Research Article

Dynamic Behavior of Geosynthetic-Reinforced Expansive Soil under Freeze-Thaw Cycles

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Expansive soil has a significant impact on the stability of many key construction projects in cold regions. To study the physical and mechanical properties of expanded soil under the condition of freeze-thaw cycle, cryogenic cyclic triaxial tests were conducted on the dynamic and the displacement characteristics of geosynthetic-reinforced expansive soil subjected to the freeze-thaw cycles. Compared with the unreinforced expansive soil samples, the effects of freeze-thaw cycles on the soil dynamics were discussed. The dynamic shear modulus ($G_d$) and damping ratio ($\lambda$) of the expansive soil samples are improved by reinforcement. Reinforced soil can inhibit the axial compression of the sample and restrain the frost heave deformation of the sample during the freezing process. Meanwhile, it can delay the structural damage effect caused by frost heave and reduce the rate of change of the $G_d$ and the $\lambda$ with the freeze-thaw cycle. At the same time, reinforced soil can inhibit the axial expansion, reduce the rate of reduction of the $G_d$, stabilize it with a higher rate, and reduce the influence of the freeze-thaw cycles on the $\lambda$ of the expansive soil sample. Finally, the change of mechanical properties of expansive soil under the condition of reinforcement is obtained. The main conclusions of this paper can be used to reinforce the roadbed and foundation engineering of frozen soil in a cold region and provide support for the fiber reinforcement method of expansive soil.

1. Introduction

Expansive soil, identified as unsuitable construction materials for engineering, is low-graded because of its inferior mechanical properties, such as low strength and high potential for swelling and shrinkage [1, 2]. Due to seasonal environments, the cyclic volume change of expansive soil causes severe damage to the lightly loaded structures founded on them [3, 4]. The problems posed by expansive soil have been reported worldwide. Therefore, it requires engineering solutions to alleviate the impacts on human activities [5]. As the third largest permafrost country in the world, China covers a vast area of permafrost [6]. Geological disasters and engineering practice reveal that, under the conditions of the freeze-thaw environment in seasonally frozen and abundant groundwater, the freeze-thaw cycles and traffic dynamic load have become essential factors that affect the stability of the slope and will induce landslides [7, 8]. Meanwhile, frost damage and its prevention have been demonstrated [9, 10]. Influenced by the annual freeze-thaw cycles, train transportation load will induce subgrade boiling, slope collapsing, settlement, destabilization, and strength reduction because of the destruction of soil structure [11, 12]. At present, the main method to improve the mechanical properties of expansive soil under different working conditions is reinforcement [13, 14], and good progress has been made. However, little is known about the mechanical damage of reinforced expansive soil under freeze-thaw cycles. The special variation based on different stress conditions is not clear enough.
Studies have shown that the dynamic behavior of soil is significantly influenced by the dynamic shear modulus and damping ratio [1], which indicates the importance to select the dynamic shear modulus and damping ratio of soil in the construction in the seasonally frozen soil area in the south of Heilongjiang Province, northeastern Inner Mongolia, and northwestern Jilin Province. At present, the characteristics of expansive soil under different environments and conditions have been reported. The freeze-thaw cycles test of expansive soil under different water content conditions was carried [10], revealing that during the freeze-thaw cycle, the volume will reduce when freezing meanwhile swell when thawing under the low moisture content situation; on the contrary, it will be a totally opposite position under the high moisture content. With the deformation measurement, unconfined compression tests, and microstructure tests [15] studied the permanent deformation and dynamic characteristics of expansive soil and modified expansive soil under repeated loading by dynamic triaxial tests, revealing the relationship between elastic strain, cumulative plastic strain, and dynamic strain of expansion soil under different confining pressures and repeated dynamic load. Mao and Qiu [16] reported the variation of dynamic shear modulus and damping ratio of unsaturated expansive soil, the trend of dynamic shear modulus, and damping ratio with the increase of shear strain. Soil freezing and thawing have been well-elucidated, including the physical characteristics [17, 18] and stress-strain relationships of soil [19] after freezing and thawing. The strength reduction for unreinforced soil subjected to freeze-thaw cycles was also observed in previous studies [11, 20, 21]. However, there are few studies on the dynamic response of expansive soil under freeze-thaw cycles.

Especially, geosynthetic-reinforced soil structures including retaining walls, slopes, embankments, roadways, and load-bearing foundations, have gained increasing attention, in which several distinct advantages over their conventional counterparts have been demonstrated. As for expansive soil, the geosynthetic-reinforced method is an efficient mechanical way. Geosynthetics have great significance for the prevention and control of geologic hazards in constructions. The dynamic characteristics of expansive soil are affected by many parameters, such as the properties of rebar, freeze-thaw cycle, loading times, confining pressure, frequency, and the amplitude of shear strain. Shahnazari et al. [22] studied the influence of geogrids on the dynamic characteristics of sand through the triaxial test, and the result shows that the shear modulus of reinforced sand decreases under low confining pressure (<100 kPa) and increases under high confining pressure. Konrad [23] carried out triaxial tests on geotextiles in reinforced silty sand, and the result shows that the dynamic modulus of silt content increases and the cyclic ductility of silty sand decreases with the increase of the pressure and the number of geotextile layers. Besides, with the addition of silt up to about 35%, the dynamic axial modulus decreases, and the cyclic ductility

2. Experimental Scheme

2.1. Materials. Laboratory physical and dynamic tests were carried out on a disturbing expansive soil, and the samples are yellowish-brown. The basic physical index and particle composition were analyzed after drying, crushing, and sieving (shown in Table 1). The particle size distribution curve of the sample is shown in Figure 1. The sample is expansive soil, the unloaded expansion rate of which is 28.8% and compactness is 0.88 [25]. The time-history curves of expansive soil under natural water content and natural compactness are shown in Figure 2. To prepare the triaxial axis specimen, the expansive soil, which was dried, crushed, and sifted, was made into a sample with a water content of 29.8% by adding distilled water and sealing for 42 hours. The height of the sample was 140 mm, the diameter was 70 mm, and the compactness was controlled to 88%.

2.2. Methodology. The test was carried out on the positive and negative temperature static-dynamic triaxial axis instrument developed in the British GDS (shown in Figure 3).

In this test, three influencing factors for the expansive soil samples including confining pressure, freezing-thawing cycles, and reinforcement were considered. The confining pressure of soil is 50 kPa and 10 kPa, considering different soil stress conditions. The test took the expansive soil of a slope as the research object, so the consolidation method is nonisostatic consolidation because of the shear stress. The unidirectional grille, which is a reduced scale representation, was selected for the reinforcement in this test. The specific parameters are shown in Table 2, the layout is shown in Figure 4, and the detailed arrangement is shown in Table 3.

After the specimen was consolidated, the prescribed vibration load was applied. To ensure that the specimen would not be damaged due to excessive deformation during repeated dynamic loading, a cyclic loading mode of sinusoidal wave controlled by strain was considered. Under the condition of draining, dynamic load controlled by dynamic strain was applied step by step and the dynamic load cycle of each stage reached 20 times. To avoid the influence of the
latter load made by the former one, after the former loading is completed, it should be restored to the initial setting value through advanced loading and stabilize for 1-2 minutes.

The conventional test method for freezing and thawing cycle is in the sealed position: place it in high and low-temperature test chamber, run the freeze-thaw cycle under the conditions of no confining pressure, and then conduct the dynamic triaxial tests [26]. The temperature was set at −15°C and 20°C. The time of freezing or melting of the soil sample is the standard way, demanding that the change of soil sample displacement is less than 0.01mm within 2 hours. All the samples were subjected to the freeze-thaw cycles for 7 times, and the single freeze-thaw cycle is 24 hours. Then, a dynamic load was applied while every freeze-cycle was completed. Finally, the different results were obtained under the various freeze-cycle situation.

3. Results and Discussion

3.1. Effect of Single Freeze-Thaw. Characteristics of soil will show different changes under a single freeze-thaw condition [10]. The expansive soil samples under the unreinforced and reinforced states showed the change rule of frost heave and thaw settlement, as shown in Figure 5. When the temperature was reduced to −3°C, the samples were frozen and the volume increased rapidly, and the axial expansion appeared. When the temperature started to rise, the volume of the sample decreased. Meanwhile, the axial compressive deformation occurred, with the decreased back pressure-volume, and the moisture in the sample is discharged. Compared with unreinforced samples, it is obvious that due to the permeability of the geotextile layer, water can freely move and penetrate from the soil mass. During the freezing phase, ice crystals were formed, while these crystals melt and free water appeared in the sample during the thawing phase. The geotextile permeability facilitated water movement so that the change of the back pressure-volume of reinforced samples is more than that of the unreinforced samples after every freeze-thaw cycle.

When the confining pressure is 50 kPa, the axial frost heave deformation increases by 0.03 mm when the sample of the unreinforced expansive soil was frozen, while the deformation increases by 0.5 mm when the reinforced expansive soil was frozen, which is shown in Figure 5(a). The axial frost heave deformation of the reinforced sample is obviously higher than that of the unreinforced one, which is due to the radial constraint caused by reinforcement. This radial constraint was induced to have a larger expansion deformation in the axial direction of the samples. When the unreinforced sample was melted, the axial compression deformation was 1.03 mm, while the reinforced expansive soil sample was 1.35 mm. In the meantime, the axial

| Natural water content $\omega$ (%) | Natural density $\rho$ (g/cm$^3$) | Natural dry density $\rho_d$ (g/cm$^3$) | Optimal water content $\omega_{opt}$ (%) | Maximum dry density $\rho_{max}$ (g/cm$^3$) | Liquid limit $\omega_L$ (%) | Plastic limit $\omega_P$ (%) |
|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| 26.8                              | 1.63                              | 1.45                              | 21.5                              | 1.65                              | 41                               | 29                               |

![Figure 1: Curve of the grain size distribution.](image1)

![Figure 2: Curve of Expansion rate and time without load.](image2)

![Figure 3: Static-dynamic triaxial axis instrument and sensor placement on the sample (developed by GDS).](image3)
The compression deformation of the reinforced sample is also higher than the unreinforced sample. It will be the reinforcement that weakens the radial frost heave when the sample was frozen and made the axial frost heave more significant. After a freeze-thaw cycle, the axial cumulative compressive deformation of the unreinforced sample is 1 mm, while the reinforced sample is 0.8 mm under this stress condition, which shows that reinforcement can reduce axial compression deformation caused by a freeze-thaw when the confining pressure is 50 kPa. Although the ultimate deformation of unreinforced soil is less than that of reinforced soil, according to Figure 5(a), the deformation value of reinforced soil during a freeze-thaw process is greater than that of unreinforced soil because the expansive soil will reduce in freezing and swell in thawing. The thermal conductivity of the added geogrid is greater than the thermal conductivity of the expansive soil, compared with the unreinforced soil.

When the environment temperature drops below 0°C, the soil moisture starts to freeze. As a result, ice crystals are formed in a freezing procedure and the sample is subjected to volumetric change. The volume of the crystal will increase up to 9 times and exert notable stress on soil aggregates, resulting in the change of soil characteristics in micro- and macroscales [23]. The influence rule of reinforcement on axial deformation of the sample under the stress state of 10 kPa is consistent with the influence rule under the stress state of 50 kPa, which is shown in Figure 5(b). The axial frost heave deformation of unreinforced expansive soil increases by 0.4 mm, while the reinforced one increases by 0.55 mm when the sample was frozen. The axial compression deformation of unreinforced expansive soil decreases by 0.23 mm while the reinforced one decreases by 0.5 mm when the sample is melted. After a single freeze-thaw, the axial cumulative expansion deformation of the unreinforced sample is 0.17 mm, while the reinforced sample is 0.03 mm under this stress condition, which shows that reinforcement can reduce axial expansion deformation caused by a single freeze-thaw when the confining pressure is 10 kPa. It indicates that the decrease and increase values are not the same and the specimens will not recover to their initial height.

Figures 5(a) and 5(b) indicate that the axial displacement of the expansive soil sample varies under different stress states during the freeze-thaw process. The maximum volume change rate of the expansive soil sample at confining pressure of 50 kPa occurs at the compactness stage of the soil after melting, while the sample at 10 kPa confining pressure occurs during the expansion phase of the soil after freezing. This is because different stress states lead to different consolidation effects of the expansive soil sample. The axial deformation of the reinforced expansive soil samples under two stress states decreases after freezing and thawing. When the confining pressure is 50 kPa, freeze-thaw caused reconsolidation of expansive soil samples and axial compression deformation under high confining pressure, so reinforcement can restrain the axial compression deformation; when the confining pressure is 10 kPa, freeze-thaw caused expansion of expansive soil samples and axial expansion deformation under low confining pressure so that reinforcement can restrain the axial expansion deformation.

### Table 2: Basic information of selected geogrid.

| Grille model | Tensile strength under different strain (10%)/(kN/m) | Maximum tensile strength (kN/m) |
|--------------|--------------------------------------------------|--------------------------------|
| BOP series   | 2.98, 3.24, 4.57                                  | 5.78                           |

### Table 3: The stiffening condition, the loading condition, and the number of freeze-thaw cycles of different groups of test samples.

| Group | Confining pressure (kPa) | Partial stress (kPa) | Reinforced (yes/no) | Freezing thawing cycle |
|-------|--------------------------|----------------------|---------------------|------------------------|
| 1     | 50                       | 12.5                 | N                   | 0~7                    |
| 2     | 50                       | 12.5                 | Y                   | 0~7                    |
| 3     | 10                       | 2.5                  | N                   | 0~7                    |
| 4     | 10                       | 2.5                  | Y                   | 0~7                    |

### 3.2 Effect of Freeze-Thaw Cycles on Axial Displacement.

The reinforced expansive soil shows different height changes, which indicated that the variety of axial displacement is smaller than the unreinforced soil under different freeze-thaw cycles. This change is the result of under the cycles shown in Figure 6. Geogrid can restrain the axial deformation of expansive soil samples under freeze-thaw conditions. When the confining pressure is 50 kPa, the axial compression displacement of the reinforced expansive soil sample is 9.32% lower than that of the unreinforced expansive soil sample after the seventh freeze-thaw cycles. As a comparison, under the confining pressure of 10 kPa, the axial expansion displacement of the reinforced expansive is 54.17% lower than the unreinforced one after the seventh freeze-thaw cycles. In addition, these results are consistent.
with the findings of Wang and others [21] who reported the soil cohesion decreases with increasing the number of freeze-thaw cycles because voids between clay particles may increase due to forming ice lenses, and thus, the volume increases.

The confining pressure has a significant effect on the axial displacement [27], and similarly, due to the change of the freeze-thaw state of the soil layer, the moisture content will also have an impact on the stress change of the soil layer [28, 29]. It can be found in Figure 7(a) that the maximum...
axial displacement occurred when the sample went through the first freeze-thaw cycle under the stress of 50 kPa. With the increase of freeze-thaw cycles, the variation of the axial displacement decreases continuously, and the reinforced sample tends to be stable earlier than the unreinforced one, and the displacement changes tend to be consistent after the sixth freeze-thaw cycle. It can be found in Figure 7(b) that with the increase of freeze-thaw cycles, compared with the unreinforced sample, the absolute value of axial displacement of the reinforced sample decreases faster, and the axial displacement stopped after the fourth freeze-thaw cycle. It can be found in Figure 7(b) that the reinforced sample tends to be stable earlier than the unreinforced one, and the displacement changes tend to be consistent after the sixth freeze-thaw cycle. k´_his is because the freeze-thaw cycle can cause consolidation or expansion effect caused by freeze-thaw cycle [32].

By fitting the axial displacement of the expansive soil sample with the number of the freeze-thaw cycles, it indicates a significant exponential function change law between the two factors with R² large than 0.9, and it can be expressed as in the following equation, where the values of parameters are shown in Table 4:

$$\Delta h = A \cdot e^{(FT/B)} + C,$$

where Δh is a variation of axial displacement; FT is freeze-thaw cycles; A, B, C are coefficients related to confining pressure.

3.3. Effect of Freeze-Thaw Cycles on Dynamic Shear Modulus $G_d$ The dynamic shear modulus will be tuned by the freeze-thaw cycle in Figure 8. There are two hypotheses to explain this effect: (a) consolidation or expansion effect caused by freeze-thaw cycle [30, 31]; (b) structural damage effect caused by freeze-thaw cycle [32].

It can be found in Figures 8(a) and 8(b) that the dynamic shear moduli of the unreinforced and reinforced samples increase after the first freeze-thaw cycle under the same dynamic stress condition. The largest increase amplification of $G_d$ is 28% and 19%, respectively, in the dynamic strain of $1 \times 10^{-5}$. The decrease extent of $G_d$ of the unreinforced samples after the second freeze-thaw cycle is 16%, while the decrease amplification of the reinforced samples after the third freeze-thaw cycle is 9%. This is because the freeze-thaw cycle not only induces new consolidation of soil under the high-stress state but also causes the pores and cracks in the soil because of Frost Heave and Thaw, which alters the soil skeleton and particle characteristics, transfers the soil structure, and changes the stress system. Therefore, the dynamic shear modulus of soil decreases [33]. Ghazavi and Roustaie [11] reported the use of a geotextile layer could reduce the effect of freeze-thaw cycles on the mechanical characteristics of the soil by decreasing the triaxial strength reduction amount from 43% for unreinforced samples to 14% for geotextile reinforced samples. The time for the dynamic shear modulus begins to decrease when the reinforced sample is delayed. This is because the reinforcement restrains the frost heave deformation of samples during freezing and delays the structural damage effect caused by frost heave.

It is illustrated that the dynamic shear modulus both of the unreinforced and reinforced one also decreases with the increase of freeze-thaw cycles, under the strain condition of 10 kPa, from Figures 8(c) and 8(d). The decrease amplification of $G_d$ is 27% and 22%, respectively, after the seventh freeze-thaw cycle. This is because the freeze-thaw cycle can
lead to the expansion of samples and the decrease of density under the condition of low confining pressure and low partial stress, which reduce the dynamic shear modulus of the samples as freeze-thaw cycles destroy the original soil skeleton structure. Compared with the unreinforced sample, the reduction rate of the dynamic shear modulus of the reinforced sample decreases after freeze-thaw cycles, and the trend of dynamic shear modulus is more stable under this stress condition. These results are in good accordance with the findings [11], who conducted tests on friction angle during freeze-thaw cycles. The results indicated the unreinforced samples experience a negligible increase in the friction angle during freeze-thaw cycles, the friction angle of reinforced samples remained relatively constant.

From the relationship curve of dynamic shear modulus and dynamic strain in freeze-thaw cycles under the stress state of 50 kPa and 10 kPa, it can be found that the dynamic shear modulus of the reinforced expansive soil samples increases under these two stress states. When the confining pressure is 50 kPa, $G_d$ of the reinforced expansive soil samples without freeze-thaw cycles is increased by 4%; when the confining pressure is 10 kPa, $G_d$ is increased by 6%. This indicates that the effect of reinforcement on dynamic shear modulus is more significant under the two stress states. Reinforcement inhibits the trend that the dynamic shear modulus of expansive soil samples increases with the increase of freeze-thaw cycles. When the confining pressure is 10 kPa, the expansive soil sample with geogrid has a more

**Figure 8:** The relationship between dynamic shear modulus $G_d$ and dynamic strain $\varepsilon_e$ of the unreinforced and reinforced expansive soil under the conditions of the freeze-thaw cycle. (a) $\sigma_3 = 50$ kPa, unreinforced samples. (b) $\sigma_3 = 50$ kPa, reinforced samples. (c) $\sigma_3 = 10$ kPa, unreinforced samples. (d) $\sigma_3 = 10$ kPa, reinforced samples.
significant inhibition on the change of dynamic shear modulus caused by freeze-thaw cycles.

3.4. Effect of Freeze-Thaw Cycles on Damping Ratio $\lambda$. It shows that the freeze-thaw cycle has an effect on the damping ratio of expansive soil in Figure 9. The damping ratio of the unreinforced and reinforced expansive soil under different stress states have a different variation pattern due to the influence of the freeze-thaw cycles.

The maximum variation of damping ratio occurred in the first freeze-thaw cycle when the dynamic strain is $1 \times 10^{-3}$. The damping ratios of the unreinforced and reinforced samples are increased by 36% and 19%, respectively. This is because a large number of cracks in the microstructure of the soil are produced due to Frost Heave and Thaw caused by freeze-thaw cycles, which leads to the increase of energy consumption during the propagation of the dynamic wave and greatly improves the damping ratio. Geogrid can constrain the frost heave deformation of samples during freezing and reduce the number of cracks and delay the structural damage effect caused by frost heave. The damping ratio of the unreinforced and reinforced samples decreases with the increase of freeze-thaw cycles starting from the third and fourth freeze-thaw cycles, respectively. This is because the consolidation effect caused by freeze-thaw cycles increases the soil compactness, while the effect of the freeze-thaw cycle on soil pore structure and soil

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**Figure 9:** The relationship between damping ratio and dynamic strain of the unreinforced and reinforced expansive soil samples under these two stress states after different freeze-thaw cycles. (a) $\sigma_3 = 50$ kPa, unreinforced sample. (b) $\sigma_3 = 50$ kPa, reinforced sample. (c) $\sigma_3 = 10$ kPa, unreinforced sample. (d) $\sigma_3 = 10$ kPa, reinforced sample.
particle skeleton is weaker than the previous two freeze-thaw cycles [10]. It can be found in Figures 9(c) and 9(d) that the damping ratio of the unreinforced and reinforced samples increases with the increase of freeze-thaw cycles under the same dynamic stress condition. This is because the freeze-thaw cycle can lead to the expansion of samples and the decrease of density under the stress state. Meanwhile, a large number of cracks are produced in the microstructure of soil due to Frost Heave and Thaw, which leads to the increase of the sample damping ratio. After the seventh freeze-thaw cycle, the damping ratio of unreinforced samples at the strain in $1 \times 10^{-3}$ is increased by 28% and the damping ratio of reinforced samples at the strain in $1 \times 10^{-3}$ is increased by 30%. The effect of freeze-thaw cycles on the damping ratio of expansive soil samples does not change noticeably due to reinforcement.

It can be found from the relationship curve of damping ratio and dynamic strain in freeze-thaw cycles under the stress state of 50 kPa and 10 kPa that the damping ratio of the reinforced expansive soil samples increases under these two stress states. When the confining stress is 50 kPa and the strain is $1 \times 10^{-3}$, the damping ratio $\lambda$ of the reinforced expansive soil samples without freeze-thaw cycles increased by 13%; when the confining stress is 10 kPa and the strain is $1 \times 10^{-3}$, $\lambda$ is increased by 11%. It shows that the variation of the confining pressure has a negligible effect on the damping of the reinforced soil. The results are in agreement with the previous results obtained by Naeini and Gholampoor [34]. The growth trend of dynamic strain and damping ratio of the reinforced expansive soil sample is faster than that of the unreinforced sample under the two stress states. This is because the larger the dynamic strain, the more the energy dissipation of reinforcement.

In addition, both the dynamic shear modulus and the damping ratio change significantly after the first two freeze-thaw cycles, and the value gradually decreases as the number of freeze-thaw cycles increases because of the crack development effect on it [35]. The general feature of the development of cracks in the soil is that the new cracks develop rapidly, and the later cracks develop slowly. With the completion of the first freeze-thaw cycle, cracks in the soil developed rapidly. As the cracks developed, the damping ratio and dynamic shear modulus began to change rapidly. However, the crack development tends to stabilize after a certain number of times, and the influence that comes from confining pressure will make the damping ratio and dynamic shear modulus change relatively small [36].

4. Conclusion

Comparing the dynamic shear modulus and damping ratio of reinforced expansive soil and unreinforced expansive soil under different confining stress through freeze-thaw cycle experiments, the geosynthetic-reinforced grille influence on the expansive soil under the freeze-thaw cycle condition was discussed. The change of the axial deformation, dynamic shear modulus, and damping ratio of the sample under different confining stress in one freeze-thaw cycle or multiple freeze-thaw cycles was also calculated. The main conclusions are as follows:

1. The axial displacement of the samples varies under different stress states. There is a significant exponential increase of the axial displacement of the expansive soil sample with the number of freeze-thaw cycles. The characteristics of reinforced expansive soil under two stress states after a freeze-thaw cycle are as follows: at 50 kPa confining pressure, reinforcement can restrain the axial compression deformation; at 10 kPa confining pressure, reinforcement can restrain the axial expansion deformation.

2. The reinforced expansive soil shows smaller strain changes than the unreinforced soil under different freeze-thaw cycles and reinforcement can restrain the axial deformation of expansive soil samples under freeze-thaw conditions. The axial compression or expansive displacement of the reinforced sample is lower than the unreinforced one, both in a confining pressure of 50 kPa and 10 kPa, after seven freeze-thaw cycles. It shows that reinforcement can alleviate the frost heave of expansive soil significantly.

3. Reinforcement can increase the dynamic shear modulus of the expansive soil sample and delay the structural damage effect caused by frost heave. The dynamic shear modulus of the unreinforced and reinforced samples increases after the first freeze-thaw cycle. It decreases after the second freeze-thaw cycle in the unreinforced one. The decrease of the dynamic shear modulus of the reinforced sample is delayed by a freeze-thaw cycle compared with the unreinforced one. The dynamic characteristics of expansive soil show complex changes under the coupling of structural damage caused by Frost Heave and Thaw and consolidation compactness, which needs to be further studied.

4. Reinforcement can increase the damping ratio of expansive soil under the two stress states. The $\lambda$ of the reinforced expansive soil samples without freeze-thaw cycles is increased when the confining pressure is 50 kPa and the deformation is $1 \times 10^{-3}$; the $\lambda$ is increased in 10 kPa confining pressure and $1 \times 10^{-3}$ deformation. It shows that the variation of confining pressure has a negligible effect on the damping of the reinforced soil. The energy dissipation effect of reinforced expansive soil is more significant with the increase of dynamic strain, which shows that the growth
trend of the damping ratio of reinforced expansive soil samples is higher than that of unreinforced samples.

Through triaxial tests of samples with or without reinforcement and under different pressure conditions under freeze-thaw cycle, the influence of reinforcement on soil layer under freeze-thaw damage is clarified, which can provide a solution for engineering construction in seasonal frozen soil area.

Data Availability

The data were obtained from independent experiments and are not submitted.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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