2): 38–43.

[12] WANG Jun, CAI Yuan-qiang, DING Guang-ya, et al. Experimental research on changing rules of dynamic modulus and damping ratio of saturated soft clay under bidirectional exciting cyclic loading[J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(2): 423–432.

[13] Mona El Mosallamy, Tarek Abd El Fattah, Mohammed El Khouly. Experimental Study on the Determination of Small Strain-Shear Modulus of Loess Soil[J]. HBRC Journal, 2014, 35: 1−10.

[14] Bo Lin, Feng Zhang, Decheng Feng, et al. Dynamic shear modulus and damping ratio of thawed saturated clay under long-term cyclic loading[J]. Cold Regions Science and Technology, 2018, 145: 93−105.

[15] WANG Li-xia, HU Qing-li, LING Xian-zhang, et al. Experimental study on dynamic shear modulus of remolded frozen silty clay for Qinghai-Xizang Railway[J]. Earthquake Engineering and Engineering Vibration, 2007, 27(2): 177−180.

[16] XU Yang, ZHU Zhan-yuan. Experimental study on dynamic characteristics of silty clay in permafrost subgrade[J]. Shanxi Architecture, 2014, 40(9): 39–42.

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