J. Mt. Sci. (2023) 20(1): 242-255 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
https://doi.org/10.1007/s11629-022-7378-6

Original Article

Dynamic mechanical characteristics of frozen subgrade soil subjected to freeze-thaw cycles

WANG Dan[1,2] https://orcid.org/0000-0003-1812-7045; e-mail: dwang1922@lzb.ac.cn

LIU En-long[1,3*] https://orcid.org/0000-0001-7994-4466; e-mail: liuenlong@lzb.ac.cn

YANG Cheng-song[1] https://orcid.org/0000-0002-2746-1873; e-mail: ychsong@lzb.ac.cn

LIU You-qian[4] https://orcid.org/0000-0002-7918-0766; e-mail: 539845873@qq.com

ZHU Sheng-xian[4] https://orcid.org/0000-0001-5740-7635; e-mail: 296215752@qq.com

YU Qi-hao[1] https://orcid.org/0000-0002-4671-8128; e-mail: yuqh@lzb.ac.cn

**Corresponding author*

1 *Northwest Institute of Eco-Environment and Resources, State Key Laboratory of Frozen Soil Engineering, Chinese Academy of Sciences, Lanzhou 730000, China*

2 *University of Chinese Academy of Sciences, Beijing 100049, China*

3 *State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resources and Hydropower, Sichuan University, Chengdu 610065, China*

4 *Qinghai-Tibet Railway Company, Qinghai 810000, China*

Citation: Wang D, Liu EL, Yang CS, et al. (2023) Dynamic mechanical characteristics of frozen subgrade soil subjected to freeze-thaw cycles. Journal of Mountain Science 20(1). https://doi.org/10.1007/s11629-022-7378-6

Abstract: As a widely-applied engineering material in cold regions, the frozen subgrade soils are usually subjected to seismic loading, which are also dramatically influenced by the freeze-thaw (F-T) cycles due to the varying temperature. A series of dynamic cyclic triaxial experiments were conducted through a cryogenic triaxial apparatus for exploring the influences of F-T cycles on the dynamic mechanical properties of frozen subgrade clay. According to the experimental results of frozen clay at the temperature of -10°C, the dynamic responses and microstructure variation at different times of F-T cycles (0, 1, 5, and 20 cycles) were explored in detail. It is experimentally demonstrated that the dynamic stress-strain curves and dynamic volumetric strain curves of frozen clay are significantly sparse after 20 F-T cycles. Meanwhile, the cyclic number at failure (N_f) of the frozen specimen reduces by 89% after 20 freeze-thaw cycles at a low ratio of the dynamic stress amplitude. In addition, with the increasing F-T cycles, the axial accumulative strain, residual deformation, and the value of damage variable of frozen clay increase, while the dynamic resilient modulus and dynamic strength decrease. Finally, the influence of the F-T cycles on the failure mechanisms of frozen clay was discussed in terms of the microstructure variation. These studies contribute to a better understanding of the fundamental changes in the dynamic mechanical of frozen soils exposed to F-T cycles in cold and seismic regions.

Keywords: Freeze-thaw cycles; Frozen clay; Dynamic triaxial test; Dynamic mechanical properties

Received: 02-Mar-2022
1st Revision: 16-May-2022
2nd Revision: 26-Aug-2022
Accepted: 13-Sep-2022

1 Introduction

The construction of structures and foundations in cold regions is frequently affected by freeze-thaw (F-T) cycles due to periodic fluctuations in ambient temperatures near the freezing point (Matsuoka and Murton 2008). Generally speaking, the freeze-thaw cycle is a physically weathering process (Zhang et al. 2013; Deprez et al. 2020) that significantly affects the mechanical and deformation features of frozen soils (Qi et al. 2008). During the freezing process, soil particles will sustain internal stresses, which might be caused by the phase change of moisture transition from water to ice. While during the thawing process, the stresses are released, which consequently changes the arrangement and bonding of soil particles (Edwin et al. 1979). The processes of freezing and thawing have outstanding complexity and diverse behavior, which will have a strong impact on the environment, soil foundation, and engineering construction (Zhou et al. 2000; Wu et al. 2005), such as railways, highway engineering, oil pipeline constructions, hydropower station. Besides, the dynamic loading directly leading to the failure of frozen soil in cold regions is another inescapable issue in cold and seismic zones, such as the south-west and north-west zones in China, where earthquakes occur frequently. Frozen soil will be permanently deformed under cyclically dynamic loading, with gradual loss of strength, and appearance of the nonlinear deformation and accumulative plastic strain (Zhao et al. 2020). These damage and deformation characteristics will profoundly influence the stability of infrastructural projects in cold regions (Vinson 1975; Zhu et al. 2011; Liu et al. 2016; Hu et al. 2021). Since the ground in cold regions has been experiencing F-T cycles, the mechanical behaviors will become more complex if the dynamic loading is applied. Herein, special attentions should be paid to exploring the mechanical features of frozen soil in response to the coupled influence of dynamic stress state and F-T cycles.

Some of the earliest concerns have emphasized the specific impacts of F-T cycles on the physical features of frozen soils, like the particle distribution, pores, density, distribution of pores, and soil structures (Viklander 1998; Hauck et al. 2004; Yang et al. 2004; Aldaood et al. 2014; Ma et al. 2015; Hendry et al. 2016; Fan et al. 2021a; Wang et al. 2020). The change in soil structure caused by freeze-thaw cycles will inevitably bring about the variation of mechanical features of frozen soils (Chang et al. 2013). Specifically, the internal friction angle, uniaxial compressive strength, shear strength, resilient modulus, elastic modulus, and cohesion of frozen soils are affected in some degree by the F-T cycles (Xie et al. 2015; Wang et al. 2007; Qi et al. 2008). Although many researchers have carried out experimental and theoretical studies on the static mechanical properties of frozen soils subjected to freeze-thaw cycles (Vinson 1975; Vinson 1980; Zhao et al. 2014; Balandin et al. 2020), the methods and the conclusions are considerably different in some conditions. For example, Alkire and Morrison (1983) perfomrmed a series of isotropic, consolidated, undrained triaxial tests to explore the influence of freeze-thaw cycles and repeated loadings on strength and deformation characteristics of Manchester silt and Elo clay, and the results showed that freeze-thaw cycles or repeated-load conditions cause a strength increase. While, Li et al. (2012) undertook a series of tests including freeze-thaw (F-T) (after 0, 2, 5, 11, 21, and 31 freeze-thaw cycles, respectively), unconfined compression (UC), and unconsolidated-undrained triaxial compression (UUTC) tests to establish a correlation between the mechanical behavior and freeze-thaw cycles, and confirmed the weakened and deteriorated effects of freeze-thaw actions on the compacted fine-grained soil. In addition, Qi et al. (2008) studied the influence of freeze-thaw on the engineering properties of silty soil under different freezing conditions and dry unit weights, and pointed out that the elastic modulus of the samples was increased after freeze-thaw cycles. Liu et al. (2016) conducted a set of triaxial compression tests on frozen silty sand with different freeze-thaw cycles, and found that the elastic modulus of silty sand decreases at first and then increases with the increasing freeze-thaw cycles, which is in agreement with the studies from Wang et al. (2007), but different from Qi et al. (2008). Moreover, Xie et al. (2015) believed that the shear strength of Qinghai-Tibet clay decreases with the increase of freeze-thaw cycles. On the contrary, Chang et al. (2013) studied the influence of freeze-thaw cycles on the mechanical properties of Qinghai-Tibet silt and pointed out that as the freeze-thaw cycles increase, the strength of samples decreases first and then increases. Some researchers also demonstrated that the strength of soil samples remains unchanged before and after freezing and thawing actions. These previously mentioned studies demonstrate that the mechanical properties of frozen soils have distinct tendencies under freeze-thaw cycles, in which some factors (like the soil type, temperature, confining pressure, and load type) significantly affect the variation of their mechanical properties.

Compared to the experimental studies on the effects of freeze-thaw cycles on the static mechanical behavior of frozen soils, few studies have been conducted on the description of the dynamically mechanical behaviors of frozen soil subjected to freeze-thaw cycles. Recently, some efforts were made toward describing dynamic mechanical properties of soils subjected to freeze-thaw cycles (Liu et al. 2010; Ling et al. 2015; Orakoglu et al. 2017; Zhang et al. 2019; Luo et al. 2020; Fan et al. 2021b), while the corresponding understanding of dynamically mechanical features of frozen soils experiencing freezing-thawing actions are still in the initial stage of development. For example, Xu et al. (2019) presented the variation of the accumulative deformation on frozen clay exposed to several F-T cycles under dynamic loading. Additionally, Fan et al. (2021b) presented the coupled influence of freezing and thawing action and stress conditions on the dynamic mechanical features of the frozen clay, and experimentally confirmed that the evolution of the accumulative deformation of frozen clay has two stages. Although some studies have been studied on the dynamic mechanical behaviors of frozen soil subjected to freeze-thaw cycles, the influence of freeze-thaw on the mechanical behavior of soils is difficult to clarify without more extensive investigations, and conclusions remain open (Qi et al. 2006). A systematic study is needed in terms of the various testing procedures on frozen soils, in which the confining pressure, the ratio of dynamic stress amplitude (R_{DSAR}), and F-T cycles are all examined. Therefore, understanding the dynamic mechanical of frozen soil subjected to freeze-thaw cycles has the potentials for providing the design guidance for the practical projects in cold regions.

In view of the lack of references reported on the dynamic properties of frozen soil subjected to freeze-thaw cycles and cyclic loading simultaneously, this paper investigates the dynamic mechanical properties of frozen soils subjected to the F-T cycles under cyclic loading. Herein, a sequence of cyclic triaxial compression experiments on frozen clay experiencing F-T cycles was carried out. The evolution of the dynamic stress–strain relationship, volumetric strain, hysteresis curves, accumulative axial strain, dynamic resilient modulus, residual deformation, damage variables, and dynamic strength of frozen clay experienced F-T cycles were analyzed in detail. Moreover, the microstructure of soil underwent different freeze-thaw cycles was studied by scanning electronic microscopy (SEM) tests in order to analyze the variation rules of dynamically mechanical properties.

2 Materials and Methods

2.1 Soil properties and specimen preparation

The clay used in the study is a typical soil deposited in cold regions on the eastern side of the Qinghai-Tibet Plateau in China (Sichuan Province, Ganzi). Table 1 and Fig. 1 present the grain-size distribution and basic index properties of clay, respectively.

Table 1 Basic physical properties of tested clay

Physical properties	Value
Liquid limit (%)	27.5
Plastic limit (%)	15.9
Plastic index	11.6
Maximum dry density (g/cm^3)	1.81
Optimal water content (%)	16.8

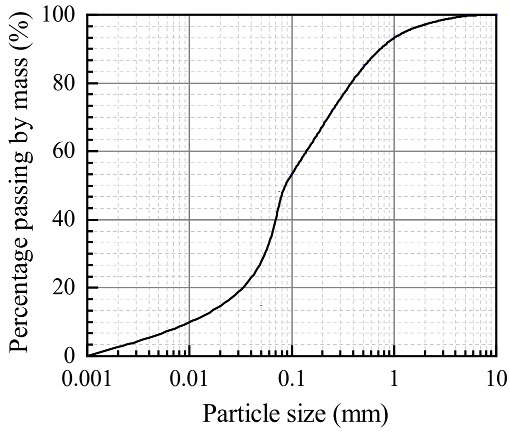

Fig.1 Particle size distribution curve of soil samples.

The specific preparation of the standard frozen clay specimens for the dynamic triaxial test is described as follows: (i) The tested soil was naturally air-dried and sieved through a 2.0mm screen; (ii) After the procedure (i), tested soil was prepared

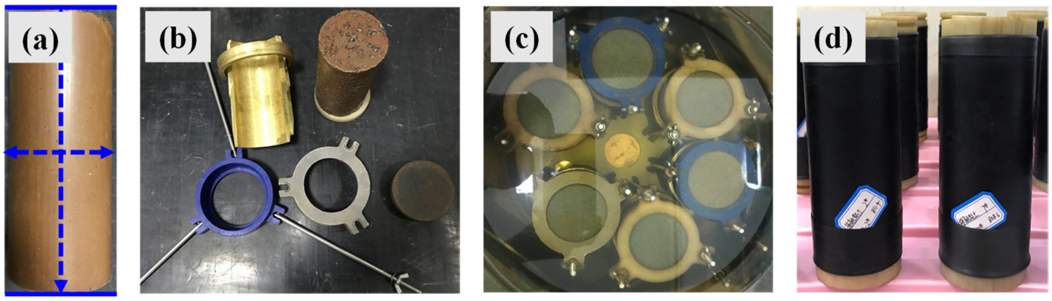

Fig. 2 Specimens preparation: (a) Soil samples; (b) Preparation; (c) Saturation; (d) Freeze-thaw cycles.

Table 2 Summary of the specimen tested conditions

Specimen number	Confining pressure σ_3 (MPa)	Freeze-thaw cycles N_{F-T}	Ratio of dynamic stress amplitude R_{DSAR}
DT-C-01~12	0.3	0, 1, 5, 20	0.80, 0.90, 0.98
DT-C-13~24	1.0	0, 1, 5, 20	0.80, 0.90, 0.98
DT-C-25-36	1.4	0, 1, 5, 20	0.80, 0.90, 0.98

according to its optimal water content of 16.8%, and they were placed in sealed bags for 24h to ensure the uniformity of moisture content; (iii) The sample-making machine was used to compress the soil to form the specimens, having a diameter size of 61.8 mm, a height size of 125 mm (Fig. 2 (a)), and 1.89 g/cm³ of the dry density; (iv) Each specimen was mounted in the steel split mold with porous stones at each end (Fig. 2 (b)). Subsequently, all the specimens were put in the apparatus for vacuuming. The vacuuming and saturating processes lasted 3 h and 12 h, respectively (Fig. 2 (c)), to make sure the degree of saturation of the specimens was more than 95%. After that, the porous stones were dropped and the epoxy resin platens were placed on both ends; and (v) To avoid moisture migration and frost heaving during the initial freezing, the specimens were put in a temperature-controlled apparatus at -30°C for 48 h to freeze. Finally, all the specimens were removed from the split molds, covered with new rubber sleeves, and then prepared for freeze-thaw cycles and dynamic triaxial test (the temperature is -10°C) (Fig. 2 (d)).

2.2 Test apparatus and methodology

The tests conducted here include the freeze-thaw test and the dynamically cyclic mechanical test, in which the freeze-thaw test is carried out, followed by the mechanical test. The specific experiment procedures are shown in Table 2.

2.2.1 F-T cycle test

According to the seasonal temperature conditions of the cold regions, the test specimens were frozen at -10°C for 12h and then melted at indoor temperature (23°C) for 12h, namely, a single freeze-thaw cycle was considered as 24 hours. The specimens subsequently experienced different cycles of F-T processes under closed conditions. Notably, all the specimens were covered with rubber sleeves to avoid moisture evaporation. After the frozen specimens underwent F-T cycles at 0, 1, 5, and 20 times, we took out a group of specimens for the dynamic cyclic triaxial tests, and the rest of the samples continued to freeze and thaw until 20 F-T cycles are completed.

2.2.2 Mechanical test

The dynamic mechanical test equipment adopted is the modified triaxial material test device MTS-810 at the State Key Laboratory of Frozen Soil Engineering of the Chinese Academy of Sciences (CAS), as is shown in Fig. 3. The cryogenic test apparatus consists of the refrigerating devices, loading equipment, confining pressure chamber, and a data acquisition system including mechanical data acquisition and temperature acquisition. The results of data acquisition during the specimen testing include temperature, time, axial displacement, axial force, confining displacement, and confining pressure. The equipment was able to test static mechanical and dynamic features of frozen soil, and the temperature error was controlled at ±0.1°C. The references have described the test instrument in detail (Zhang et al. 2007; Zhang et al. 2019).

In this paper, the frozen samples that experienced F-T cycles were subjected to dynamically

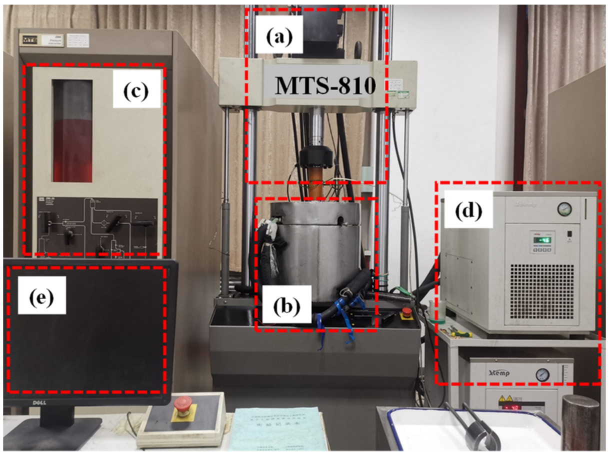

Fig. 3 MTS-810 test system: (a) Loading equipment; (b) Confining pressure chamber; (c) Pressure intensifier; (d) Refrigerating devices; (e) Data acquisition system.

cyclic triaxial tests at -10°C temperature. Three levels of dynamic stress amplitude ratios (R_{DSAR}=0.80, 0.90, and 0.98) were carried out under the confining pressure σ_3 of 0.3 MPa, 1.0 MPa, and 1.4 MPa, respectively. To express the dynamic stress amplitude, a stress parameter R_{DSAR} is introduced, which is given by the ratio of the dynamic stress (σ_d) to the corresponding static strength (q_{static}), namely, expressed as $R_{DSAR} = \sigma_d / q_{static}$. It should be noted that the corresponding static strength was obtained from the corresponding static test of frozen clay. In this study, the three groups of the dynamic triaxial tests were carried out by adopting an axial stress-controlled loading system, as is shown in Fig. 4(a). The loading frequency was kept at 1.0Hz and the loading path is depicted in Fig. 4(b), in which the sinusoidal loading form was employed, as is shown in Fig. 4(c). Before the cyclic loading, the confining pressure was applied and kept for 5min. The frozen specimens will fail once the axial strains reach 5%.

3 Dynamic Test Results

Following the dynamically cyclic triaxial tests of frozen soil experienced the F-T cycles, the influences of the F-T cycles on the variation of dynamic stress-strain, hysteresis loop, accumulative axial strain, dynamic resilient modulus, residual deformation, damage variables, and dynamic strength were investigated. The dynamically mechanical features of frozen soil undergoing the F-T cycles will be explored and discussed in the following statements.

3.1 Effect of F-T cycles on dynamic stress-strain curves and volumetric strain curves

The dynamic stress–strain curves and volumetric strain curves of frozen clay can intuitively declare the dynamic deformation features. To understand the effects of the F-T cycles on the deformation behaviors, a series of dynamic triaxial experiments on frozen clay was carried out. For example, Fig. 5 presents the experimental results of frozen clay when the confining pressure is 0.3 MPa (where R_{DSAR}=0.98) and the cycles of F-T processes range from 0 to 20 times. The outcomes demonstrate that the dynamic stress–strain curves of frozen clay beneath cyclically dynamic loading show hysteresis, nonlinearity, and plastic strain accumulation. Compared with thawed soil, frozen soils exhibit ideal viscoelastic features during the cyclic process, and its dynamic hysteresis loop is an open curve. Meanwhile, as the dynamic loading cycles increase, the dynamic stress-strain curve gradually becomes dense from the sparse, and finally reaches the failure state. The variation of volumetric curves exhibits initial contraction followed by dilatancy tendency. Moreover, the curves of dynamic stress–strain and volumetric strain of frozen clay gradually become sparse along with the increasing

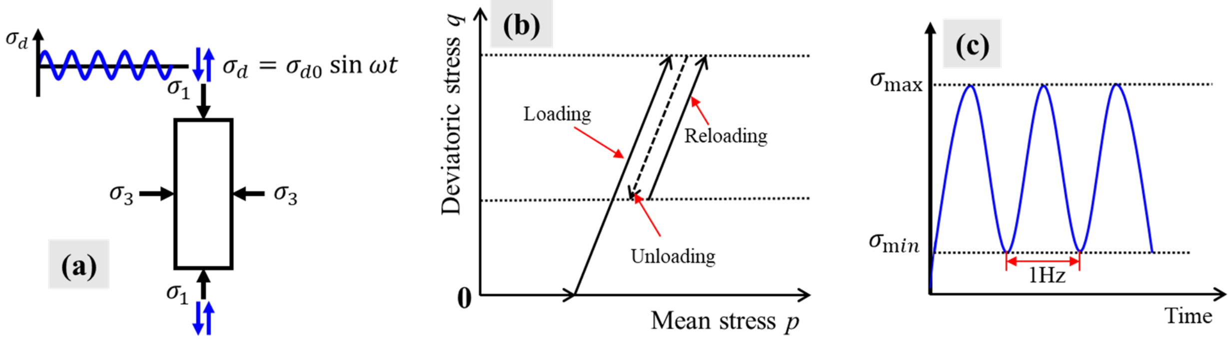

Fig. 4 Scheme of the loading path and the cyclic loading: (a) Loading mode; (b) Loading path; (c) Loading waveform.

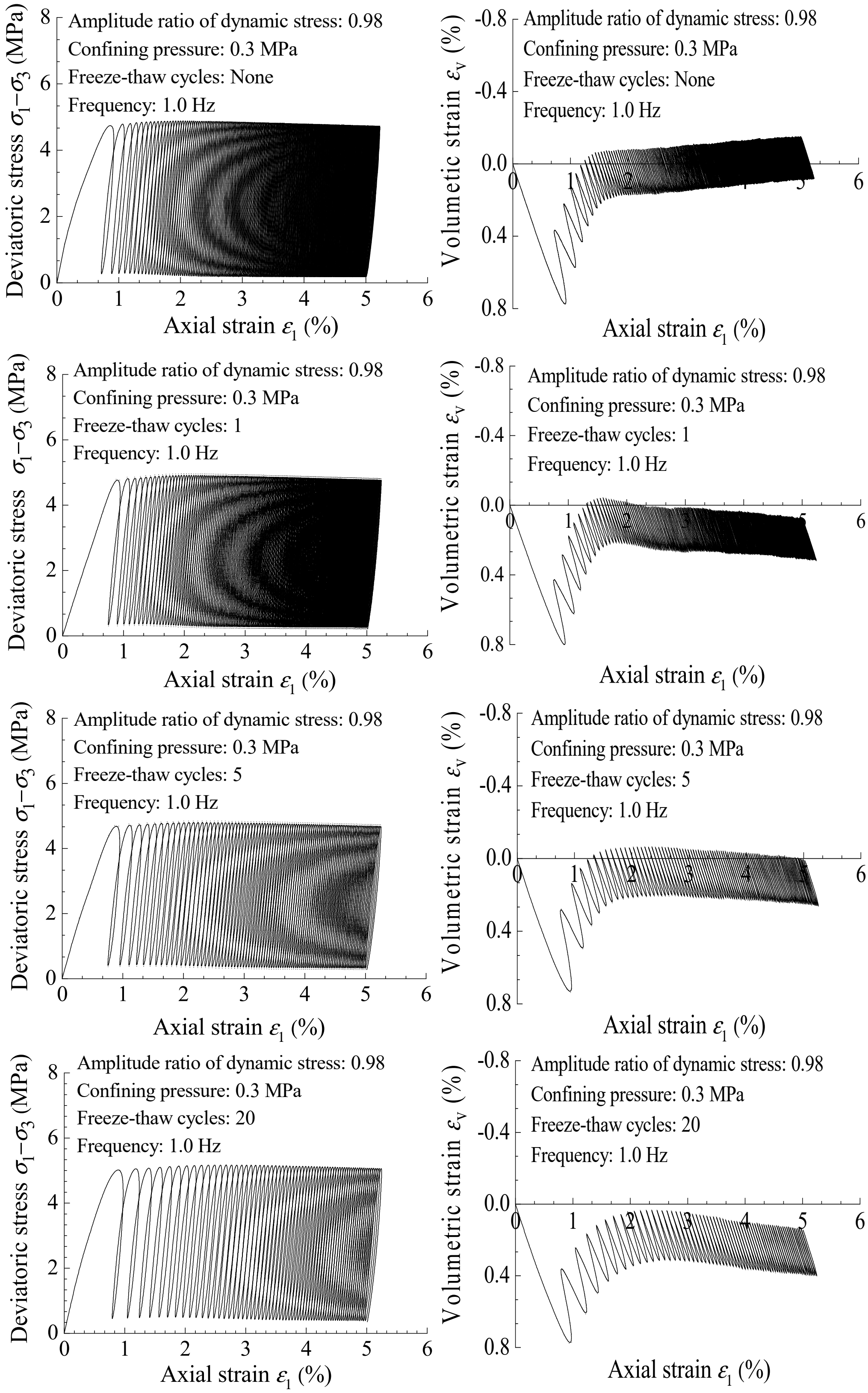

Fig. 5 Dynamic stress-strain relationship and volumetric strain curves of frozen soil under different freeze-thaw cycles (σ_3=0.3MPa; R_{DSAR}=0.98).

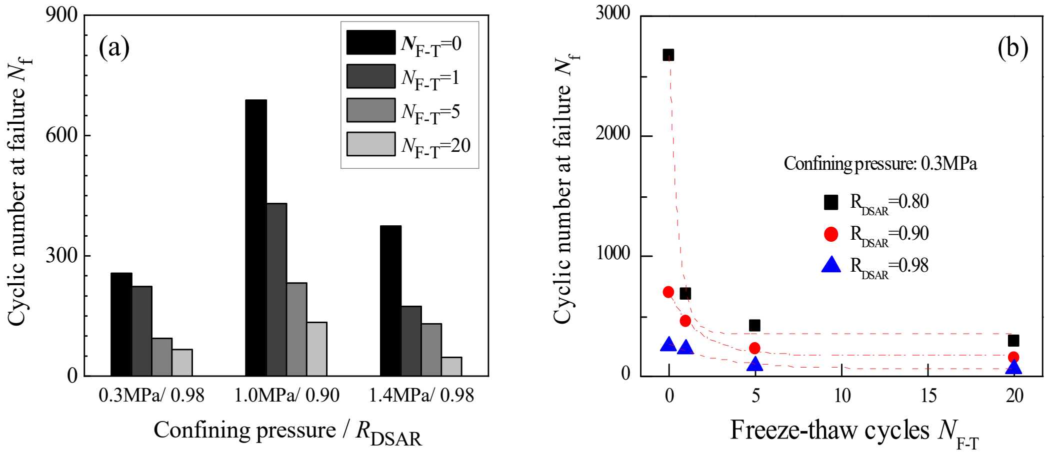

Fig. 6 Cyclic number at failure of frozen clay under different conditions: (a) Different freeze-thaw cycles; (b) Different amplitude ratio of dynamic stress.

times of F-T cycles, which means the more F-T cycles, the less the cyclic number at failure N_f, as is shown in Fig. 6. For frozen clay, the cyclic number at failure occurs around the 261st loading cycle. When the frozen clay experiencing F-T cycles after 20 times, the loading cycle at failure is reduced to 26. This is mainly due to that the repeated freeze-thaw cycles have degraded the connection between the soil particles, leading the soil particles to be rearranged and weakening the carrying capacity of frozen samples. Meanwhile, Table 3 gives the cyclic triaxial compression test results of frozen soil subjected to different freeze-thaw cycles.

3.2 Effect of F-T cycles on the hysteresis loop

The hysteresis loop is used to describe the dynamic stress-strain variation with time for each loading-unloading cycle of the soil specimens under cyclically dynamic loading. The study of the hysteresis loop plays an important role to understand the evolution of dynamic features of soil, which reflects the energy dissipation of frozen soil during the cyclically dynamic loading process, including the plastic dissipation, viscous dissipation, and damage dissipation. Fig. 7 presents the relationships between the hysteresis loops and the loading cycles (N=1, 100, 1000) at 0, 1, 5, and 20 cycles of the F-T processes. The hysteresis loop is found to be non-closed at the initial stage of the dynamic deformation (N=1), and the opening at the lower end of the hysteresis curve gradually becomes larger as the times of F-T cycles increased, indicating that frozen clay experienced F-T cycles are more prone to energy dissipation and a

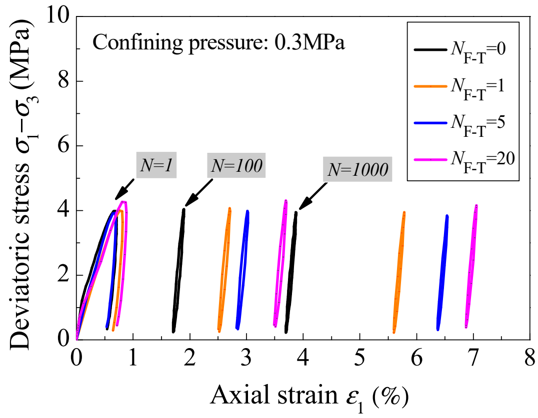

Fig. 7 The hysteresis curves of frozen clay under different freeze-thaw cycles with different cyclic numbers.

greater plastic deformation generated in the first cyclically dynamic loading. With the increasing loading cycles (N=100, 1000), the hysteresis curves gradually take the shape of closed willow leaves, and the development of hysteresis curves with strain for frozen clay without freezing and thawing action lags behind that for specimens with 1, 5, and 20 times of F-T cycles. Additionally, as the increase of F-T cycles, the hysteresis loop of frozen clay develops faster under the same vibration, which indicates that the freezing and thawing action makes frozen clay less capable of withstanding dynamic loads, and the specimens are more likely to produce larger deformations.

3.3 Effect of F-T cycles on axial accumulative strain

The axial accumulative strain refers to the

Table 3 The results of cyclic triaxial compression test for frozen soil subjected to different freeze-thaw cycles

Temperature (℃)		$N_{F\text{-}T}$	σ_3 (MPa)	R_{DSAR}	Failure strain (%)	N_f
Freeze	Thaw					
-10	23	0	0.3	0.80	5	2666
-10	23	0	0.3	0.90	5	692
-10	23	0	0.3	0.98	5	256
-10	23	0	1.0	0.80	5	2469
-10	23	0	1.0	0.90	5	688
-10	23	0	1.0	0.98	5	294
-10	23	0	1.4	0.80	5	2448
-10	23	0	1.4	0.90	5	636
-10	23	0	1.4	0.98	5	374
-10	23	1	0.3	0.80	5	683
-10	23	1	0.3	0.90	5	452
-10	23	1	0.3	0.98	5	223
-10	23	1	1.0	0.80	5	677
-10	23	1	1.0	0.90	5	430
-10	23	1	1.0	0.98	5	148
-10	23	1	1.4	0.80	5	830
-10	23	1	1.4	0.90	5	282
-10	23	1	1.4	0.98	5	174
-10	23	5	0.3	0.80	5	419
-10	23	5	0.3	0.90	5	230
-10	23	5	0.3	0.98	5	94
-10	23	5	1.0	0.80	5	267
-10	23	5	1.0	0.90	5	232
-10	23	5	1.0	0.98	5	66
-10	23	5	1.4	0.80	5	798
-10	23	5	1.4	0.90	5	280
-10	23	5	1.4	0.98	5	130
-10	23	20	0.3	0.80	5	292
-10	23	20	0.3	0.90	5	155
-10	23	20	0.3	0.98	5	66
-10	23	20	1.0	0.80	5	274
-10	23	20	1.0	0.90	5	134
-10	23	20	1.0	0.98	5	58
-10	23	20	1.4	0.80	5	251
-10	23	20	1.4	0.90	5	144
-10	23	20	1.4	0.98	5	47

Notes: $N_{F\text{-}T}$, Freeze-thaw cycles; σ_3, Confining Pressure; R_{DSAR}, Amplitude ratio of dynamic stress; N_f, Cyclic number at failure.

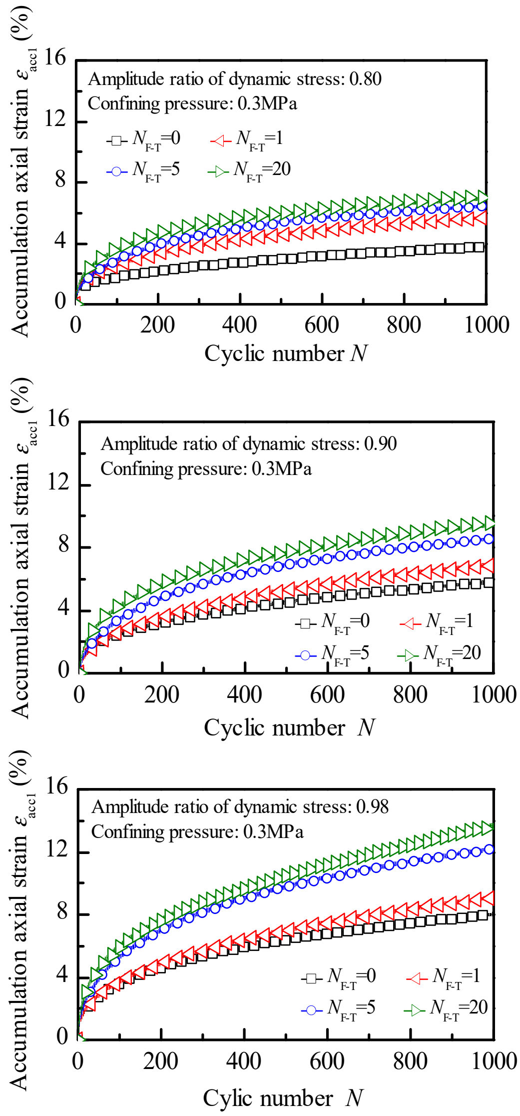

Fig. 8 The accumulative axial strain with different freeze-thaw cycles under different dynamic stress amplitude.

accumulation of the axial deformation in each loading cycle along with the cyclically loading cycles throughout the dynamic loading process, and its magnitude can be determined by the original data of triaxial cyclic loading, which is the basis for studying the long-term deformation of foundation soil under the action of load. Fig. 8 presents the difference of F-T cycles on the evolution of the axial accumulative strain for frozen clay by three groups of cyclic experiments. Taking the 0.3MPa confining pressure for example, when the dynamic stress amplitude ratio (R_{DSAR}) is respectively 0.80, 0.90, and 0.98, the evolution tendency of the axial accumulative strain versus the cycles of F-T processes among different R_{DSAR} is uniform. It is noteworthy that the F-T cycle increases the axial accumulative strain. When R_{DSAR}=0.80, the axial cumulative strain of frozen clay undergoing 0, 1, 5, and 20 cycles of F-T processes ranges from 3.87% to 7.05%. In addition, at a high-stress amplitude ratio, the influence of F-T cycles on the development of the axial accumulative strain in frozen clay is little. For example, when R_{DSAR}=0.80, the axial accumulative strains of frozen clay experienced 1, 5, and 20 F-T cycles increase by 49.2%, 68.9%, and 82.0% compared with the frozen clay without F-T cycles experience. While, when R_{DSAR}=0.98, the axial accumulative strain of frozen clay after 1, 5, and 20 F-T cycles increases by 13.3%, 51.5%, and 69.9% on average. Further analysis shows that the increase rate of the axial accumulative strain in 20 F-T cycles is relatively slow compared with the other F-T cycles (0, 1, and 5 cycles). Taking R_{DSAR}=0.90 for example, there is a significant difference among the four F-T cycles on frozen clay, the axial accumulative strain of the specimen that experienced 5 freeze-thaw cycles increases by 23.3%, while the axial cumulative strain of the samples that experienced 20 freeze-thaw cycles increases by only 10.6% compared with those that experienced 5 freeze-thaw cycles. The reason is that frozen clay is subjected to relatively small external loading, microcracks are gradually closed and ice crystals in the interface make the soil aggregates compact more tightly. To sum up, these results indicate that the F-T cycles exhibit a noticeable impact on the evolution of the axial accumulative strain for frozen clay.

3.4 Effect of F-T cycles on dynamic resilient modulus

The dynamic resilient modulus (E_R) is an important indicator of the kinetic parameters of frozen soil, which is defined as the slope between the unloading curve and reloading curve, and the calculation method is interpreted in Fig. 9. The dynamic resilient modulus is defined as:

$$E_R = \frac{\sigma_A - \sigma_B}{\varepsilon_{A,max} - \varepsilon_{B,min}} \quad (1)$$

where σ_A and σ_B stand for the stress of point A and point B, $\varepsilon_{A,max}$ and $\varepsilon_{B,min}$ stand for the strain of point A and point B, respectively.

From the experimental and calculated results, the variation of dynamic resilient modulus for frozen clay under the same external loading conditions with different times of F-T is revealed in Fig. 10. The evolution characteristics for the dynamic resilient modulus of frozen clay under 0, 1, 5, and 20 F-T cycles are summarized as follows: (1) Freezing and thawing action causes the reduction of the dynamic resilient modulus (Simonsen et al. 2002; Qi et al. 2008), and the dynamic resilient modulus of frozen clay is negatively correlated with different times of F-T cycles. Herein, with the increasing number of F-T cycles, the resilient modulus gradually decreases and eventually reaches a stable value. This phenomenon can be explained as the freezing and thawing action that makes soil particles and ice crystals rearrange

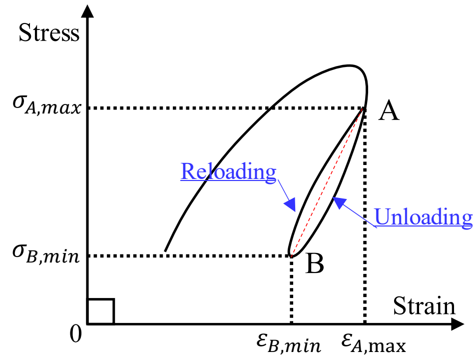

Fig. 9 The calculate method of the dynamic resilient modulus.

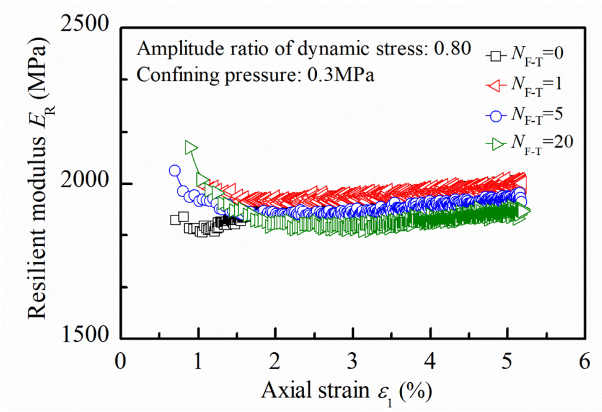

Fig. 10 The variation of resilient modulus of frozen clay under different freeze-thaw cycles.

and change the loose structure of the soil. When the long-term loading is applied, deformation is more likely to occur and thus the dynamic modulus of the frozen clay is reduced; and (2) for frozen clay, when the axial strain is within 2%, the dynamic resilient modulus gradually increases with the development of the axial strain, and then slowly tends to a stable value. However, the underlying trends of the dynamic resilient modulus for frozen clay which experienced F-T cycles are observed to be significantly different in this study. For frozen clay experiencing F-T cycles, with the development of the axial strain, its dynamic resilient modulus gradually decreases and then tends to a constant value. It is mainly because the structural changes caused by the external loading are the main reason for the evolution of dynamically mechanical features of frozen clay. During the initially cyclical loading process, the ice crystal in the sample is damaged leading the dynamic resilient modulus to change greatly. With the continuing application of dynamic loading, the particles in the frozen soil are slippage by shear, the open pores are gradually close, and it is not easy to produce deformation, thus the rebound modulus gradually tends to a constant value.

3.5 Effect of F-T cycles on residual deformation

The deformation behaviors of frozen soil that undergo dynamic cyclic loading is a significant portion of soil dynamics research. The residual deformation of the soil is the most important part to express the dynamic deformation, and it is defined as the axial strain which reaches a minimum value in each loading cycle (Liu et al. 2016). During the entire dynamic loading process, the residual deformation gradually increases, and the deformation cannot be recovered after the dynamic test ends. Fig. 11 presents the axial residual strain of frozen clay undergoing different F-T cycles with the same R_{DSAR} and different confining pressures (0.3 MPa, 1.0 MPa). In Fig. 11, we can find that the residual strain exhibits an increasing trend along with the number of the increasing dynamic loading cycles and the residual strain of frozen clay increases with the cycles of F-T processes under the same loading cycles. Taking 0.3 MPa confining pressure and R_{DSAR}=0.8 as an example,

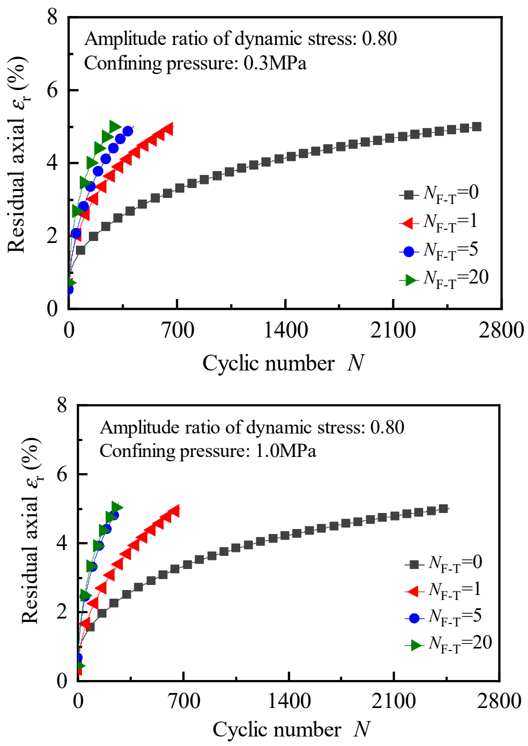

Fig. 11 The relationship between residual axial strain and the number of freeze-thaw cycle of frozen clay.

when the number of loading cycles reaches 100, the residual strain is 1.70% for frozen clay without freeze-thaw, and 2.52%, 2.85%, and 3.51% for the specimens with 1, 5, and 20 F-T cycles, respectively. The experimental results demonstrate the freezing and thawing action makes the frozen clay to be more susceptible to irrecoverable deformation. Another important finding is that when the confining pressure increases to 1.0 MPa, the residual strain of the frozen clay undergoes 5 and 20 F-T cycles are 3.36% and 3.58% at 100th dynamic loading cycles, respectively, and the rate of variation between them is only 0.22%. It means the residual strain of frozen clay experienced 5 and 20 F-T cycles remain almost the same tendency with increasing load cycles. The reason might be that in the saturated clay some kinds of structures were gradually formed and the effects were weakened after 7 times of F-T cycles (Othman et al. 1993; Lin et al. 2017). This phenomenon proves that the F-T cycle and confining pressure affect the evolution of residual deformation features of frozen clay under cyclically dynamic loading.

3.6 Effect of F-T cycles on damage properties

In this study, the damage variables D_{FTD} in terms of the residual axial strain of frozen soil experienced different F-T cycles are proposed. Take the 1.0MPa confining pressure and R_{DSAR}=0.8 for example. According to the failure mechanism, the specimen after 20 freeze-thaw cycles fail when loaded 247 times. To describe the effects of the freezing and thawing action on damage properties of frozen clay, the value of the residual axial strain at the 40th, 80th, 120th, 160th, 200th, and 240th loading cycles are selected and the corresponding D_{FTD} is calculated. The definition of D_{FTD} is given in Eq. (2), in which we keep a watchful eye on the variation tendency of the damage variables with the cycles of F-T processes and consider the damage variables of non-experienced F-T cycle samples as a reference substance.

$$D_{\mathrm{FTD}} = \frac{\varepsilon_{N,ras}^{N_i} - \varepsilon_{1,ras}^{i}}{\varepsilon_{N,ras}^{240^{th}} - \varepsilon_{1,ras}^{240^{th}}} \tag{2}$$

where $\varepsilon_{1,ras}^{i}$ is the residual axial strain (RAS) for the non-experienced freeze-thaw cycles specimen, $\varepsilon_{N,ras}^{N_i}$ is the RAS for frozen clay which experienced 1, 5, and 20 freeze-thaw cycles, respectively. $\varepsilon_{1,ras}^{240^{th}}$ is the RAS for the non-experienced freeze-thaw cycles specimen at 240th loading cycles, $\varepsilon_{N,ras}^{240^{th}}$ is the RAS for frozen clay which experienced 1, 5, and 20 times of F-T cycles at 240th loading cycles, respectively.

As shown in Fig. 12, the damage variable takes values in the range of 0~1. When the stress conditions are the same, the value of damage variables is larger along the number of F-T cycles increases. The phenomenon mentioned above illustrate the freezing and thawing action makes the dynamic damage variables of frozen clay exaggerate. In addition, the increasing tendency of damage variables of frozen clay experienced 1, 5, and 20 cycles of F-T which are dependent on the dynamic loading cycles, while its variation tendency exhibits difference. Specifically, the increasing tendency of frozen clay experienced after 1 freeze-thaw cycle increases sharply compared with the other two freeze-thaw cycles.

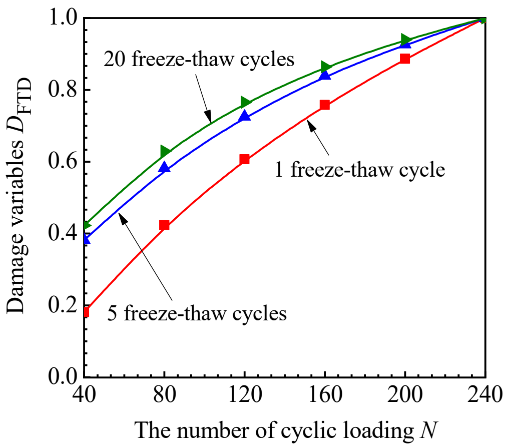

Fig. 12 The evolution of damage variables of frozen clay under different freeze-thaw cycles subjected to cyclic loadings (1.0 MPa confining pressure).

3.7 Effect of F-T cycles on dynamic strength

According to the definition of dynamic strength, the damage strain method is employed to calculate the dynamic strength of frozen clay. Hence, the ultimate failure strain of frozen clay is regarded as the 5% of the axial strain. The dynamic strength variation curve is plotted according to the dynamic stress value corresponding to the deteriorated strain, where lgN_f is the horizontal coordinate and the dynamic stress ratio $\sigma_d/(2\sigma_3)$ is the vertical coordinate. Herein, three sets are shown in Fig. 13. Firstly, the dynamic strength of frozen clay decreases linearly with the increase of cyclically dynamic loading numbers under the same stress loading conditions and numbers of F-T cycles. Additionally, the dynamic strength of frozen clay decreases as the cycles of F-T increase. The possible reason is that the freezing and thawing action reduces the dynamic strength of frozen clay and leads to the loosing of structure. Moreover, the dynamic strength of frozen clay response to the confining pressure is not remarkable after freeze-thaw cycles.

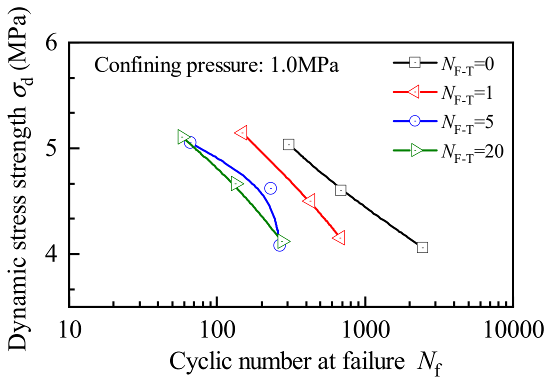

Fig. 13 The dynamic strength for frozen clay subjected to different freeze-thaw cycles (1.0MPa confining pressure).

4 Failure Mechanisms and Discussion

Unlike unfrozen soils, saturated frozen soil is a complex multiphase material consisting of soil particles, ice crystals, and unfrozen water (Liu et al. 2016). The presence of ice crystals makes the structure, mechanical properties, and deformation characteristics of frozen soil highly sensitive to temperature. Freeze-thaw cycles are a crucial environment influencing factor (Zhang et al. 2013), which can change the dynamic mechanical features of frozen soil by altering microstructure and particle arrangement (Viklander 1998; Tian et al. 2019; Kong et al. 2020). Herein, the variation of mechanical properties for frozen soil is affected by freeze-thaw cycles, which are mainly caused by alterations in the soil structures, and can be elaborated by a re-structuring of soil microstructure. As is shown in Fig. 14, the microstructures of frozen clay subjected to different freeze-thaw cycles (0, 1, 5, and 20 cycles) were obtained to investigate the influence of freeze-thaw cycles on dynamic mechanical properties from the micro-scale. As shown by the example of frozen clay, the shape and orientation of soil aggregates, along with the generated ice crystals and cementation, should be taken into account for a comprehensive

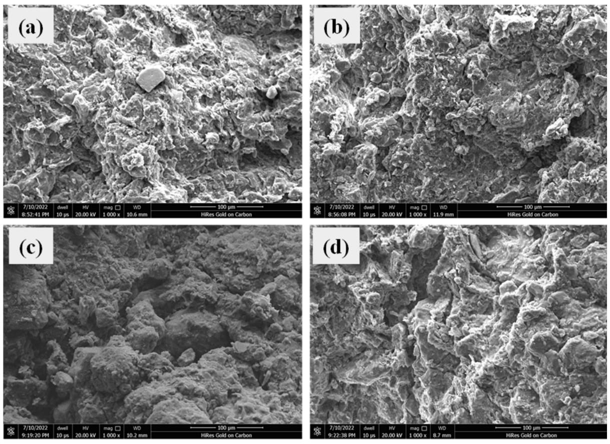

Fig. 14 SEM images of clay after different freeze-thaw cycles (magnification 1000X): (a) 0 F-T cycle; (b) 1 F-T cycle; (c) 5 F-T cycles; (d) 20 F-T cycles.

understanding of the degradation of the dynamic mechanical properties of frozen soils that experienced freeze-thaw cycles. Different morphological characteristics of the geometric transformation of frozen soil structure after experiencing F-T cycles are described. For an undisturbed initial frozen structural status of clay samples, soil aggregates and ice crystals coexist and have bonds between them, and can be seen as face-to-face clumps about aggregation structure, as shown in Fig. 14(a). Herein, the curves of the dynamic stress–strain and volumetric strain of frozen clay are relatively dense, which means the frozen specimen has a higher capability of withstanding cyclic loads with non-experienced F-T cycles. When the temperature increases gradually, the ice crystals in the soil samples turn from a solid into a liquid and resulting in a smaller volume. After the melting of ice crystals or thaw consolidation of an undisturbed initial frozen soil experiences thawing action, the inter-granular pores often develop and the micro fissures can still be open, leading to a rearrangement of the aggregates, as shown in Fig. 14(b). When the cyclically dynamic loading is applied on frozen clay experiencing a single F-T cycle, newly created pores are firstly compressed and the pore ice crystals between soil particles begin to crush firstly companied by the excess moisture generated to reduce the friction of particles, and then the stress applying to the soil particles leading frozen soil to failure. Consequently, compared to undisturbed initial frozen clay, the frozen soil is re-structured due to a single F-T cycle which increases dynamic deformation (hysteresis loop, axial accumulative strain, residual deformation, and damage properties) and decreases dynamic strength (including dynamic resilient modulus). When repetitive F-T cycles affect frozen soil, the re-structural microstructure is affected by the phase transition of water, aggregate damage, particle translocation, and internal pores growth, as shown in Fig. 14(c). Briefly, the frozen clay that experienced times of F-T cycles has more pores, smaller soil aggregates, more pore ice, and weaker cementation between soil and ice crystals, the repeated ice-water phase transitions between particles, causing the large-size clay aggregate to break up and split (Hallet et al. 1991; Hall et al. 2011), as shown in Fig. 14(d). Admittedly, F-T cycles exhibit a great influence on the dynamic mechanical properties of frozen soil, where the soil aggregates and ice crystals together contribute to the main bearing capacity of the soil elements. When the dynamic loading applied, the cementation of particles is damaged, and frozen soil is more readily to failure. Correspondingly, repeated freezing and thawing cycles are leading to a conspicuous reduction in the dynamic strength and an increase in dynamic deformation characteristics (hysteresis loop, axial accumulative strain, and residual deformation).

5 Conclusions

Based on the experimental works presented in this study on frozen clay after different freeze-thaw cycles (0, 1, 5, and 20 cycles) under dynamically cyclic loading, the following main conclusions can be summarized:

(1) The dynamic mechanical properties of frozen clay are strongly sensitive to F-T cycles. With the increasing F-T cycles, the dynamic stress–train relationship curves and volumetric strain curves gradually tend to spare. This indicates that the frozen clay undergoing F-T cycles produces larger plastic deformation. Meanwhile, with the increasing cycles of F-T, the cyclic number at failure decreases nonlinearly.

(2) As the F-T cycles increase, the dynamic deformation of the frozen clay always increases. Specifically, the evolution of the hysteresis loop curves shows a strong increasing tendency with the increase of the F-T cycles. Additionally, the trend of the axial accumulative strain in the first five freeze-thaw cycles (0, 1, and 5 cycles) increases more rapidly than 20 F-T cycles under the same loading conditions.

Moreover, the effect of F-T cycles on the axial accumulative strain evolution in frozen clay is little at the high-stress amplitude ratios.

(3) With the increasing F-T cycles, the resilient modulus gradually decreases and eventually reaches a stable value. For frozen soil that has not experienced F-T cycles, the dynamic resilient modulus gradually increases when the axial strain is within 2%, while the underlying trends of the dynamic resilient modulus decreases for frozen clay that has experienced F-T cycles.

(4) The value of the residual strain and damage variables exhibits an increasing trend along with the increasing F-T cycles. Additionally, the increasing trend of F-T cycles always results in a low value of dynamic strength. Moreover, repeated freezing and thawing cycles lead to a loose microstructure, which makes the frozen soil prone to deformation and failure under dynamic loading.

Acknowledgments

The work is funded by the National Natural Science Foundation of China (NSFC) (Grant Nos. U22A20596 and 41771066), and the Science and Technology Project of Qinghai-Tibet Railway Company (QZ2021-G03). In addition, the authors greatly appreciate associate professor Jianfeng Zheng (State Key Laboratory of Frozen Soil Engineering, Chinese Academy of Sciences) for his help in the experiments.

References

Aldaood A, Bouasker M, Al-Mukhtar M (2014) Impact of freeze-thaw cycles on mechanical behavior of lime stabilized gypseous soils. Cold Reg Sci Tech 99(1): 38-45. https://doi.org /10.1016/j.coldregions.2013.12.003

Alkire BD, Morrison JM (1983) Change in soil structure due to freeze-thaw and repeated loading. Transport Res Rec 918.

Balandin VV, Kochetkov AV, Krylov SV, et al. (2020) Experimental studies of the deformation properties of frozen soils under static and dynamic loads. Int J Physics Conference Series 1459: 012004. https://doi.org/10.1088/1742-6596/1459/1/012004

Chang D, Liu JK (2013) Review of the influence of freeze-thaw cycles on the physical and mechanical properties of soil. Sci Cold Arid Reg 5(4): 0457-0460.

Deprez M, Kock DT, Schutter DG, et al. (2020) A review on freeze-thaw action and weathering of rocks. Earth-Sci Rev 203: 103143. https://doi.org/10.1016/j.earscirev.2020.103143

Edwin JC, Anthon YJG (19790 Effect of freezing and thawing on the permeability and structure of soils. Eng Geol 13(1/2/3/4): 73-92. https://doi.org/10.1016/B978-0-444-41782-4.50012-9

Fan C, Zhang W, Lai Y, et al. (2021b) Mechanical behaviors of frozen clay under dynamic cyclic loadings with freeze-thaw cycles. Cold Reg Sci Tech 181: 103184. https://doi.org/10.1016/j.coldregions.2020.103184

Fan WH, Yang P, Yang ZH (2021a) Freeze-thaw impact on macropore structure of clay by 3D X-ray computed tomography. Eng Geol 280: 105921. https://doi.org/10.1016/j.enggeo.2020.105921

Hauck C, Isaksen K, Muhll DV, et al. (2004) Geophysical surveys designed to delineate the altitudinal limit of mountain permafrost: An example from Jotunheimen, Norway. Permafrost Periglac 15(3): 191-205. https://doi.org/10.1002/ppp.493

Hendry MT, Onwude LU (2016) A laboratory investigation of the frost heave susceptibility of fine grained soil generated from the abrasion of a diorite aggregate. Cold Reg Sci Tech 123: 91-98. https://doi.org/10.1016/j.coldregions.2015.11.016

Hu F, Li Z, Tian Y, et al. (2021) Failure patterns and morphological soil-rock interface characteristics of frozen soil-rock mixtures under compression and tension. Applied Sciences 11(1): 461. https://doi.org/10.3390/app11010461

Kong XX, Tian S, Tang L, et al. (2020) Dynamic behavior of coarse-grained materials with different fines contents after freeze-thaw cycles under multi-stage dynamic loading: Experimental study and empirical model. Cold Reg Sci Tech 175: 103078. https://doi.org/10.1016/j.coldregions.2020.103078

Li GY, Ma W, Zhao SP, et al. (2012) Effect of freeze-thaw cycles on mechanical behavior of compacted fine-grained soil. //Cold Regions Engineering 2012: Sustainable Infrastructure Development in a Changing Cold Environment 72-81. https://doi.org/10.1061/9780784412473.008

Lin B, Zhang F, Feng D, et al. (2017) Accumulative plastic strain of thawed saturated clay under long-term cyclic loading. Eng Geol 231: 230-237. https://doi.org/10.1016/j.enggeo.2017.09.028

Ling XZ, Zhang F, Li QL, et al. (2015) Dynamic shear modulus and damping ratio of frozen compacted sand subjected to freeze-thaw cycle under multi-stage cyclic loading. Soil Dyn Earthq Eng 76: 111-121. https://doi.org/10.1016/j.soildyn.2015.02.007

Liu JK, Chang D, Yu QM (2016) Influence of freeze-thaw cycles on mechanical properties of a silty sand. Eng Geol 210: 23-32. https://doi.org/10.1016/j.enggeo.2016.05.019

Liu EL, Lai YM, Liao MK, et al. (2016) Fatigue and damage properties of frozen silty sand samples subjected to cyclic triaxial loading. Can Geotech J 53(12): 1939-1951. https://doi.org/10.1139/cgj-2016-0152

Liu J, Wang T, Tian Y (2010) Experimental study of the dynamic properties of cement-and lime-modified clay soils subjected to freeze–thaw cycles. Cold Reg Sci Tech 61(1): 29-33. https://doi.org/10.1016/j.coldregions.2010.01.002

Luo Y, Qu DX, Wang G, et al. (2020) Degradation model of the dynamic mechanical properties and damage failure law of sandstone under freeze-thaw action. Soil Dyn Earthq Eng 132: 106094. https://doi.org/10.1016/j.soildyn.2020.106094

Ma W, Zhang LH, Yang CS (2015) Discussion on applicability of the generalized Clausius Clapeyron equation and the frozen fringe process. Earth-Sci Rev 142: 47-59. https://doi.org/10.1016/j.earscirev.2015.01.003

Matsuoka N, Murton J (2008) Frost weathering: recent advances and future directions. Permafrost Periglac 19: 195–210.
https://doi.org/10.1002/ppp.620.
Orakoglu ME, Liu JK, Niu FJ (2017) Dynamic behavior of fiber-reinforced soil under freeze-thaw cycles. Soil Dyn Earthq Eng 101: 269-284.
https://doi.org/10.1016/j.soildyn.2017.07.022
Othman MA, Benson CH (1993) Effect of freeze-thaw on the hydraulic conductivity and morphology of compacted clay. Can Geotech J 31(2): 236-246.
https://doi.org/10.1139/t93-020
Qi JL, Ma W, Song C (2008) Influence of freeze–thaw on engineering properties of a silty soil. Cold Reg Sci Tech 53(3): 397-404.
https://doi.org/10.1016/j.coldregions.2007.05.010
Qi JL, Vermeer PA, Cheng GD (2006) A review of the influence of freeze-thaw cycles on soil geotechnical properties. Permafrost Periglac 17: 245-252.
https://doi.org/10.1002/ppp.559
Simonsen E, Janoo CV, Lsacsson U (2002) Resilient properties of unbound road materials during seasonal frost conditions. J Cold Reg Eng 16(1): 28-50.
https://doi.org/10.1061/(ASCE)0887-381X(2002)16:1(28)
Tian S, Tang L, Ling XZ, et al. (2019) Experimental and analytical investigation of the dynamic behavior of granular base course materials used for China's high-speed railways subjected to freeze-thaw cycles. Cold Reg Sci Tech 157: 139-148.
https://doi.org/10.1016/j.coldregions.2018.10.003
Viklander P (1998) Permeability and volume changes in till due to cyclic freeze-thaw. Can Geotech J 35 (3): 471-477.
https://doi.org/10.1139/t98-015
Vinson TS (1975) Cyclic triaxial test equipment to evaluate dynamic properties of frozen soils. Final Report Michigan State Univ.
Vinsor TS (1980) Parameter effects on dynamic properties of frozen soils closure. J Geotech Geoenviron 106(ASCE 14109).
https://worldcat.org/oclc/3519342
Wang D, Yang CS, Cheng GD, et al. (2020) Experimental study on pore water pressure and microstructures of silty clay under freeze-thaw cycles. Transportation Soil Engineering in Cold Regions, Singapore 2: 239-254.
https://doi.org/10.1007/978-981-15-0454-9-26
Wang DY, Ma W, Niu YH, et al. (2007) Effects of cyclic freezing and thawing on mechanical properties of Qinghai–Tibet clay. Cold Reg Sci Tech 48(1): 34-43.
https://doi.org/10.1016/j.coldregions.2006.09.008
Wu ZW, Liu YZ (2005) Frozen Soil Foundation and Engineering Construction. Maritime Press: Beijing.
Xie S, Qu JJ, Lai YM, et al. (2015) Effects of freeze-thaw cycles on soil mechanical and physical properties in the Qinghai-Tibet Plateau. J Mt Sci 12(4): 999-1009.
https://doi.org/10.1007/s1629-014-3384-7
Xu XT, Zhang WD, Fan CX, et al. (2019) Effect of freeze-thaw cycles on the accumulative deformation of frozen clay under cyclic loading conditions: experimental evidence and theoretical model. Road Mater Pavement Design 4:925-941.
https://doi.org/10.1080/14680629.2019.1696221
Yang CS, He P, Cheng GD, (2004) Freeze thaw experiment influence on moisture content distribution of soil. J Glaciol Geocryol 26(suppl): 50-55.
https://doi.org/1000-024(2004)suppl.-0050-06
Zhang D, Li Q, Liu EL, et al. (2019) Dynamic properties of frozen silty soils with different coarse-grained contents subjected to cyclic triaxial loading. Cold Reg Sci Tech 157: 64-85.
https://doi.org/10.1016/j.coldregions.2018.09.010
Zhang SJ, Lai YM, Sun ZZ, et al. (2007) Volumetric strain and strength behavior of frozen soils under confinement. Cold Reg Sci Tech 47: 263-270.
https://doi.org/10.1016/j.coldregions.2006.10.001
Zhang Z, Ma W, Qi JL, (2013) Structure evolution and mechanism of engineering properties change of soils under effect of freeze-thaw cycle. J Jinlin Univ (Earth Sci Ed) 43(6): 1904-1914. (in Chinese)
https://doi.org/10.13278/j.cnki.jjuese.2013.06.017
Zhao LZ, Yang P, Wang JG et al. (2014) Cyclic direct shear behaviors of frozen soil structure interface under constant normal stiffness condition. Cold Reg Sci Tech 102: 52-62.
https://doi.org/10.1016/j.coldregions.2014.03.001
Zhao YH, Lai YM, Pei WS, et al. (2020) An anisotropic bounding surface elastoplastic constitutive model for frozen sulfate saline silty clay under cyclic loading. Int J Plast 129: 102668.
https://doi.org/10.1016/j.ijplas.2020.102668
Zhou YW, Guo DX, Cheng GD, (2000) Frozen soil of China. Science Press: Beijing. (In Chinese)
Zhu Z, Ling X, Chen S, et al. (2011) Analysis of dynamic compressive stress induced by passing trains in permafrost subgrade along Qinghai–Tibet Railway. Cold Reg Sci Tech 65(3): 465-473.
https://doi.org/10.1016/j.coldregions.2010.10.011