A Constitutive Model for Damage of Highway Subgrade Soil under the Coupling of Freeze-Thaw Cycles and Loads

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Abstract. To investigate the influence of freeze-thaw cycles and loading on the mechanical characteristics of highway subgrades, a damage constitutive model under the coupled effect of freeze-thaw cycles and loading was constructed by integrating the Weibull distribution with Lemaitre's effective stress principle, based on statistical principles and damage mechanics. The theoretical expressions for model parameters were determined according to the geometric conditions at the peak point of the stress-strain curve. The proposed damage constitutive model was validated using experimental data. Results indicated that the developed damage constitutive model showed good agreement with the experimental stress-strain curves, and all required parameters could be obtained through triaxial tests. With the number of freeze-thaw cycles held constant, the peak stress and elastic modulus of the highway subgrade increased with rising confining pressure. Conversely, keeping the confining pressure unchanged, the peak stress and elastic modulus decreased with an increase in the number of freeze-thaw cycles. The model effectively described the stress-strain relationship of subgrade soils in seasonal frozen ground regions and provided a theoretical reference for subgrade engineering in permafrost areas.

Keywords: Highway subgrade soil; freeze-thaw cycle; Coupling effect; Damage constitutive model

1 INTRODUCTION

In high-latitude and high-altitude regions, infrastructure must withstand the severe challenges posed by seasonal temperature fluctuations. With the cyclical changes in climate, freeze-thaw cycles become a critical factor affecting the stability and durability of subgrade soils. During repeated freezing and thawing processes, the physical state of subgrade materials undergoes drastic changes, resulting in pronounced dynamic characteristics in their mechanical properties. Concurrently, persistent traffic loads exert additional pressures on the subgrade, coupling with the natural freeze-thaw cycles, which exacerbates the accumulation of material damage and performance degradation.

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Regarding the issue of freeze-thaw cycling in highway subgrade soils, scholars have conducted extensive research employing methods such as experimentation, theoretical analysis, and numerical simulation. In terms of experimental research, Wang Chaohui et al.[1] explored the deformation law of salt rock fill under the interaction of multiple factors during a single cooling process using the orthogonal experimental method. Chen Dun et al.[2] studied the shear deformation characteristics and anisotropic properties of saturated frozen clay by using the frozen soil hollow cylinder instrument.. Yang Xiaohua et al.[3] conducted indoor temperature cycling tests to study the effect of temperature changes on the deformation of coarse-grained sulfate saline soil subgrade. In theoretical model research, Liu Jiashun et al.[4] developed a fractional-order cumulative plastic strain prediction model for freeze-thaw eolian soil under intermittent cyclic loading based on the dual Abel viscoplasticity theory. Jin Liqiang et al.[5] established a computational model and method by considering the interaction between high-speed rail dynamic loads and the freeze-thaw cycle process. Peng Junhui et al.[6] integrating the Kelvin model, they developed a viscoelastic resilient modulus prediction model that comprehensively considers factors like density, moisture content, stress state, and load duration. In numerical simulation, Zhang Yunlong et al.[7] through ANSYS, finite element models were established to investigate the influence of freeze-thaw cycles on the stability factor of slopes. Qi Shouchen[8] utilized Comsol Multiphysics to simulate cold region high-speed railway cutting projects, studying the general characteristics of temperature field evolution over time. Ge Qi et al.[9] employed FLAC3D, a numerical modeling software based on the finite difference method, to study the soil slopes under different numbers of freeze-thaw cycles.

In summary, the research on the coupling of freeze-thaw cycle and load of highway subgrade is mostly focused on indoor test and numerical simulation, while the theoretical model based on the combination of statistical principle and damage mechanics principle is less studied. In this paper, Weibull distribution and Lemaitre effective stress principle are combined to explore the mechanical properties and damage evolution law of highway subgrade under the combined action of freeze-thaw cycle and external load.

2 MODEL BUILDING

During the service period, highway embankments are required to withstand the repeated loads caused by daily traffic. Under heavy and high-frequency traffic conditions, fatigue damage to the roadbed materials can occur (Figure 1a). Highway embankments are also affected by seasonal climate change and environmental factors, and undergo freeze-thaw cycles. The moisture in the roadbed freezes into ice, expands in volume, and generates strong frost heave force, which can cause the surface of the roadbed to bulge and induce the generation and expansion of micro cracks inside the roadbed soil (Figure 1b). Under the mutual influence of two factors, a coupled damage effect is ultimately formed (Figure 1c).

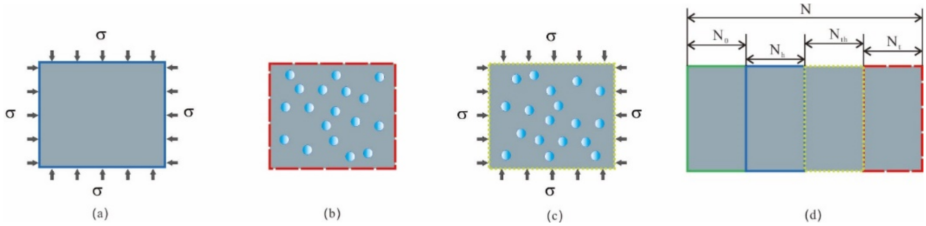


Fig. 1. Causes and microelement composition of damage to roadbed soil. (a) Damage caused by load action; (b) Damage caused by freeze-thaw cycles; (c) Damage caused by the coupling effect of freeze-thaw cycles and loads; (d) Microelement composition of roadbed soil.

The relationship between the total number of microelements N in the compression process of roadbed soil and the number of microelements damaged by various factors is

$$N = N_t + N_h + N_{th} + N_0 \tag{1}$$

The moisture in the roadbed soil will undergo volume expansion under freeze-thaw cycles, causing damage to the roadbed soil. The damage D_t caused by freeze-thaw cycles can be expressed as

$$D_t = \frac{N_t}{N} \tag{2}$$

The damage factor D_h caused by the load on the roadbed soil can be defined as

$$D_h = \frac{N_h - N_{th}}{N - N_t} \tag{3}$$

According to Figure 1 (d), the total damage factor D of the roadbed soil under the coupling effect of freeze-thaw cycles and loads can be expressed as

$$D = \frac{N_h - N_{th} + N_t}{N} \tag{4}$$

By combining equations (1) to (4), the total damage variable under the coupled effect of freeze-thaw cycles and loading can be expressed as

$$D = D_t + D_h - D_t D_h \tag{5}$$

Assuming that the subgrade soil is composed of a large number of microelements, and that the strength of these microelements follows a Weibull distribution, the probability density function for the strength of the microelements can be expressed as

$$P(F)=\frac{m}{F_0}\left(\frac{F}{F_0}\right)^{m-1}\exp\left[-\left(\frac{F}{F_0}\right)^m\right] \tag{6}$$

Where F is the strength distribution variable of the microelement, F_0 and m are the parameters of the Weibull distribution.

By combining equations (6) can obtain the damage variable of the subgrade soil under any loading condition

$$D_h = 1-\exp\left[-(\frac{F}{F_0})^m\right] \tag{7}$$

The Drucker-Prager (D-P) criterion is a widely used elastoplastic constitutive model in the fields of civil engineering and rock mechanics, particularly suitable for describing the mechanical behavior of subgrade materials. Assuming that the subgrade soil obeys the D-P criterion, the expression for the strength of the subgrade soil microelement can be obtained as

$$F=\frac{E\varepsilon_1}{\sigma_1-2v\sigma_3}\left[\alpha\left(\sigma_1+2\sigma_3\right)+\frac{1}{\sqrt{3}}(\sigma_1-\sigma_3)\right] \tag{8}$$

Where σ_1、σ_3 are principal stresses, ε_1 is strain, E is the elastic modulus of the subgrade soil, υ is the Poisson's ratio of the subgrade soil.

Freeze-thaw cycles have a significant impact on the elastic modulus of subgrade soils. The damage caused by freeze-thaw cycles can be represented as

$$D_t = \frac{E_n}{E_0} \tag{9}$$

Where E_n is the elastic modulus of subgrade soil after n freeze-thaw cycles, E_0 is the initial elastic modulus of the subgrade soil.

By combining equations (5) and (7) through (9), the expression for the damage variable under the coupled effects of freeze-thaw cycles and loading can be obtained as

$$D=1-\frac{E_n}{E_0}\exp\left[-\left(\frac{F}{F_0}\right)^m\right] \tag{10}$$

Combining the generalized Hooke's law, the constitutive model of subgrade soil damage under the coupling of freeze-thaw cycles and loading can be obtained.

$$\sigma = E_{\mathrm{n}} \varepsilon \exp\left[-\left(\frac{E\varepsilon_1\left[\alpha\left(\sigma_1+2\sigma_3\right)+\frac{1}{\sqrt{3}}(\sigma_1-3\sigma_3)\right]}{F_0\left(\sigma_1-2\nu\sigma_3\right)}\right)^m\right]+2\nu\sigma_3 \tag{11}$$

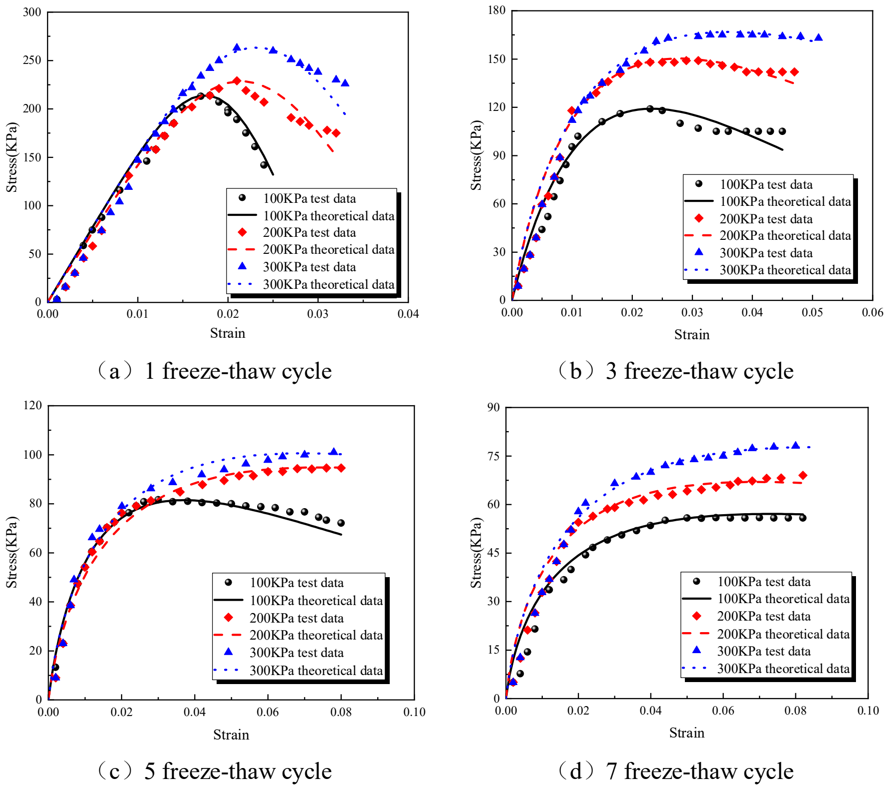
3 MODEL VALIDATION

To verify the rationality and accuracy of the established damage constitutive model, conventional triaxial compression test data on subgrade soil samples subjected to different numbers of freeze-thaw cycles, as conducted by Li Yongjing et al.[10], were utilized for validation against the damage constitutive model constructed in this study. The comparison between experimental results and theoretical predictions is illustrated in the following Figure 2.

As shown in Figure 2, under different confining pressures and freeze-thaw cycles, the model curve shows good agreement with the experimental curve, and the variation pattern presented by the theoretical curve is basically the same as the experimental curve. Keeping the confining pressure constant, as the number of freeze-thaw cycles increases, the stress-strain curve gradually flattens, the peak stress gradually decreases, and the peak strain continuously increases. The failure mode of the specimen changes from brittle to ductile. This is because under the action of freeze-thaw cycles, the cracks and water present in the pores of the roadbed soil cause frost heave, resulting in frost heave force and an increasing number of cracks in the roadbed soil, leading to varying degrees of initial damage and a continuous decrease in the strength of the specimens. Under the same number of freeze-thaw cycles, as the confining pressure increases, the slope of the elastic stage curve continuously increases, that is, the elastic modulus continues to increase, the peak stress and its corresponding strain significantly increase, and the rate of stress reduction in the post peak stage of the stress-strain curve slows down. The roadbed soil gradually transforms from brittle failure to ductile failure. From this, it can be seen that the mechanical properties exhibited by the roadbed soil under stress depend on its own properties and are closely related to the environment. Both confining pressure and freeze-thaw cycles can alter the mechanical properties of roadbed soil, and have similar effects on the elastic-plastic properties and peak stress of roadbed soil. The theoretical model curve has a high degree of fit with the experimental curve, which can better describe the stress-strain relationship of highway roadbed soil in seasonal frozen soil areas.

4 MODEL ANALYSIS

As shown in the Figure 3, both the number of freeze-thaw cycles and changes in confining pressure will affect the peak stress and elastic modulus of the roadbed soil. Under a certain number of freeze-thaw cycles, as the confining pressure increases, the peak stress and elastic modulus of the roadbed soil both show an upward trend. Taking three freeze-thaw cycles as an example, as the confining pressure increases from 100KPa to 300KPa, the peak stress of the roadbed soil increases by 21.3% and 36.4%, and the elastic modulus increases by 9.6% and 12.9%, respectively. This indicates that confining pressure has a compaction effect on the roadbed soil. When the confining pressure increases, the pores and microcracks inside the roadbed soil tend to close, preventing crack propagation, increasing the peak stress of the soil, and enhancing the soil's ability to resist deformation, manifested by an increase in the elastic modulus. Under a certain confining pressure, as the number of freeze-thaw cycles increases, the peak stress and elastic modulus of the roadbed soil both show a decreasing trend. Taking the confining pressure of 200KPa as an example, as the number of cycles increased from 1 to 7, the peak stress of the roadbed soil decreased by 33.3%, 55.4%, and 64.6%, respectively, and the elastic modulus increased by 10.3%, 13.8%, and 20.6%. This indicates that with the increase of freeze-thaw cycles, the freezing and expansion of water in the pores of the roadbed soil repeatedly act, leading to the generation and propagation of microcracks, and the accumulation of damage significantly reduces the peak stress and elastic modulus of the roadbed soil.



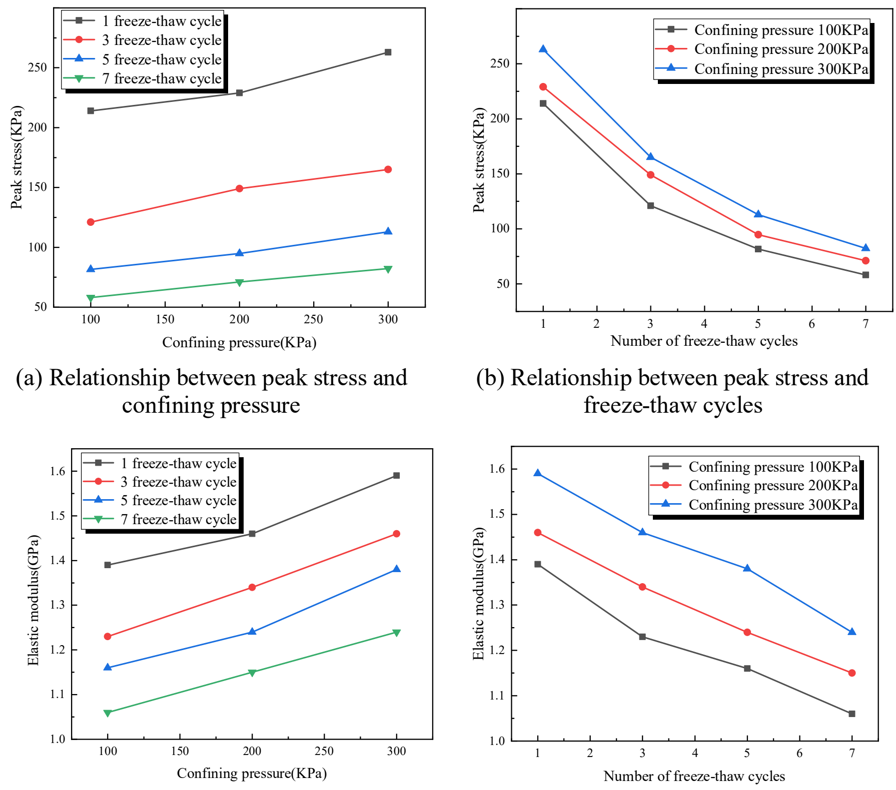
（a） 1 freeze-thaw cycle

（b） 3 freeze-thaw cycle

（c） 5 freeze-thaw cycle

（d） 7 freeze-thaw cycle

Fig. 2. Test results and theoretical results of subgrade soil under different freeze-thaw cycles



(a) Relationship between peak stress and confining pressure

(b) Relationship between peak stress and freeze-thaw cycles

(c) Relationship between confining pressure and elastic modulus

(d) Relationship between freeze-thaw cycles and elastic modulus

Fig. 3. The relationship between peak pressure, elastic modulus and freeze-thaw cycles, confining pressure.

5 CONCLUSION AND FORESIGHT

In this paper, Weibull distribution and Lemaitre effective stress principle are combined to construct the damage evolution equation and damage constitutive model of highway subgrade under the coupling action of freeze-thaw cycle and load. Based on the triaxial compression test data of different confining pressures and different freeze-thaw cycles, the damage constitutive model constructed in this paper is verified. The conclusions are as follows : The theoretical model curves under different confining pressures and different freeze-thaw cycles are in good agreement with the test curves The increase of confining pressure and freeze-thaw cycles makes the subgrade soil gradually transform from brittle failure to ductile failure. Both confining pressure and freeze-thaw cycles have a great influence on the peak stress and elastic modulus of subgrade soil. Under a certain number of freeze-thaw cycles, with the increase of confining pressure, the peak stress and elastic modulus of subgrade soil are on the rise. Under a certain confining pressure, the peak stress and elastic modulus of subgrade soil decrease with the increase of freeze-thaw cycles.

In view of the research on the coupling of freeze-thaw cycle and load of highway subgrade, this paper only constructs the damage constitutive model through theoretical analysis. This problem can also be studied by combining experiment and numerical simulation. In the aspect of experimental research, the similar simulation materials of highway subgrade soil are prepared, and the triaxial compression test schemes under different conditions are formulated based on the actual working conditions. The mechanical characteristics, failure modes, acoustic emission characteristics and energy evolution law of highway subgrade soil are analyzed. In the aspect of numerical simulation, the geometric model is created by COMSOL Multiphysics numerical simulation software and the corresponding material properties of subgrade soil are given. The coupling of freeze-thaw cycle and load is simulated by the coupling of temperature field and solid mechanical field. The influence of freeze-thaw cycle and load coupling conditions on the temperature field, stress field and deformation of subgrade is analyzed. Through the combination of theory, experiment and numerical simulation, it can be more perfect and reliable to lay the foundation for solving practical engineering problems.

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