J. Cent. South Univ. (2020) 27: 2113−2122
DOI: https://doi.org/10.1007/s11771-020-4434-7

Springer

Evaluation of dynamic characteristics of silt in Yellow River Flood Field after freeze-thaw cycles

JIN Qing(金青)[1], ZHENG Ying-jie(郑英杰)[1], CUI Xin-zhuang(崔新壮)[1],
CUI She-qiang(崔社强)[2], QI Hui(齐辉)[3], ZHANG Xiao-ning(张小宁)[1], WANG Shuai(王帅)[1]

1. School of Civil Engineering, Shandong University, Ji’nan 250061, China;
2. Department of Civil and Environmental Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong;
3. Qilu Transportation Development Group, Ji’nan 250101, China

Abstract: Frothing is a main disease of highways in Yellow River Flood Field, due to the loss of dynamic strength of roadbed soils under the couple effects of temperature, salt, and vehicle traffic load. This is strongly linked to the dynamic characteristics of silt in this region. To analyze these couple effects on the dynamic characteristics of silt, a series of tests (i.e., freeze-thaw cycling tests, vibration triaxial tests and ultrasonic wave velocity tests) were conducted and two kinds of silt (i.e., salt-free and 3%-salt silt) were designed. The results indicate that the dynamic shear strength and dynamic modulus decrease with increasing freeze-thaw cycles, while the damping ratio simultaneously increases. Furthermore, compared to salt-free silt, the decrement of dynamic shear strength and dynamic modulus of silt with 3% salt is more significant, but the damping ratio of 3%-salt silt is larger. In ultrasonic wave velocity tests, ultrasonic wave velocity of frozen soil specimens decreases as the number of freeze-thaw cycles increases. Based on the results of ultrasonic wave velocity tests, a preliminary model is proposed to evaluate damage of silt through field measurement ultrasonic data. The study could provide a theoretical basis for the treatment of silty soil highway.

Key words: silt of Yellow River Flood Field; dynamic triaxial; soil dynamic characteristic; ultrasonic wave velocity

Cite this article as: JIN Qing, ZHENG Ying-jie, CUI Xin-zhuang, CUI She-qiang, QI Hui, ZHANG Xiao-ning, WANG Shuai. Evaluation of dynamic characteristics of silt in Yellow River Flood Field after freeze-thaw cycles [J]. Journal of Central South University, 2020, 27(7): 2113−2122. DOI: https://doi.org/10.1007/s11771-020-4434-7.

1 Introduction

As the Yellow River diversion frequently happens in Chinese history, the Yellow River Delta is newly formed covering a large area. Through the Loess Plateau, the Yellow River carries and brings about deposit sediments into the Bohai Sea. Subsequently, more deposit sediments accumulated at the estuary when the water velocity slowed down. Thus, the Yellow River Delta was gradually formed during this process. As the delta was developed under consolidated deposit, the soil is well-known as alluvial silt, and it owns some unique characteristics, such as small cohesion, low liquid limit and plastic index, intensive capillarity and poor graduation and water stability. These features illustrate that the alluvial silt is a kind of liquefiable soil.

In recent years, with the development of transportation in Yellow River Flood Field, frothing has been a common disease in this area, which is

---

Foundation item: Project(2018YFB1600100) supported by the National Key Research and Development Project of China; Projects(51778346, 51508310) supported by the National Natural Science Foundation of China; Project(2019GSF111007) supported by Key Research and Development Project of Shandong Province, China
Received date: 2020-05-29; **Accepted date:** 2020-06-23

Corresponding author: CUI Xin-zhuang, PhD, Professor; E-mail: cuixz@sdu.edu.cn; ORCID: 0000-0003-1501-3931.

due to the loss of dynamic strength of silt subgrade under freeze-thaw cycling. In view of the dynamic characteristics of non-cohesive soil, many scholars from all over the world have done a lot of research work. IZARLING [1] studied the influence of secondary consolidation time on the properties of silt. It seemed that the internal angle of friction and pore structure of silt were related to secondary consolidation time. XU et al [2] systematically analyzed the dynamic deformation characteristics of silt before and after liquefaction by using discrete element method (CFD-DEM). FINN et al [3] revealed the mechanism of the periodic variation of pore pressure in saturated sands, and proposed the models for calculating interstitial pressure. LIU et al [4, 5] studied the deformation law of saturated silt after liquefaction. YE et al [6] found that the excess internal friction angle of Hangzhou silt is smaller than that of dynamic strength index. In addition, the impact of cycles of freezing and thawing on the mechanical and physical properties of soils has been investigated in many previous studies [7−9]. The freeze-thaw effect always happens in the permafrost region because of the daily, and multi-annual variations changes in temperature, especially in regions of high latitudes and altitudes [10]. When the water inside soil freezes, the soil volume expands, and hence the soil microstructure is changed during the freezing process and physical and mechanical natures of those soils are also altered [11−15]. Furthermore, VIKLANDER [16] considers that the change of void ratio with cycles of freezing and thawing of two different compactness soil samples is studied, and that the void ratio tends to be stable at a certain number of cycles of freezing and thawing. ZHANG [17] studied the liquefaction resistance of natural Mabel Creek silt in Alaska, and evaluated the influence of cycles of freezing and thawing on dynamic elastic modulus and damping coefficient. The conclusion was that the dynamic elastic modulus of thawed soil rose along with the cycles of freezing and thawing. In the above literatures, their studies mainly focus on the freeze-thaw effects in clay and rocks. However, there is no research on dynamic properties of saline silt after freeze-thaw cycling, and the corresponding dynamic performance evolution model has not been established.

In addition, Yellow River Flood Field of Shandong Province is a seasonally frozen area with a relatively thick silt layer on the surface. The groundwater level in the area is shallow and the concentration of salt in the water is high. Due to the capillary action of the silt, salinization is widespread and contributes to frothing in this area. There are also many previous studies about influence of salt on the properties of soils. BETTENAY et al [18] and others visited Belka Valley in Western Australia and explored the relationship between soil salinization and dynamic cycle of water. With more researches about frozen soil conducted, some scholars combined saline soil with frozen soil, and considered the changes of salt heave and frost heave during freezing process. NIXON [19] and WIJEWEERA and JOSHI [20] studied the strength and creep characteristics of fine-grained saline soil during freezing process through laboratory experiments. The relationship between deformation and strength of saline soil under freezing condition was analyzed. At the same time, some scholars, such as GHASSEMI et al [21], summarized the relationship between saline soil and water resources, and made a case study of the relevant governance activities. In the 21st century, more and more scholars began to study saline soil, including indoor simulation tests and related models. MAO et al [22] studied the variation of soil properties (i.e., salt content) in a Robinia pseudoacacia vegetation and coastal eco-restoration over one year. DOBROVOL'SKII and STASYUK [23] put forward some mechanical indexes used in pavement design and construction, based on the state of water and heat in the transport of saline soil. Therefore, it is concluded that salt has an important influence on roadbed diseases. However, the effect of salt on dynamic characteristics of roadbed silt in Yellow River flooding area after freeze-thaw has not been revealed. It is significant to study the impact imposed by salt on the dynamic natures of roadbed silt.

Nowadays, using ultrasound testing method to study mechanical properties of soils has gradually become a hotspot. Ultrasound testing is very convenient in non-destructive testing of mechanical properties of frozen soil, which reduces the testing workload [24, 25]. In this paper, to study the dynamic characteristics of silt after freeze-thaw cycling, a series of tests (i.e., freeze-thaw cycling tests and vibration triaxial tests) were conducted, with considering the salt content and number of freeze-thaw cycles. This study mainly targeted at discovering whether the dynamic shear strength, dynamic modulus and damping coefficient of silt in Yellow River Flood Field was influenced by cycles of freeze-thaw and salt, and also quantifying the damage of silt after cycles of freezing and thawing by detecting ultrasonic wave velocities.

2 Test

2.1 Materials

This study sampled the soil from the working section of Dongying expressway, and the subsoil in this area is featured by the low liquid limit silt and geomechanical parameters are shown in Table 1. And the gradation of soil samples is shown in Figure 1.

Table 1 Geomechanical parameters of subsoil

Soil layer/m	Liquid limit/%	Plastic index/%	Moisture content/%	Porosity/%
0−0.6	25	7.4	17.6	0.602
0.6−10	27	9.8	18.9	0.603

Saturation	Effective cohesion/kPa	Effective friction angle/(°)	Compression modulus/MPa
0.78	31.8	22.9	7.45
1.00	26.6	20.5	15.86

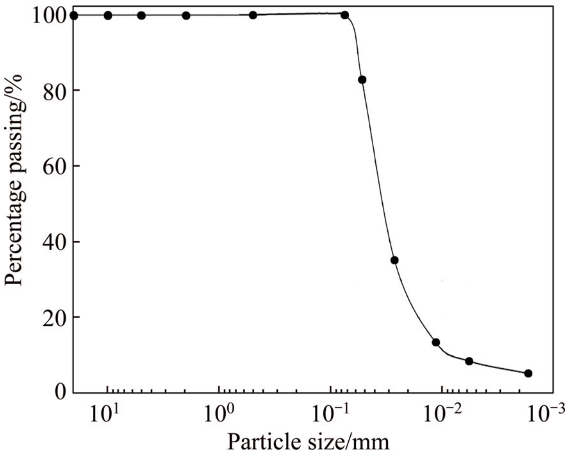

Figure 1 Particle size distribution of soil

The silt in this area originally contains a certain amount of salt, and the content is shown in Table 2. The relationship between the water content and dry density of the soil is presented in Figure 2. In order to obtain salt-free silt, these salts are washed out by using distilled water. After being dried, these salt-free silt samples were prepared with aqua destillata to reach the optimum moisture content of 18.2% corresponding to the dry density of 1.64 g/cm^3 [26], and then remolded to form a dynamic triaxial experiment specimen by being compacted in four layers with eight times for each layer. The sample is shaped cylindrically by using the compacting apparatus, shown in Figure 3. All the silt samples were cylinders with a diameter of 3.91 cm and a height of 8 cm. Finally, the prepared silt samples were immersed in distilled water and vacuum continuously for 2 h to saturate it.

Table 2 Mineral components of soil (mass fraction, %)

SiO_2	Fe_2O_3	Al_2O_3	TiO_2	CaO	MgO
73.18	6.48	11.19	0.74	0.57	0.48

K_2O	Na_2O	P_2O_3	SO_3	Organic materials
1.43	0.71	0.02	0.02	5.18

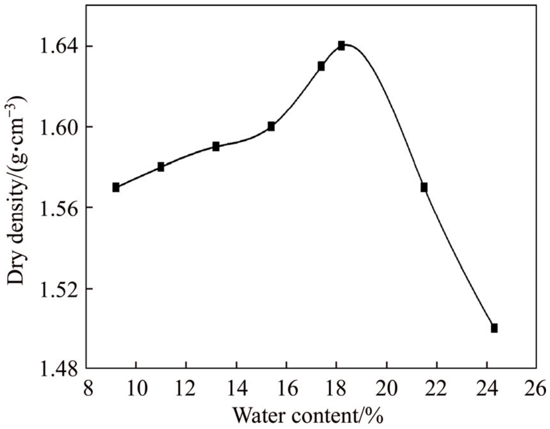

Figure 2 Relationship between water content and dry density of soil

Figure 3 Photo of compacting apparatus

2.2 Freeze-thaw cycling tests

In this study, sodium chloride was selected as the salt of silt samples, as most of the salts causing the salinization of silt in the Yellow River flooding area are chloride salts. The salt content in this test was defined as the ratio of salt mass to soil mass, and it is up to 3% based on the saline soil engineering classification in Technical Guideline for Highway Design and Construction in the Saline Soil Regions. To simulate the freeze-thawing of silt in Yellow River flooding area, the specimens were under the lowest temperature −10 °C for 24 h, and then were kept at the highest temperature at 5 °C for another 24 h. The freeze-thaw cycles were conducted in the constant temperature freezer.

Programmer of freeze-thaw tests were summarized in details in Table 3. Two kinds of silt samples (i.e., salt-free silt and silt with 3% salt) were prepared and five types of freeze-thaw cycles (i.e., 0, 1, 2, 4 and 6) were selected. In general, 5 groups of tests were conducted, with 9 specimens in each group.

Table 3 Test cases

Number of freeze-thaw cycles	Number of tested specimens	Salt content of silt specimen/%
0	9	0, 3
1	9	0, 3
2	9	0, 3
4	9	0, 3
6	9	0, 3

2.3 Vibration triaxial tests

The vibration triaxial tests were conducted through DDS-70 testing system, as shown in Figure 4. In the test, a sine function with a given frequency (i.e., f=1 Hz) was used for a fixed number of loading cycles (e.g., N=1000). The stress amplitudes are σ_3=50 kPa and σ_1=75 kPa, while the consolidation ratio K_c is 1.5. In our studies, the σ_1= 75 kPa was selected to simulate the pressure on the soil blow the 3 m of pavement surface. Also, based on the characteristics of the tested silt (i.e., softness and saturation), the coefficient of earth pressure at rest was 2/3. Therefore, σ_3 was calculated as 50 kPa. Furthermore, the failure strain ε_d is set to 5% based on the Test Methods of Soils for Highway Engineering (JTG E40-2007). The loading pattern and process are shown in Figure 4. And the typical axial strain−time history curve is shown in Figure 5.

The empirical data are acquired by an automatic data collection system matched with a dynamic triaxial apparatus, including the number of loading cycles, dynamic shear strength, dynamic modulus and damping ratio.

2.4 Data processing

As the failure strain is set to 5% in our test, the dynamic shear strength is the shear stress when axial strain is up to 5%. Furthermore, a total of 45 soil specimens were prepared and they were divided into 5 groups according to the number of cycles of freezing and thawing. Thus, each group included 9 soil specimens, and then they were tested to obtain the dynamic shear strength under 1000, 500 and 1 loading cycles, respectively.

The modulus is obtained from the tested hysteretic curve, as shown in Figure 7. ε_d is the ratio of axial strain and height of soil specimens. The slope of the line between the end of the hysteretic ellipse and the center is defined as the dynamic modulus. Therefore, the dynamic elastic modulus under different testing conditions can be obtained according to the different tested hysteretic curves.

2.5 Ultrasonic wave velocity test

The ultrasonic testing technique recently has been applied in many engineering projects, such as estimating the performance of hot-mix asphalt [27] and controlling the quality of asphalt pavement

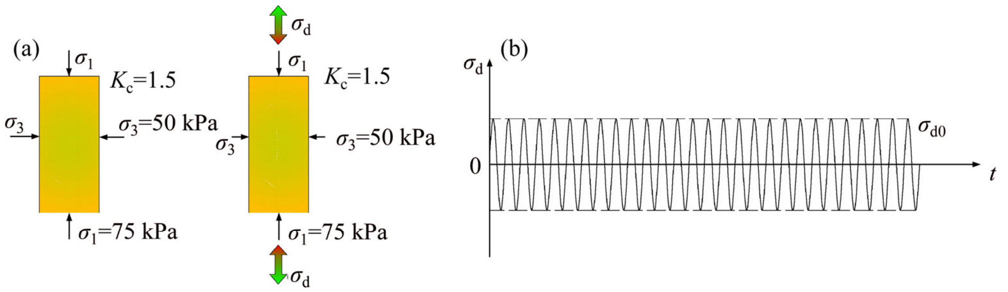

Figure 4 Process (a) and typical loading pattern (b) in test

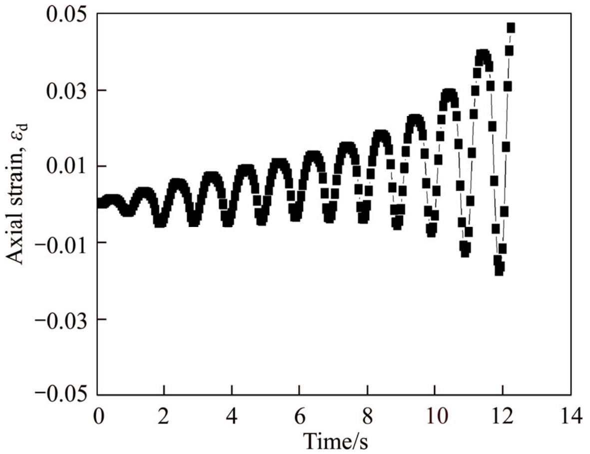

Figure 5 Typical axial strain−time history curve in vibration triaxial tests

Figure 6 Photo of DDS-70 testing system

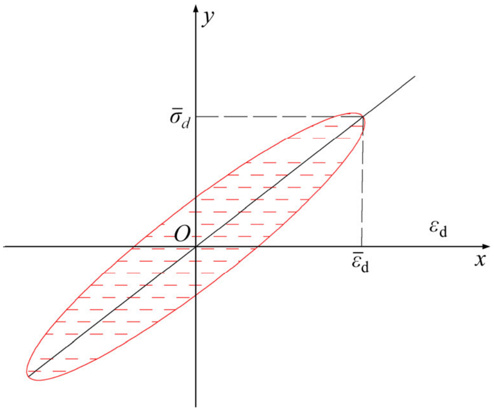

Figure 7 Typical σ_d–ε_d curves in test

construction [28]. The results in these applications indicated that ultrasonic testing technique can satisfy the requirements of many testing condition. Therefore, the ultrasonic testing technique is used in this paper to characterize damage of silt after the cycles of freezing and thawing.

In the test, the ultrasonic wave velocities of silt after the cycling of freezing and thawing were measured with a ZBL-U520/510 tester. The testing process was conducted under the temperature of −10 °C in a refrigerator.

3 Results and discussion

3.1 Mechanical properties of silt samples after freeze-thaw cycling

3.1.1 Dynamic shear strength

Figure 8 demonstrates the change curves of dynamic shear strength (i.e., τ) with the number of loading cycles. It seems that the dynamic shear strength of salt-free silt sharply decreases with number of loading cycles, while that of silt with 3% salt have a slight decrement with loading cycles. For salt-free silt, the reduction in dynamic shear strength after cyclic loading is 34.7% at most (in case of 1000 loading cycles and 6 cycles of freezing and thawing); meanwhile, the maximum value for silt with 3% salt is 19.8%. It agrees that the damage of free-salt silt evolves quickly, while that of silt with 3% salt happens slowly. Compared with salt-free silt, it is seen that cyclic loading has a poor influence on silt with 3% salt.

Figure 9 shows the relationship between the

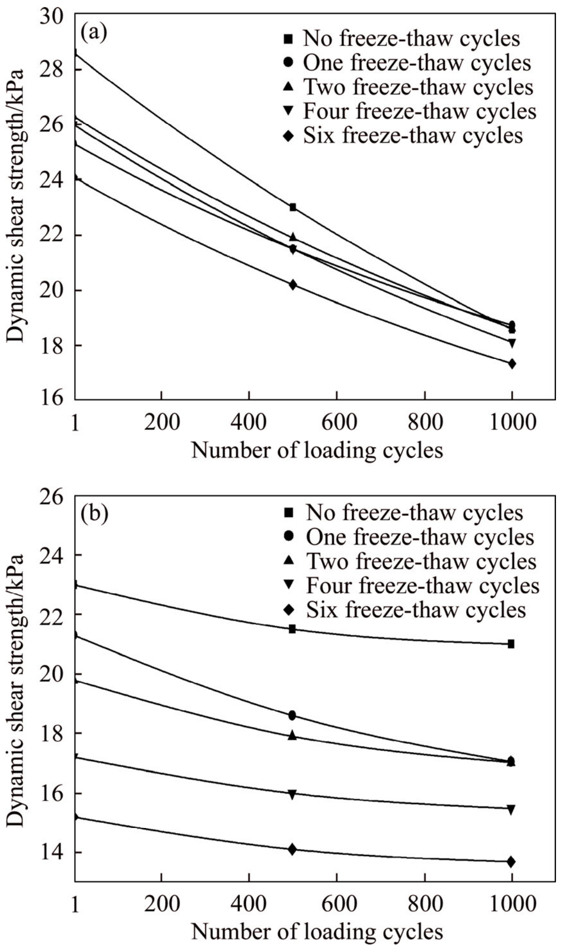

Figure 8 Change curves of τ with number of loading cycles: (a) Salt-free silt; (b) Silt with 3% salt

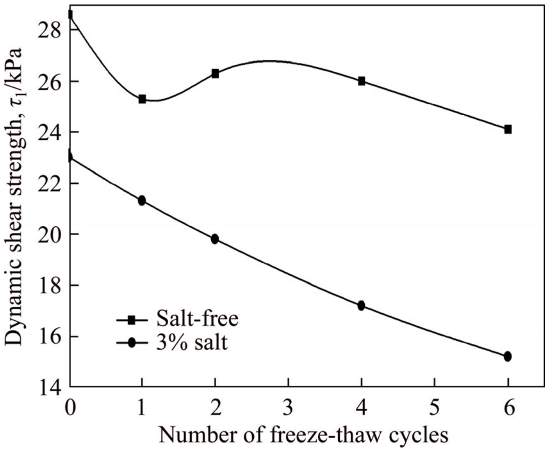

Figure 9 Change curves of τ_1 with number of freeze-thaw cycles

dynamic shear strength (i.e., τ_1) under one loading cycle and the number of cycles of freezing and thawing. It is seen that the initial dynamic shear strength decreases with the number of cycles of freezing and thawing. For salt-free silt, the initial dynamic shear strength after six cycles of freezing and thawing is reduced by 15.7%, while that of silt with 3% salt is 33.9% lower than the value after six cycles of freezing and thawing. This may be due to that during freeze-thaw cycling, the structures of silt samples have been changed by frost heaving, which results in the enlargement of spacing between particles, and the reduction of contact areas between particles. Therefore, the contact between particles becomes poor, which leads to the decline of the dynamic shear strength of silt.

In addition, there is an increase of dynamic shear strength for salt-free silt after two cycles of freezing and thawing. This may be due to the rearrangement of most particles after the secondary freeze-thaw cycle and the larger contact areas between soil particles. This phenomenon is probably related to the changes in the microstructure of soil specimens during cycles of freezing and thawing. During the cooling period of freeze-thaw cycles, the pore water inside the soil specimens becomes ice and hence increases its volume. This process will produce frost heaving force on the soil skeleton, and thus the size and grading of soli particle could be changed by this frost heaving force. But for soil specimens with 3% salt, the salt can reduce the freezing temperature and diminish the frost heaving force. Hence, compared to salt-free soil specimens, the changes in the soil microstructure is relatively slight.

3.1.2 Dynamic modulus

Figure 10 presents the change curves of E with number of loading cycles. In Figure 5, there is a sharp increase for dynamic modulus of silt with dynamic strain at the primary stage but the increasing rate reduces step by step. We can speculate that the damage of silt rises along with dynamic strain but the speed is decreasing. Compared to the dynamic modulus of salt-free silt, there are some more significant differences among 3%-salt silt samples under different cycles of freezing and thawing. It is concluded that salt plays an important role during freeze-thaw cycling.

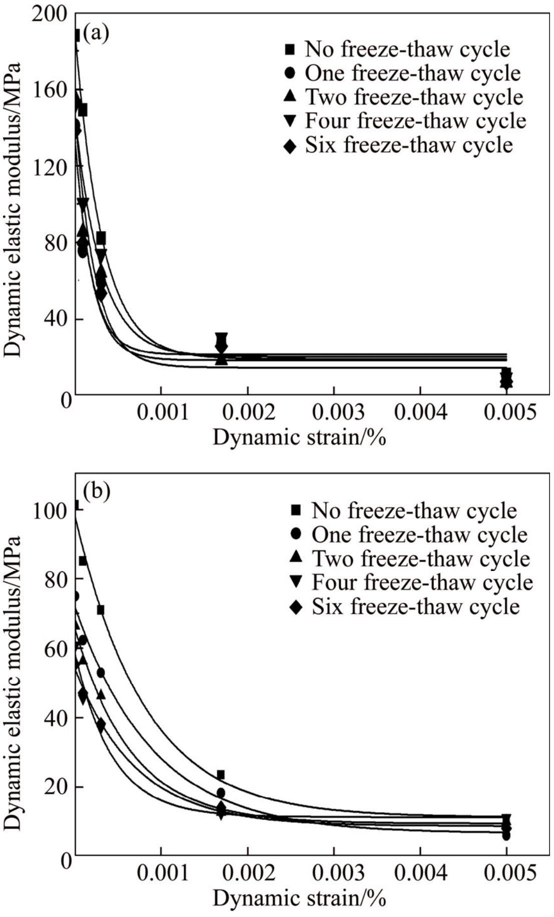

Figure 10 Change curves of E with dynamic strain: (a) Salt-free silt; (b) Silt with 3% salt

Figure 11 shows the relationship between the initial dynamic modulus (i.e., E_0) and the number of freeze-thaw cycles. It seems that E_0 decreases with the number of cycles of freezing and thawing at the beginning, and then the decreasing trend slows down. For salt-free silt, the initial dynamic modulus after six cycles of freezing and thawing is 26.5% lower compared to the salt-free silt without freeze-thaw cycling, while that of silt with 3% salt is reduced by 45.2%. The reason for the results is the same with that for the reduction of dynamic shear strength, which is that during freeze-thaw cycling, frost heaving has a damaging impact on the structures of silt and results in the contact areas between particles. Therefore, the contact between particles becomes poor, which leads to the decline of the dynamic shear strength and dynamic modulus of silt.

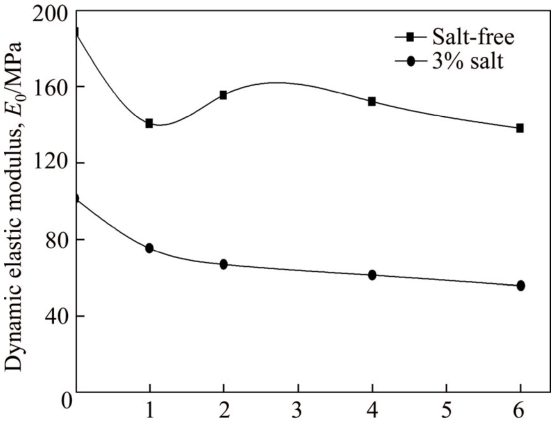

Figure 11 Change curves of E_0 with number of freeze-thaw cycles

What's more, for the same number of cycles of freezing and thawing, the dynamic modulus of silt with 3% salt is smaller than that of salt-free silt. The reasons for the results are as follows: firstly, salt will result in the reduction of the cohesion of silt, which brings the consequence that the dynamic modulus of silt with 3% salt will be smaller than that of salt-free silt; secondly, salt with the properties of water absorption and moisture retention directly leads to the increase of water film thickness and strengthens the penetration of bound water, which contributes to the larger voids in silt. The enlargement of the voids in the silt samples will have an adverse effect on the biting force and friction force between the soil particles, which means that the dynamic modulus of silt with 3% salt decreases more obviously than that of salt-free silt. As a result, for silt with 3% salt, the same strain can be accomplished by smaller stress.

3.1.3 Damping ratio

Figure 12 presents the change curves of ζ with dynamic shear strain. It seems that the damping ratio nonlinearly increases with the rise of dynamic strain, with different silt samples showing the almost similar curve patterns. In Figure 8, after six cycles of freezing and thawing, the damping ratio of salt-free silt increases by about 15.8% compared with that of salt-free silt with non-freeze-thaw cycling; meanwhile, the damping ratio of silt with 3% salt after six cycles of freezing and thawing is about 20.5% higher than that of silt with 3% salt subjected to non-freeze-thaw cycling. The conclusion is that for the same dynamic shear strain, the rising number of cycles of freezing and thawing contributes to the increment of damping ratio. This is because the freeze-thaw cycling changes the microstructure of silt and the enlargers the pore sizes, which means that more energy is consumed for the propagation of dynamic wave and leads to the larger damping ratio.

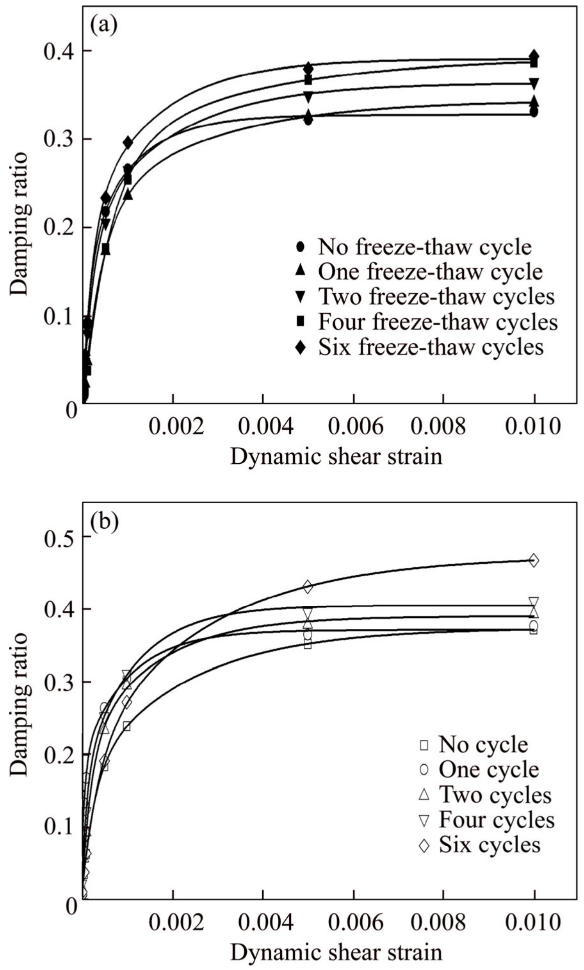

Figure 12 Change curves of ζ with shear strain: (a) Salt-free; (b) 3% salt

What's more, for the same number of cycles of freezing and thawing and dynamic shear strain, the damping ratio of salt-free silt is smaller than that of silt with 3% salt. In Figure 8, after four cycles of freezing and thawing, the salt-free silt damping ratio is about 11% lower than that of silt with 3% salt; after six cycles of freeze-thawing, the damping ratio of salt-free silt is about 15.9% lower than that of silt with 3% salt. It is demonstrated that salt enhances the degree of freeze-thaw to increase the damping ratio, and the effect of salinity on the increase of damping ratio becomes more prominent with the increase of cycles of freezing and thawing.

3.2 Study on damage model of silt based on ultrasonic tests

Figure 13 presents the relationship between the ultrasonic wave speed and number of cycles of freezing and thawing. It seems that the ultrasonic wave speed nonlinearly reduces along with the number of cycles of freezing and thawing, with almost similar curve patterns for different silt samples. Therefore, the ultrasonic wave velocity-number of cycles of freezing and thawing curves could be fitted with an exponential function as follows:

$$V=A\mathrm{e}^{\frac{N_{\mathrm{ft}}}{B}}+C \tag{1}$$

For salt-free silt: the fitting parameters A=0.297, B=2.179, C=1.759, with r^2=0.9797 (r is correlation coefficient);

For silt with 3% salt: the fitting parameters A=0.345, B=3.918, C=1.597, with r^2=0.9293 (r is correlation coefficient).

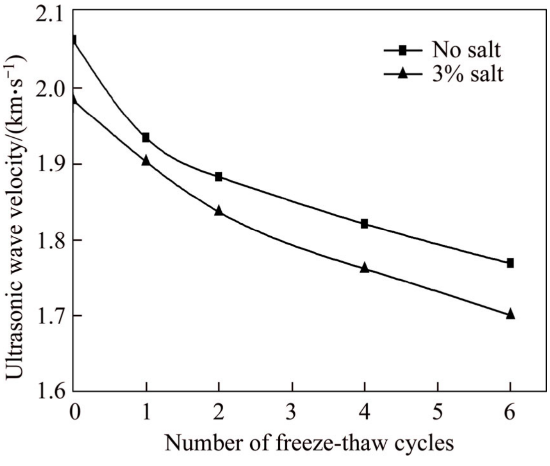

Figure 13 Change curves of ultrasonic wave velocity with number of cycles of freezing and thawing

Supposing the ultrasonic wave is propagated in specimens in one-dimension based on the wave theory, the damage characterized by the ultrasonic wave speed [29] can be expressed as follows:

$$D=1-\frac{V^2}{V_0^2} \tag{2}$$

where D is the damage of elastic modulus, V_0 and V are the ultrasonic wave speed of the silt samples before and after freeze-thaw cycling, respectively.

With Eqs. (1) and (2), a primary evaluation model of damages of silt after free-thaw cycling is put forward:

For salt-free silt:

$$D=1-(0.144\mathrm{e}^{0.459N_{\mathrm{ft}}}+0.853)^2 \tag{3}$$

For silt with 3% salt:

$$D=1-(0.173\mathrm{e}^{0.255N_{\mathrm{ft}}}+0.805)^2 \tag{4}$$

4 Conclusions

In this study, a series of tests (i.e., freeze-thaw cyclic tests, vibration triaxial tests and ultrasonic wave velocity tests) were conducted to research the impact of the cycling of freezing and thawing salt on the dynamic characteristic performances of silt in Yellow River Flood Field. Based on the results of ultrasonic wave velocity tests, a preliminary model was put forward to estimate the dynamic mechanical properties of silt after freeze-thaw loading. There conclusions are included as following:

1) In contrast to the silt before freeze-thaw cycling, both the dynamic shear strength and dynamic modulus of silt after freeze-thaw cycling decreased with number of cycles of freezing and thawing. However, freeze-thaw cycling has a significant influence on the increase of damping ratio of silt.

2) For the same cycles of freezing and thawing, the dynamic shear strength and dynamic modulus of silt with 3% salt present a more dramatic decrement than those of salt-free silt. In contrast, salt contributes to the increment of damping ratio.

3) After freeze-thaw cycling, the damage of elastic modulus of silt reduces along with the number of cycles of freezing and thawing. Based on the results of ultrasonic wave speed tests, the relationship of the ultrasonic wave velocity with number of cycles of freezing and thawing can be fitted with an exponential function.

References

[1] ZARLING J C. Changes in the mechanical behavior of non-plastic silt due to drained aging [D]. Houghton: Michigan Technological University, 2002.

[2] XU S L, SUN R, CAI Y Q. Study of sedimentation of non-cohesive particles via CFD–DEM simulations [J]. Granular Matter, 2018: 4−20. DOI: https://doi.org/10.1007/s10035-017-0769-7.

[3] FINN J R, LI M, APTE S V. Particle based modelling and simulation of natural sand dynamics in the wave bottom boundary layer. [J]. Fluid Mech, 2016, 796: 340−385. DOI: https://doi.org/10.1017/jfm.2016.246.

[4] LIU H L, ZENG Z N, ZHOU Y D. Test study on post-liquefaction deformation behavior of silt ground [J]. Rock and Soil Mechanics, 2007, 28(9): 1866−1870. DOI: 10.16285/j.rsm.2007.09.026.

[5] LIU H L, FENG T G, GAO Y F, FEI K. Multiple mechanism boundary surface plasticity model of saturated sand and its test validation [J]. Rock and Soil Mechanics, 2003, 24(5): 696−700. DOI: 10.16285/j.rsm.2003.05.006.

[6] YE Y C. Dynamic strength characteristics of silt in the Hangzhou bay [J]. Marine Sciences, 2003, 27(2): 56−59. DOI: 10.3969/j.issn.1000-3096.2003.02.017.

[7] WANG S L, LV Q F, BAAJ H, LI X Y, ZHAO Y X. Volume change behavior and microstructure of stabilized loess under cyclic freeze–thaw conditions [J]. Can J Civ Eng, 2016, 43: 865−874. DOI: dx.doi.org/10.1139/cjce-2016-0052.

[8] QI J L, MA W, SONG C X. Influence of freeze-thaw on engineering properties of a silty soil [J]. Cold Regions Science and Technology, 2008, 53(3): 397−404. DOI: 10.1016/j.coldregions.2007.05.010.

[9] MA D, MA Q, YUAN P. SHPB tests and dynamic constitutive model of artificial frozen sandy clay under confining pressure and temperature state [J]. Cold Reg Sci Technol, 2017, 136: 37−43. DOI: 10.1016/j.coldregions.2017.01.004.

[10] FIENCH H M. The periglacial environment [M]. 3rd ed. New York: Wiley and Sons, 2007.

[11] YANG N G, ZHOU K P, LEI T, LI J L, BIN F. Sandstones dynamic mechanical properties and failure characteristics under cycles of freezing and thawing [J]. Chinese Journal of Nonferrous Metals, 2016, 26(10): 2128−2187. DOI: 10.19476/j.ysxb.1004.0609.2016.10.018. (in Chinese)

[12] ZHANG Y, ZOU B, TIAN Y, FAN J. Effect on static and dynamic characteristics of concrete due to cycles of freezing and thawing [J]. Journal of PLA University of Science and Technology (Natural Science Edition), 2017, 18(1): 1−8. DOI: 10.12018/j.issn.1009-3443.20160617001.

[13] ZHANG Z, PENDIN V V, FENG W J, ZHANG Z Q. The influence of cycles of freezing and thawing on the granulometric composition of Moscow morainic clay [J]. Cold Regions Science and Technology, 2015, 3: 199−205. DOI: 10.3724/SP.J.1226.2015.00199.

[14] ZHU Z, LIU Z, XIE Q, LU Y S, LI D Y. Dynamic mechanical experiments and microstructure constitutive model of frozen soil with different particle sizes [J]. Int J Damage Mech, 2017, 27(5): 686−706. DOI: 10.1177/1056789517700967.

[15] YAO X, QI J, LIU M, FAN Y. A frozen soil creep model with strength attenuation [J]. Acta Geotech, 2017, 2: 1−9. DOI: 10.1007/s11440-017-0554-0.

[16] VIKLANDER P. Permeability and volume changes in till due to cyclic freeze-thaw [J]. Canadian Geotechnical Journal, 1998, 35(3): 471−477. DOI: 10.1139/cgj-35-3-471.

[17] ZHANG Y. Impact of freeze-thaw on liquefaction potential and dynamic prosperities of Mabel Creek Silt [D]. Fairbanks: University of Alaska Fairbanks, 2009.

[18] BETTENAY E, BLACKMORE A V, HINGSTON F J. Aspects of the hydrologic cycle and related salinity in the Belka valley, Western Australia [J]. Aust J Soil Res, 1964, 2: 187−210. DOI:10.1071/sr9640187.

[19] NIXON J F, LEM G. Creep and strength testing of frozen saline fine-grained soils [J]. Can Geotech J, 1984, 21(3): 518−529. DOI: 10.1139/t84-054.

[20] WIJEWEERA H, JOSHI R C. Creep behavior of saline fine-grained frozen soil [J]. Journal of Cold Regions Engineering, 1993, 7(3): 77−89. DOI: 10.1061/(ASCE)0887-381X(1993)7:3(77).

[21] GHASSEMI F, JAKEMAN A J, NIX H A. Salinisation of land and water resources: Human causes, extent, management and case studies [M]. Canberra, Australia: NSW University Press, 1995.

[22] MAO P, MU H X, CAO B H, QIN Y J, SHAO H B, WANG S M, TAI X G. Dynamic characteristics of soil properties in a Robinia pseudoacacia vegetation and coastal eco-restoration [J]. Ecological Engineering, 2016, 92(7): 132−137. DOI: 10.1016/ j.ecoleng.2016.03.037.

[23] DOBROVOL'SKII G V, STASYUK N V. Fundamental work on saline soils of Russia [J]. Eurasian Soil Science, 2008, 41(1): 342−353. DOI: 10.1007/s11475-008-1012-7.

[24] BUSACCA A J, ANIKU J R, SINGER M J. Dispersion of soils by an ultrasonic method that eliminates probe contact [J]. Soil Science Society of America Journal, 1984, 48(5): 1125−1129. DOI: 10.2136/sssaj1984.03615995004800050034x.

[25] MORRA M J, BLANK R R, FREEBORN L L, SHAFII B. Size fractionation of soil organo-mineral complexs using ultrasonic dispersion [J]. Soil Science Society of America Journal, 1991, 152(4): 294−303. DOI: 10.1097/00010694-199110000-00008.

[26] CUI X Z, ZHANG J, ZHANG N, ZHOU Y X, GAO Z J, SUI W. Laboratory simulation tests of effect of mechanical damage on moisture damage evolution in hot-mix asphalt pavement [J]. International Journal of Pavement Engineering, 2014, 16(8): 699−709. DOI: 10.1080/10298436.2014.943221.

[27] YI Y J, FENG D C, WANG G W, YU Z S. Application of ultrasonic test method in freeze-thaw test of asphalt mixture [J]. Journal of Highway and Transportation Research and Development, 2009, 26(11): 6−10. DOI: 10.3969/j.issn.1002-0268.2009.11.002.

[28] BIRGISSON B, ROQUE R, PAGE G C. Ultrasonic pulse wave velocity test for monitoring changes in hot-mix asphalt mixture integrity from exposure to moisture [J]. Transportation Research Record, 2003, 1832: 173−181. DOI: 10.3141/1832-21.

[29] WANG L L. Foundation of stress waves [M]. Beijing: National Defence Industry Press, 1985. (in Chinese)

(Edited by HE Yun-bin)

中文导读

冻融循环下黄泛区粉土动力特性评价

摘要：由温度、盐分和车辆交通荷载的耦合作用造成的路基土动力强度的丧失，使翻浆成为山东黄泛区公路的主要病害, 其成因与该地区粉土的动力特性密切相关。为了分析这些耦合效应对粉土动力特性的影响，本研究进行了冻融循环试验、动三轴试验和超声波试验，设计了两种粉土(无盐粉土和 3%盐粉土)。冻融循环试验和动三轴试验的结果表明，随着冻融循环次数的增加，动剪切强度和动模量降低，但阻尼比增大。另外，与无盐粉土相比，含盐量为 3%的粉土的动剪切强度和动模量下降幅度更大，但阻尼比反而增大。在超声波试验中，冻土试件的超声波速度随冻融循环次数的增加而减小。根据超声波试验结果，提出了一种通过现场实测超声波数据来评价粉土损伤的初步模型，这为粉土公路的治理提供了理论依据。

关键词：黄泛区粉土；动三轴；土动力学特性；超声波速