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Research Article

The Study of Influence of Freeze-Thaw Cycles on Silty Sand in Seasonally Frozen Soil Regions

Zhijie Yu,[1,2] **Jianhong Fang**,[2,3,4] **Anhua Xu**,[2,3,5] **and Wenjun Zhou**[2]

[1]*China University of Mining and Technology-Beijing, Beijing 100083, China*
[2]*Qinghai University, Xining, Qinghai 810016, China*
[3]*Qinghai Research Institute of Transportation, Xining, Qinghai 810016, China*
[4]*Qinghai Research and Observation Base, Key Laboratory of Highway Construction & Maintenance Technology in Permafrost Region, Ministry of Transport, Xining, Qinghai 810016, China*
[5]*Qinghai Communications Technical College, Xining, Qinghai 810016, China*

Correspondence should be addressed to Jianhong Fang; 13709719909@163.com

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Freeze-thaw cycles can cause varying degrees of damage to expressway, in order to study the influence of freeze-thaw cycles on silty sand of expressway in Qinghai seasonal frozen soil regions, triaxial compression tests were carried out on silty sand under different initial freeze-thaw temperatures and freeze-thaw cycles. The stress-strain curve, secant modulus, cohesion, internal friction angle, dynamic shear modulus, and dynamic damping ratio of soil after freeze-thaw cycles were analyzed and studied. The experimental results show that the number of freeze-thaw cycles has different effects on the stress-strain curves at different initial freezing temperatures. With the increase of freeze-thaw cycles, the secant modulus of soil increases and changes in wave shape. The cohesion decreases and the internal friction angle decreases nonlinearly. The dynamic shear modulus and damping ratio do not change significantly. The change of freeze-thaw cycles will also affect the physical structure of the soil itself. The change of freeze-thaw cycles will also affect the physical structure of the soil itself. It will change the mosaic form of soil particles, the shape of soil particles, the size of soil particles and pores, and also make the redistribution of water in the soil.

1. Introduction

In areas where seasonal or diurnal cycles of freezing and thawing occurs, the original mechanical properties of the soil can be weakened and damaged as the structure and original arrangement of soil particles change [1]. Number and change of freezing and thawing cycles substantially impact the bearing capacity of soil. Fine-grained soil and silty sand used for road engineering are particularly very sensitive to freezing and thawing cycles. Repeated phase changes of water vapor in soil can cause frost heaving and uneven settlement changes, undermining the durability and stability of road engineering [2]. However, current understanding of how freeze-thaw cycles affect the basic mechanical properties of soil has predominantly been explored in the laboratory, and we know little about how real-world conditions affect. Meanwhile, seasonal frozen soil is mainly distributed 2in the northern part of Qinghai Province, with many freeze-thaw cycles and large temperature changes.

Overall, there is little consensus as to how freeze-thaw cycles affect soil properties. Studies have alternatively found that these cycles have destructive [3–5], strengthening [6, 7], or little [8] impact on soil strength. The cohesion and internal friction angle of soil was found to decrease with increasing numbers of freeze-thaw cycles in fine-grained soils. The effect of water content on cohesion and internal friction angle is most obvious [9]. Subgrade highway soil also degraded under repeated freezing and thawing. The function that resilient modulus can be expressed as stress state variable is presented, and the general equation is given. It is pointed out that the effect of freeze-thaw cycle on constitutive relation is not obvious [10]. The cohesion on high-density soil also decreased after repeated freeze-thaw cycles; however, low-density soil cohesion decreased under the same conditions [11]. Other studies have found that the ultimate strength of frozen-thawed soil is positively correlated with the compactness [12]. Leroueil et al. [13] found that the strength of clay after freezing and thawing was lower than unfrozen undisturbed clay. And in the stress-strain curve, the frozen-thawed soil showed the nature of normal consolidated soil, while the undisturbed soil showed strong dilatancy and typical softening characteristics of overconsolidated soil behavior.

In the study of cohesion and internal friction angle of shear strength parameters of soil, due to the obvious influence of freeze-thaw cycle on the micromorphology of soil, the two parameters of cohesion and internal friction angle explained from the microscopic mechanism of soil have different changes. Swan and Greene [14] showed that the strength of soil remained basically unchanged before and after freezing and thawing. The cohesion of compacted silt decreased gradually under additional freeze-thaw cycles, while the internal friction angle first decrease and then subsequently increased after reaching a minimum value after seven freeze-thaw cycles [15, 16]. Freezing and thawing turned compacted silty clay from an unstable state to a dynamic stable state, in which failure strength first decreased and then increased to a plateau while cohesion decreased and internal friction angle fluctuated [17]. The macroscopic and microscopic properties of silty clay and loess were both altered by freeze-thaw cycles; cohesion increased and internal friction angle increased in both with a freeze-thaw cycle [18]. It was proposed that the decrease in cohesion was driven by the formation of ice crystals during the freezing process, which destroyed the connections between soil particles. The increase in internal friction angle, on the other hand, appeared to be due to a decrease in the number of large pores present in the soil after each freeze-thaw. While the internal friction angle of loess remained unchanged after repeated freeze-thaw cycles, the cohesion decreased during the first ten cycles before increasing with additional cycles [19]. In soils with high water content, freeze-thaw action has great influence on soil cohesion and decreases with the increase of freeze-thaw cycles [20]. The lower the freezing temperature, the greater the decrease in cohesion. Internal friction angle, however, remained unaffected. The stress-strain relationship curve of compacted modified clay after freezing and thawing gradually transitions from strain softening to strain hardening, with decreasing cohesion as the number of cycle processes [21, 22]. Yao et al. [23] found that the freeze-thaw cycle has a dual effect on soil engineering properties of remolded clay, which is related to the relative size of dry density and critical dry density of soil. There is no unified conclusion on how shear strength parameters under freeze-thaw cycles. However, from the literature and other data cited above, in general, cohesion tends to decrease after freezing and thawing, while the internal friction angle exhibits a variety of trends.

The above research suggests that the effect of freeze-thaw cycles on the mechanical properties of soil is highly complex (an issue that may be compounded by the wide variety of different experimental methods used). Affected by soil type and original state, remolded soil and undisturbed soil clearly demonstrate different mechanical properties after being subject to freeze-thaw cycles. As such, we selected the soil samples and analyzed the dynamic and static mechanical properties of the soils after subjecting them to different initial freezing temperatures (room temperature (25°C), -5°C, -10°C, and -15°C) and numbers of freeze-thaw cycles (0, 5, 10, 20, and 30 times).

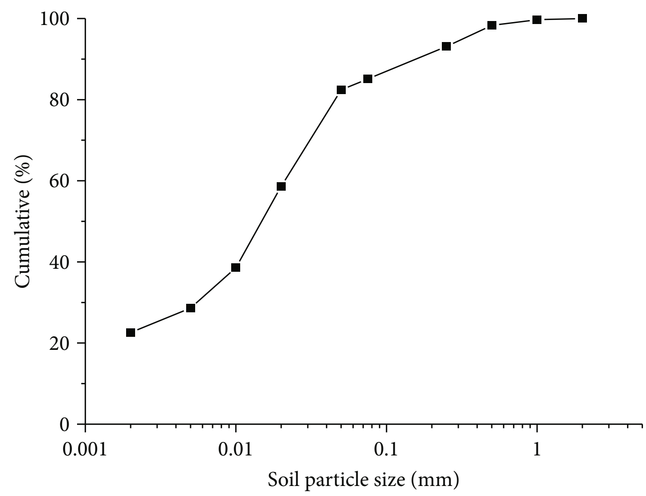

Figure 1: Particle gradation curve of the soil used in the test.

2. Soil Samples and Test Scheme

The test sampling site is the Eboling section of the Bianmen Expressway. The route, which runs northwest to southeast, starts near the maintenance boundary of Qing-Gan Highway in Biandukou, connects with the Zhangye-Biandukou Expressway planned by Gansu Province, and belongs to seasonal frozen regions. Soil was collected from extraction pile number $K34 + 258$, in Qinghai Haibei Tibetan Autonomous Prefecture.

Figure 1 shows the particle gradation curve of the soil used in the test, and Table 1 explains about physical properties of soil samples.

2.1. The Samples Were Classified as "Silty Sand" according to the Highway Geotechnical Test Specification (JTG E40-2007). Soils were subject to static load and dynamic load tests performed under confining pressure of 200 kPa based on the variation range of cold and hot temperature of the environment. The thawing temperature was set at room temperature (25°C); freezing temperatures included -5°C, -10°C, and -15°C. The number of freeze-thaw cycles tested includes 0, 5, 10, 20, and 30 cycles. The soil samples at each initial freezing temperature should undergo 0, 5, 10, 20, and 30 freezing-thawing cycles, respectively. The soil sample quality changes before and after freezing and thawing were measured to evaluate the effects of freezing and thawing temperatures and number of cycles. The specific test schemes are shown in Table 2.

3. Experimental Process

According to the guidelines for soil sample treatment and sample preparation outlined in *Highway Geotechnical Test*

Table 1: Physical properties of soil samples.

Natural moisture content w/%	Plastic limit w_p/%	Liquid limit w_L/%	Plasticity index I_p	Maximum dry density $\rho_{d\ max}$/(g/cm^3)	Optimal moisture content w_{op}/%
16.44	17.6	25.6	8.0	1.97	12.20

Table 2: Test condition settings.

Controlled conditions	Variable enactment
Testing temperature T/°C	Room temperature (25), -5, -10, -15
Freeze-thaw cycles/times	0, 5, 10, 20, 30
Loading control mode	Static load test, graded cyclic dynamic load test

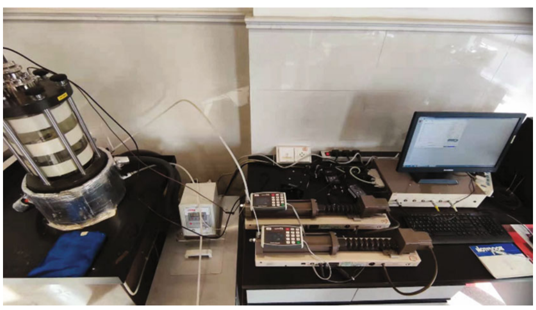

Figure 2: Triaxial test system.

Specification (JTG E40-2007), the dry density of the sample was controlled, and the triaxial test sample was prepared using the layered compaction method. After the samples were collected in a cylinder with a diameter of 39.1 mm and a height of 80 mm, they were dried in an oven and then passed through a 2 mm sieve. The sample was mixed subsequently with water according to the optimal moisture content, after which it was sealed and kept for 24 h. Soil samples were subsequently weighed and placed into three valves in five layers for compaction to ensure sample homogeneity. The sealing method of the sample is to tightly wrap the soil with plastic film and then tighten the plastic film at both ends. Wrapped samples were then put into sealing bags to minimize water loss.

The freeze-thaw test uses a special automatic high-precision freeze-thaw test box with ±0.1°C accuracy. When the prepared and sealed samples were put into the freeze-thaw box, the internal temperature was set at the test temperature (-5°C, -10°C, and -15°C) for 12 h, and then the melting test was carried out at 25°C for 12 h, to ensure the complete freezing and full melting of the sample (i.e., one freeze-thaw cycle).

The static triaxial and dynamic triaxial tests were performed on a servo motor-controlled dynamic triaxial test system DYNTTS (GDS Instruments, UK) (Figure 2). The test system is composed of three parts: a triaxial loading device, a data acquisition and pressure control system, and a software system. Test types included unconsolidated undrained (UU) compression shear tests and graded cyclic dynamic load tests. The confining pressure was set to 200 kPa with a static axial loading rate of 0.8 mm/min, a control strain of 20%, and the dynamic load is loaded step by step with 20 kPa amplitude of each stage, each stage vibration 12 cycles.

To quantify the influence of number and temperature of freeze-thaw cycles on the elastic modulus and stiffness of soil, we obtained the secant modulus at the peak point which can be calculated from the stress-strain curve relationship under static load and the modulus E_{50} which can reflect the change of soil elastic modulus. The calculation for E_{50} is

$$E_{50} = \frac{q_{50}}{\varepsilon_{50}}. \tag{1}$$

In the formula, q_{50} is a half of the peak deviatoric stress, and ε_{50} is a half of the axial strain.

The cohesion c and internal friction angle φ—shear strength parameters of soil samples—were calculated using the longitudinal intercept of the p-q curve on the coordinate axis and the tangent value of the oblique line. These parameters are calculated as follows:

$$c = \frac{d}{\cos \phi}, \tag{2}$$

$$\phi = \sin^{-1}(\tan \alpha), \tag{3}$$

where α is linear fitting line inclination, and d is linear fitting line intercept on the longitudinal axis.

The hyperbolic model is used for dynamic load analysis, and calculation as this model can better reflect the dynamic stress-strain relationship of soil under the action of the freeze-thaw cycle. This model is expressed as

$$\tau_d = \frac{\gamma_d}{a + b\gamma_d}, \tag{4}$$

$$G_d = \frac{\tau_d}{\gamma_d}, \tag{5}$$

where τ_d is dynamic shear stress, γ_d is dynamic shear strain, G_d is dynamic shear modulus, and a and b are test parameters. The corresponding dynamic damping ratio calculation formula is

$$\lambda_d = \frac{S}{4\pi S_\Delta}, \tag{6}$$

where γ_d is the dynamic damping ratio, S is the elliptical area (blue part in Figure 3), and S_Δ is the triangular OAB area (pink part in Figure 3), as shown in Figure 3.

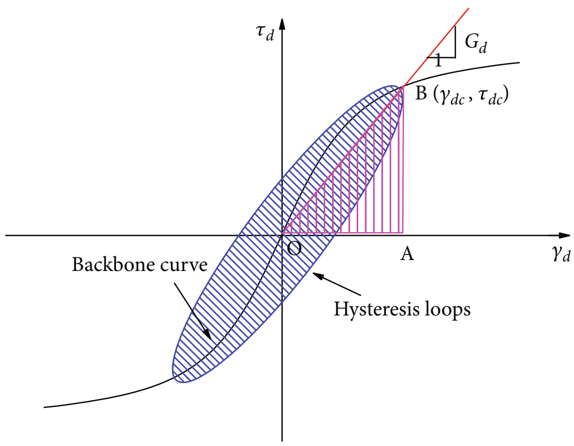

FIGURE 3: Schematic diagram of hysteresis loops.

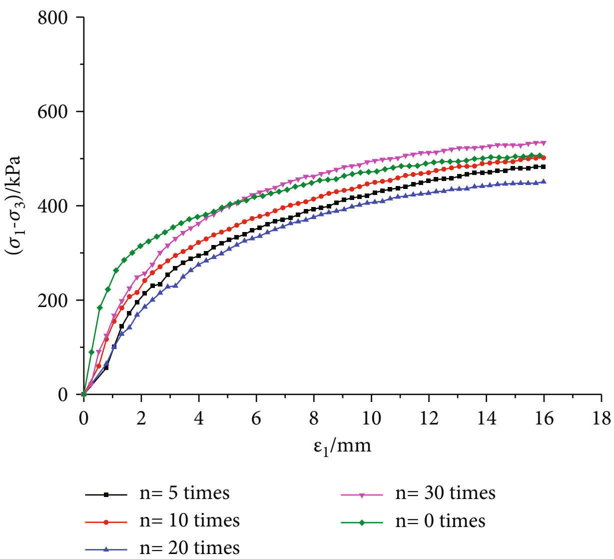

FIGURE 4: Stress-strain curves under different freeze-thaw cycles (-5°C).

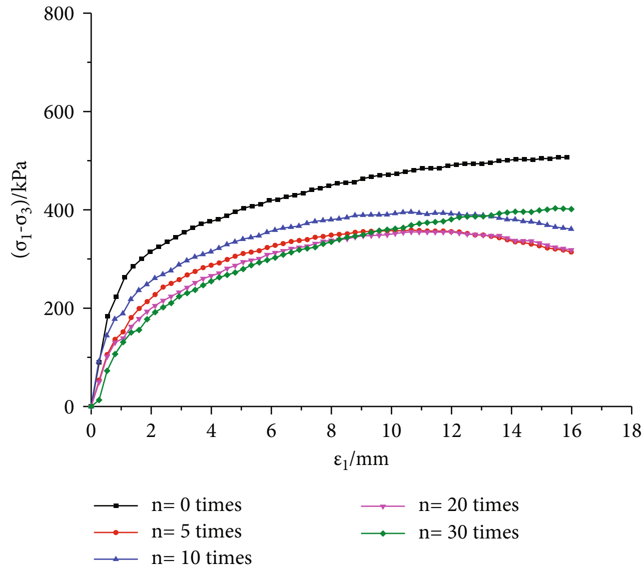

FIGURE 5: Stress-strain curves under different freeze-thaw cycles (-10°C).

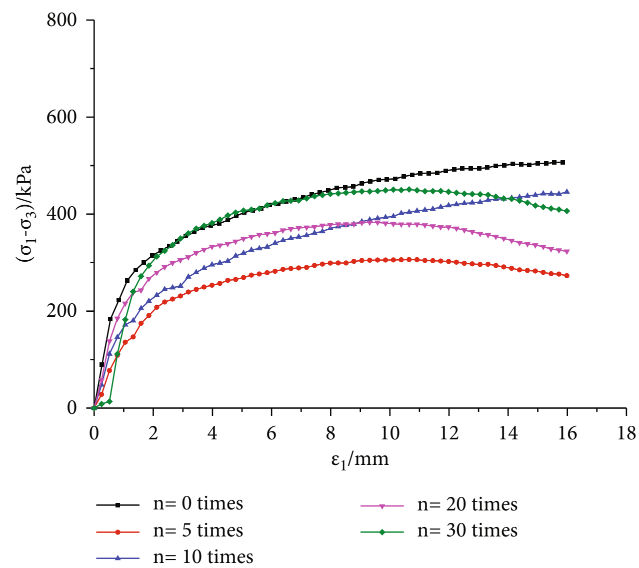

FIGURE 6: Stress-strain curves under different freeze-thaw cycles (-15°C).

4. Test Result

4.1. Static Load Test Results. At the same freezing and thawing temperature, the deviatoric stress-strain curves of silty sand subject to different numbers of freezing and thawing cycles demonstrate different types (Figures 4–6). The stress gradually increases and finally stabilizes with the strain, or the stress gradually increases with the strain, and then decreases after reaching a peak. These are strain hardening and strain softening types corresponding to elastic-plastic changes, respectively.

Overall, the stress-strain curve of soil after freezing and thawing was lower than the curve generated by unfrozen soil samples. When the freezing temperature was -5°C, the number of cycles had little effect on the curve and the curve was dense. When the freezing temperature was -10°C, the curve began to disperse. At -15°C, the number of freeze-thaw cycles had a substantial influence, strongly dispersing the curve. This is due to the fact that the lower the temperature, the higher the strength of the ice crystals inside the soil and the easier it is to disturb the internal structure of the soil. The Eboling soil sample was particularly sensitive to the number of freeze-thaw cycles and freeze-thaw temperature.

4.2. Dynamic Load Test Results. The dynamic stress-strain curves of the three figures showed a hyperbolic trend, in which the shear stress increased gradually with the increase of shear strain (Figures 7–9). Only the curve late lifting trend differed with the change of freeze-thaw cycles: under constant shear strain, shear stress gradually increased with additional cycles at -5°C but at -10°C and 15°C, the shear stress increases and decreases with the increase of freeze-thaw

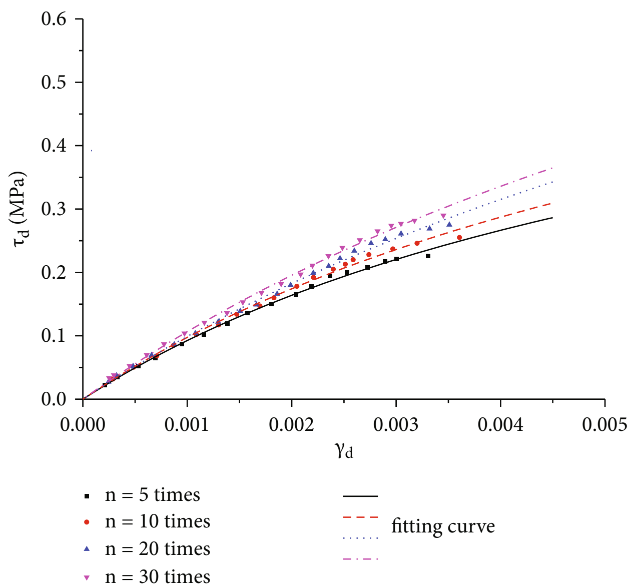

Figure 7: Dynamic stress-strain curves under different freeze-thaw cycles (-5°C).

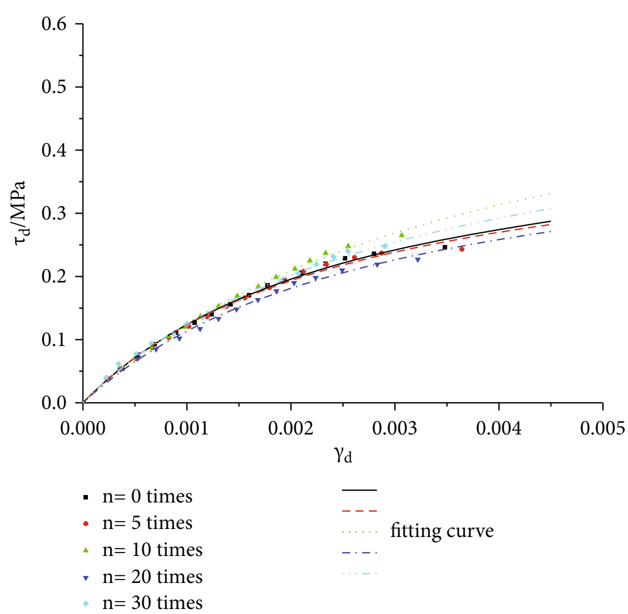

Figure 8: Dynamic stress-strain curves under different freeze-thaw cycles (-10°C).

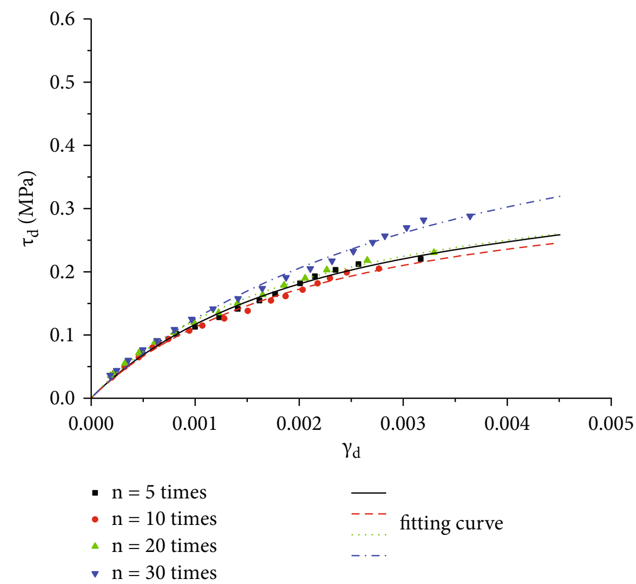

Figure 9: Dynamic stress-strain curves under different freeze-thaw cycles (-15°C).

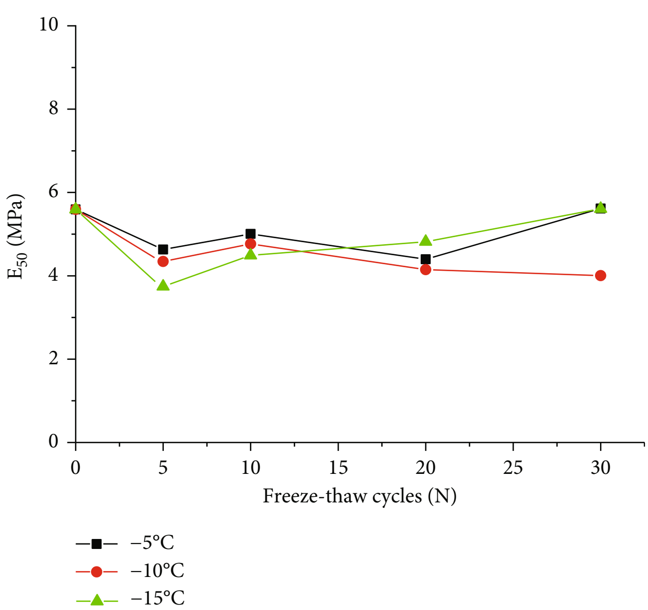

Figure 10: Relationship between different freeze-thaw cycles and secant modulus.

cycles, and the increase and decrease are different, showing wave changes.

5. Discussion

5.1. Secant Modulus. The influence of freeze-thaw cycles on the strength and modulus of soil is complex. Under different freezing temperatures, the secant modulus of silty sand increases and decreases with the increase of freeze-thaw cycles. When the number of freeze-thaw cycles is less, this trend changes obviously. With the continuous increase of freeze-thaw cycles, this trend is different (Figure 10).

Soil freezing and thawing rate are affected by soil particle size, temperature, degree of compaction, external water conditions, moisture content, and the mineral composition of the soil itself. Here, the degree of compaction and soil moisture content was held constant, such that the freezing and thawing process predominantly affected water migration. Lower freezing temperatures appeared to cause uneven migration of water through the soil. In the experimental apparatus used, freezing and melting both occurred from the outside to the inside of the soil sample. This process generates differing moisture contents in different regions of the soil sample. When the strength of soil in regions with lower

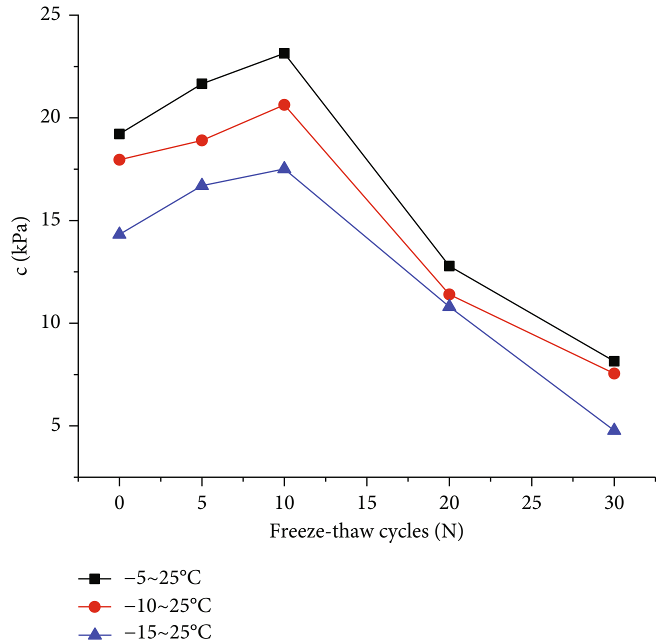

Figure 11: Relationship between freeze-thaw cycles and cohesion.

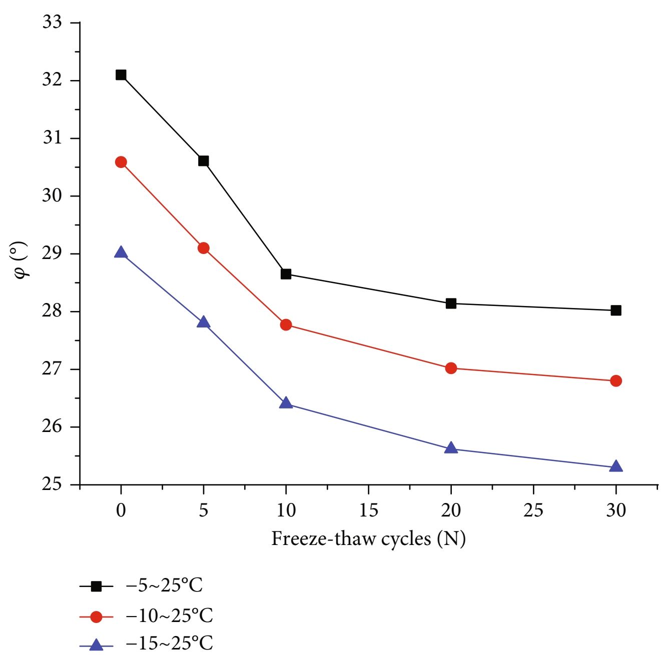

Figure 12: Relationship between freeze-thaw cycles and internal friction angle.

water content increases, strength in the high water content regions decreases, such that the gains and losses in the strength of each region is inconsistent. Therefore, the difference in the distribution of internal and external water content of soil caused by freezing and thawing cycles affects the variation in overall soil strength, resulting in the variety of observed results that soil strength remains unchanged, decreases, or increases after freezing and thawing. In addition, the number of freezing and thawing cycles makes water

Table 3: Fitting parameters of freeze-thaw cycles and internal friction angle.

Temperature	φ_0	A_1	t_1	Correlation coefficient R^2
-5°C~25°C	28.27	5.02	0.92	0.937
-10°C~25°C	26.82	4.28	0.91	0.987
-15°C~25°C	25.35	4.44	0.93	0.978

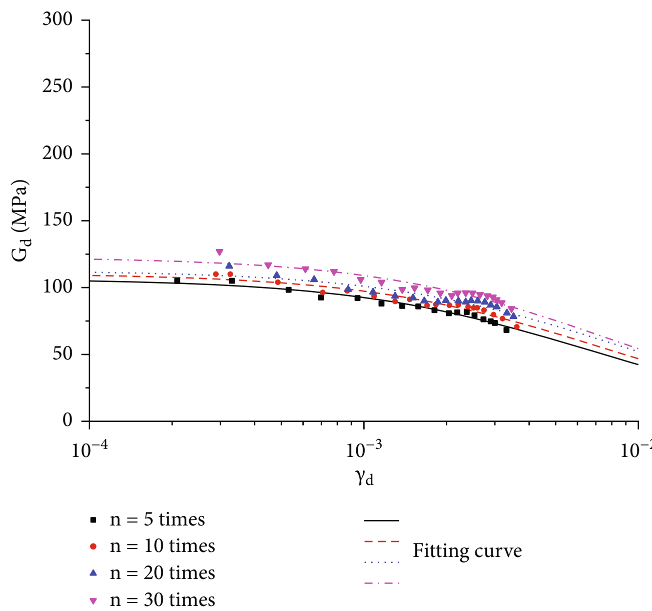

Figure 13: Dynamic shear modulus-strain curves under different freeze-thaw cycles (-5°C).

migration through the soil more complex (i.e., in duration and migration path), further modulating soil strength responses. This complex change process is also related to the nature of the soil itself, an area of study which should be examined further.

5.2. Cohesion. At present, the Mohr-Coulomb theory is widely used to predict the shear strength of soil, primarily due to its simplicity with only easily obtainable two characterization parameters. The variation law of parameter cohesion c obtained by Mohr-Coulomb criterion under freeze-thaw cycle is analyzed below.

Figure 11 shows the relationship of cohesion under different freeze-thaw cycles. Cohesion reaction is the chemical and physical force of soil particles, mainly the Van der Waals, coulomb, and particle bonding forces. For between 0 and 10 freeze-thaw cycles, cohesion gradually increased, but then decreased after 10-30 cycles (Figure 11). From the analysis of the frost heaving mechanism of water between particles, free water freezes at the beginning of the freeze-thaw cycle, squeezing the small pores in the soil and increasing the density and cohesion of the soil. Under repeated freezing and thawing cycles, the original strongly cemented large particles move further apart and break up to a certain extent, decreasing soil cementation and degrading soil structure. As a consequence, bearing capacity, load transfer capacity, and soil cohesion all decrease.

5.3. Internal Friction Angle. Another important parameter of Mohr-Coulomb equation is the internal friction angle, φ, which reflects the friction characteristics between soil particles, i.e., the roughness of the soil, the ability for soil particles to interlocking, and the adsorption friction ability caused by negative pore water pressure in soil. The results suggest that the soil internal friction angle decreases nonlinearly with increasing numbers of freeze-thaw cycles, although this trend tends to stabilize after 30 freeze-thaw cycles (Figure 12).

The change trend of freeze-thaw cycles and internal friction angle can be expressed by the following formula:

$$\phi = \phi_0 + A_1 \exp\left(t_1 \times R_x\right). \tag{7}$$

In the formula, φ_0, A_1, and t_1 are the test parameters related to the properties of the soil itself, and R_x is the number of freeze-thaw cycles. This model fit the data well, and the final test parameters are shown in Table 3.

There is no general consensus about how soil internal friction angle should change when subject to increasing freeze-thaw cycles. The results suggest that this variability can be explained by how the structure of the soil is damaged under freezing and thawing. We hypothesize that the initial freeze-thaw breaks the soil particles and alters the linkage characteristics between soil particles, which is consistent with the cohesive force analysis results. The ice crystals that form weaken the interlocking ability between particles, changing the original roughness of soil particles and further reducing the friction angle. The results suggest that this decrease in internal friction angle is the most intense between 0 and 10 freeze-thaw cycles. With additional freeze-thaw cycles, soil particle properties that affect the internal friction angle gradually adapt to the freeze-thaw environment and become stable, stabilizing the internal friction angle such that there is no subsequent fluctuation.

Under the conditions of different freeze-thaw temperature variation ranges (-5 ~25°C, -10~25°C, -15~25°C), after the same freeze-thaw cycles, the cohesion and internal friction angle of the test soil samples have obvious differences in different temperature variation ranges. First, it can be seen that the cohesion increases and then decreases, and the friction angle decreases all the time. Under the same freeze-thaw cycle, the cohesion and friction angle decrease with

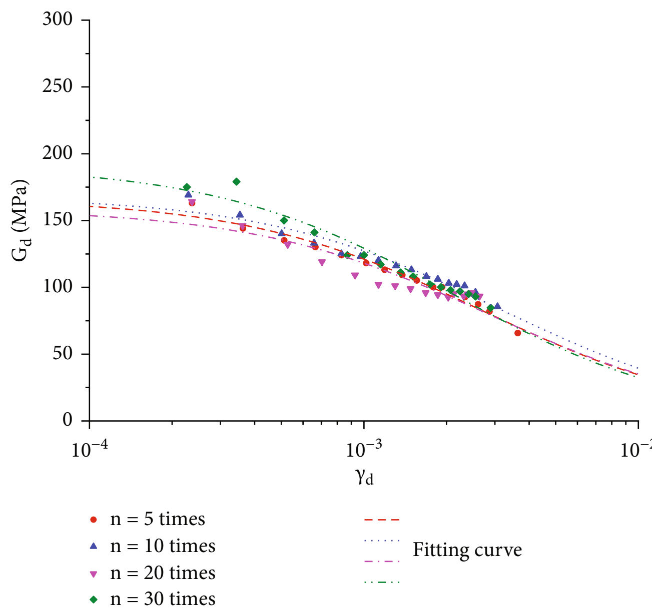

FIGURE 14: Dynamic shear modulus-strain curves under different freeze-thaw cycles (-10°C).

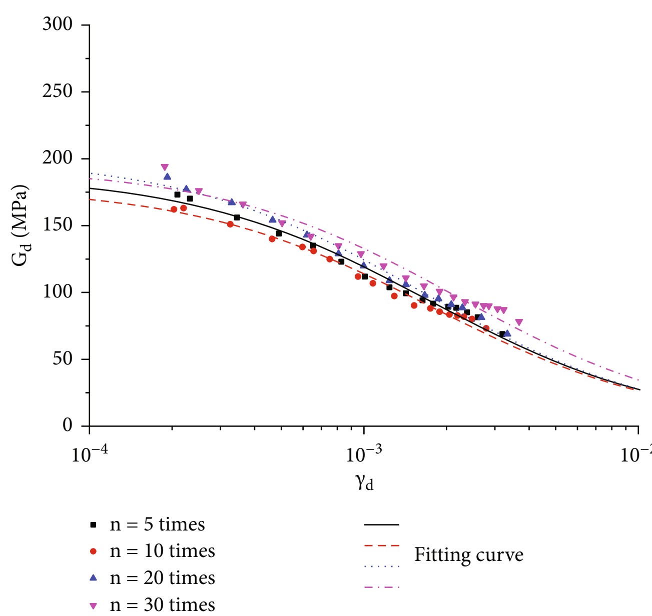

FIGURE 15: Dynamic shear modulus-strain curves at different freeze-thaw cycles (-15°C).

the decrease of freezing temperature, because the ice content of soil increases with the decrease of freezing temperature after freeze-thaw cycle. The volume of water in the soil increases during the freezing process, filling the gap of soil particles and promoting the migration of soil particles so that the porosity of frozen soil increases. And the mutual position of soil particles in the soil is very different from before, which destroys the original structure of the soil to a certain extent and changes the cohesion of the soil. The lower the temperature is, the smaller the cohesion and the friction angle after the freeze-thaw cycle are. With the increasing number of freeze-thaw cycles, the friction angle gradually tends to be stable, indicating that the freeze-thaw cycle process makes the soil develop from unstable state to dynamic stable state. Repeated freeze-thaw cycles change the original soil properties make the soil develop towards a new dynamic stable equilibrium state. The dry bulk density of soil no longer changes with the number of freeze-thaw cycles and the soil structure tends to be stable, and the friction angle also tends to be relatively constant.

The redistribution of water also affected the change of soil water and soil potential. This further altered the matric suction of unsaturated soil, changing the water content in different regions of the soil sample. For example, when the change in soil surface and internal water content differ, soil cohesion and internal friction angle are affected.

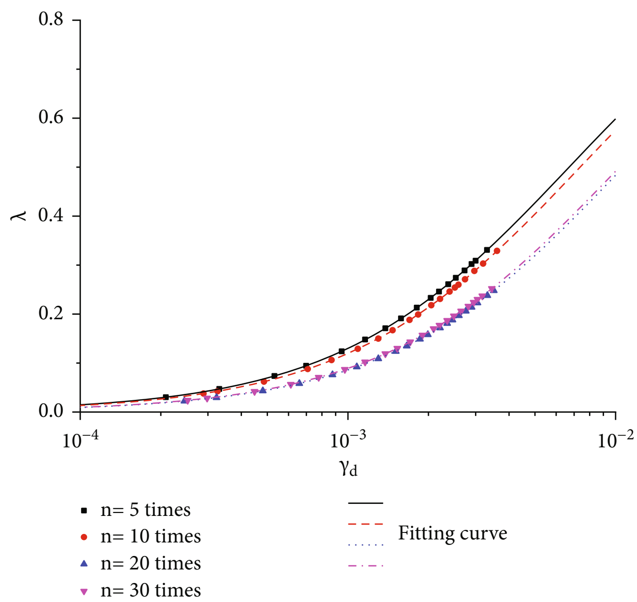

FIGURE 16: Damping ratio-strain curves under different freeze-thaw cycles (-5°C).

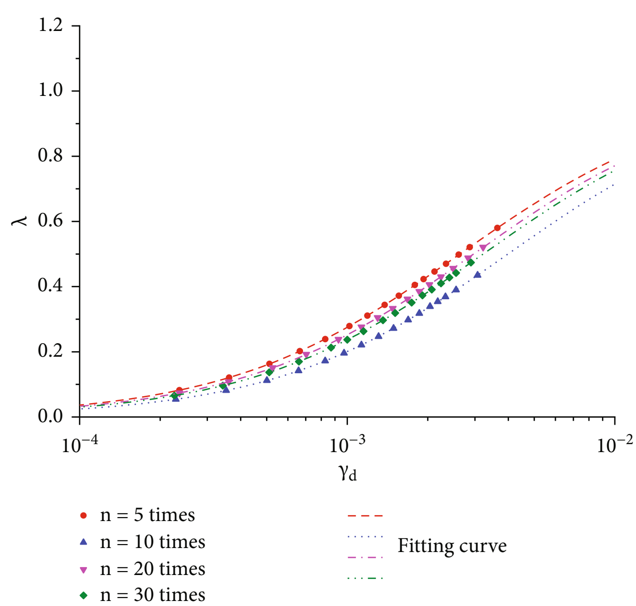

FIGURE 17: Damping ratio-strain curves under different freeze-thaw cycles (-10°C).

5.4. Dynamic Shear Modulus. The change of dynamic shear modulus is calculated by the strain curve of soil. The variation law of curves at different temperatures was similar (Figures 13–15). With increasing shear strain, the dynamic shear modulus decreased gradually, such that the whole curve decreased slowly and the slope of the curve is small at higher freezing temperature. When the freezing temperature is high, the whole curve decreased rapidly, and the slope of the curve increased. Under the same shear strain, the dynamic shear modulus increased with increased number of freeze-thaw cycles at -5°C, but increases and decreases

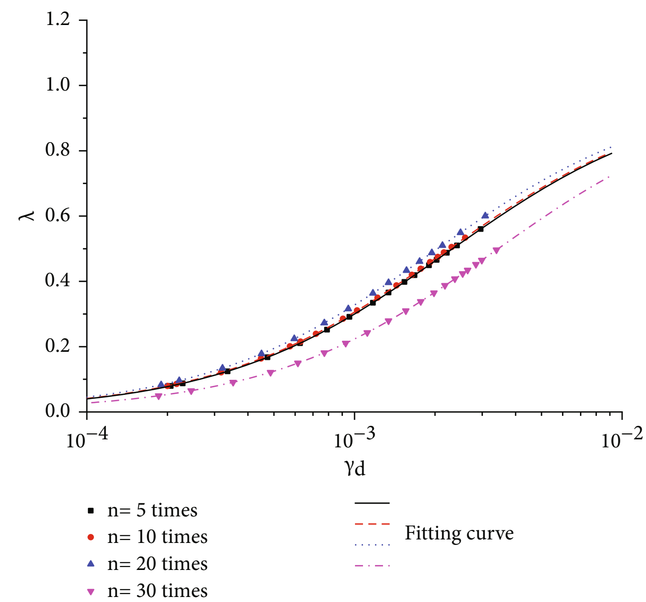

FIGURE 18: Damping ratio-strain curves under different freeze-thaw cycles (-15°C).

unstably with freeze-thaw cycle number at -10°C and -15°C. However, this change occurs in a small range without great fluctuation.

5.5. Dynamic Damping Ratio. With an increase of dynamic shear strain, the dynamic damping ratio increased slowly from the initial stage to 10^{-3} and then increased rapidly (Figures 16–18). That is to say, when the strain was small, the graded dynamic load was also small. With increasing strain, the graded load amplitude, energy dissipation, and dampening ratio also increased. At a freezing temperature of -5°C and constant shear strain, the damping ratio decreased with increase freezing and thawing cycles until 20 and 30 cycles, when the damping ratio stopped changing. When the freezing temperature was -10°C and -15°C, the damping ratio varied with an increase in the number of freeze-thaw cycles.

5.6. Dynamic Shear Modulus. At the same freezing temperature, the maximum dynamic shear modulus changed little with freeze-thaw cycles, but at -5°C, the maximum dynamic shear modulus decreased significantly without freezing and thawing (Figure 19). The final shear stress amplitude reflects the speed of the strain rate in the loading process. The reference shear strain amplitude at -5°C increased substantially with number of freezing and thawing cycles, but then stabilized, indicating that the strain rate transformation was fastest at this time (Figure 20). The reference shear strain amplitude at the other two freezing temperatures changed little with additional freezing and thawing cycles, which is consistent with the variation law of the maximum dynamic shear modulus and the maximum damping ratio behind (4.7 part). As such, the influence of freezing and thawing cycles on the dynamic shear modulus depends on the magnitude of the freezing temperature.

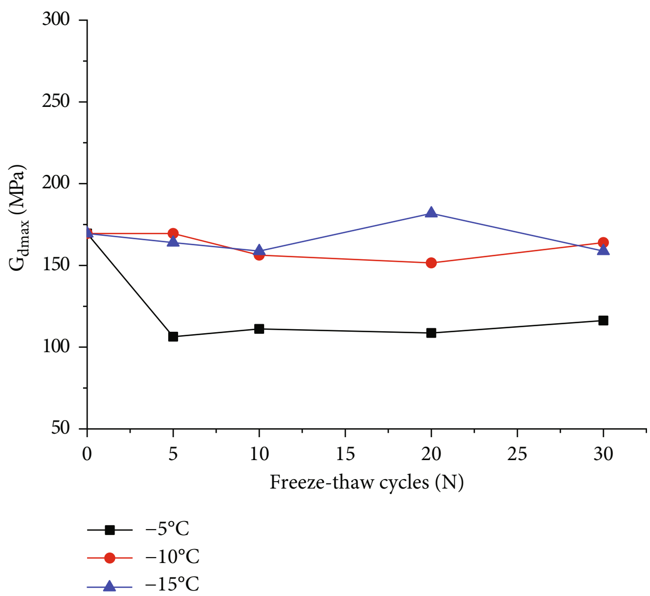

Figure 19: Curve of maximum dynamic shear modulus and freeze-thaw cycles at different freezing temperatures.

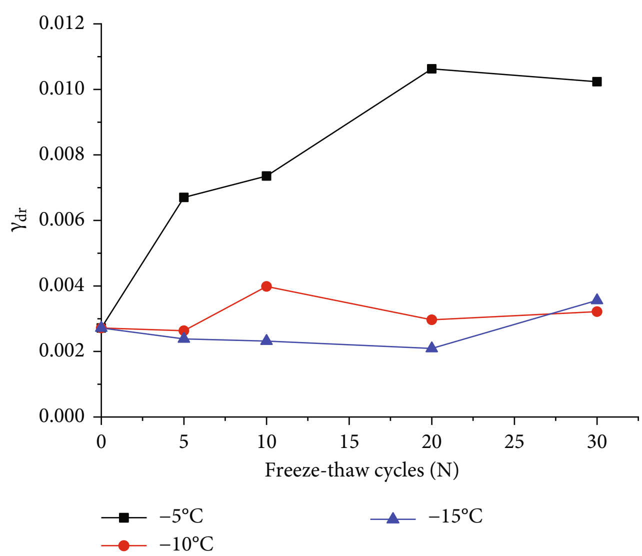

Figure 20: Curve of reference shear strain amplitude and freeze-thaw cycles at different freezing temperatures.

Moisture migration through frozen soil is related to the change of soil water potential gradient and temperature gradient during the freezing process, the nature of the soil itself, the boundary setting conditions, the freezing speed, and other factors. In the study, the soil samples exhibited different structural changes with an increase in the number of freezing and thawing cycles. These changes are similar to those of the previous static loading samples. The change of soil porosity caused by frost heaving and shrinkage causes uneven distribution of water on the inside and outside of the soil due to the uneven water migration and formation of the freezing edge, affecting soil strength. At -5°C, large pores are further compacted under the slow extrusion of

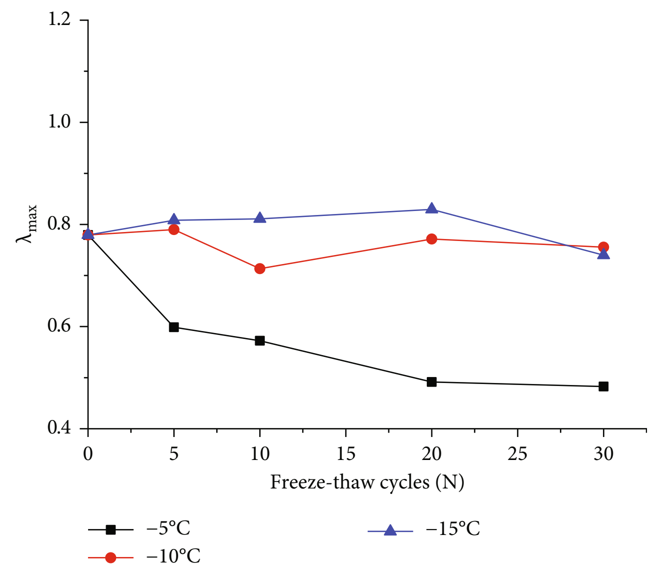

Figure 21: Curve of maximum damping ratio and freeze-thaw cycles at different freezing temperatures.

ice crystals. Due to the application of dynamic load, coarse particles change from being dense to loosely compacted, substantially reducing the maximum dynamic shear modulus compared with the soil sample that did not undergo freeze-thaw. On the other hand, rapid freezing and thawing of soil samples under low temperatures can make the soil particles become loose. When the graded dynamic load is applied, the soil gradually changes from small amplitude to large amplitude and the soil becomes dense again. As such, the maximum dynamic shear modulus is not affected. However, these are small fluctuations compared to other moisture migration, water potential, and temperature gradient changes.

5.7. Dynamic Damping Ratio. The reason why the number of freeze-thaw cycles affects the damping ratio is consistent with the reason why the number of freeze-thaw cycles affects the dynamic shear modulus described in the second paragraph of part 4.6. At a freezing temperature of -5°C, the maximum dynamic damping ratio decreases substantially as the number of freezing and thawing cycles increases (Figure 21). This is due to the slow freezing process and the formation of freezing edge compacting the soil gap, which causes the dynamic shear modulus and the stiffness to increase. At this time, the energy consumption of the soil under dynamic load decreases, so the area of the formed hysteresis loop decreases, and the damping ratio decreases accordingly.

When the freezing temperature is reduced to -10°C and -15°C, the fast freezing speed and the rapid formation of ice crystals and freezing edges cause the pores of the soil to be expanded by ice crystals, loosening the soil. The dynamic shear modulus subsequently decreases and the damping increases. However, due to the application of graded cyclic dynamic load, the vibration load has a vibration-tight effect on the loose soil, which makes up for the original damage of the soil. Therefore, as a whole, it has a certain repair effect on soil damage caused by freeze-thaw cycles. Therefore, the dynamic shear modulus fluctuation is not obvious, and the stiffness loss is not large. In the same principle, the energy loss will not be significantly increased; the damping ratio changes little accordingly.

6. Conclusions

The number of freeze-thaw cycles had a significant impact on the silty sand, in which the secant modulus changed in wave form with increasing numbers of cycles. Furthermore, large numbers of freeze-thaw cycles affected the physical structure of the soil itself resulting in soil stress-strain changes, including soil particle size, pore size, the soil particles mosaic, and redistribution of water.

The cohesion of silty sand decreased substantially with increasing numbers of freeze-thaw cycles, while the internal friction angle also decreased but in a nonlinear fashion. The transformation law can be described by an exponential function. The freeze-thaw cycling action continuously rounds the irregular soil particles and weakens the embedded friction between the particles, thus, causing the internal friction angle to decrease.

The dynamic shear modulus, maximum dynamic shear modulus, damping ratio, maximum damping ratio, and other dynamic characteristic parameters did not change significantly with the increase of freeze-thaw cycles. This is due to the graded cyclic dynamic load has a restorative effect on the soil after freeze-thaw cycles, such that the damage microcracks or pores created by freeze-thaw cycles have vibration densification (especially under small amplitude load). Therefore, this study can provide a certain reference value for engineering practice.

Data Availability

The data required has been included in this article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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