

## Research Article

# Critical Dynamic Stress and Accumulative Deformation Evolution of Embankment Silty Clay Subjected to Cyclic Freeze-Thaw

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Received 28 June 2021; Revised 23 August 2021; Accepted 30 August 2021; Published 23 September 2021

Academic Editor: Amr A. Nassr

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In cold regions, the permanent settlement of embankment is mainly caused by the repeated freeze-thaw process and long-term repeated train loads. Meanwhile, the critical dynamic stress ( $\sigma_{dcr}$ ) is an important parameter index for determining embankment stability. Therefore, the accumulative permanent deformation evolution and critical dynamic stress of embankment soil subjected to cyclic freeze-thaw were studied using dynamic triaxial tests. Firstly, a numerical model for calculating critical dynamic stress considering the repeated freeze-thaw process was proposed, which shows that the critical dynamic stress of embankment soil rapidly decreases in the first two repeated freeze-thaw cycles, whereas it tends to be stable after the subsequent freeze-thaw process. Next, based on the normalization of the critical dynamic stress, an explicit model for predicting accumulative plastic strain ( $\epsilon_p$ ) of embankment soil was established. The above model considers freeze-thaw times, repeated dynamic stress amplitude ( $\sigma_d$ ), and loading times, in which all material parameters of Qinghai-Tibet silty clay were presented. Thus, the critical dynamic stress and accumulative plastic strain models established in this paper can be applied to judge the embankment stability and predict the embankment settlement induced by train loads in cold regions.

## 1. Introduction

In China, the wide-latitude, high-altitude, geological topography causes a huge difference in the distribution of cold and warm zones. Permafrost is widely distributed in China, including  $2.15 \times 10^6 \text{ km}^2$  of permafrost area and  $5.14 \times 10^6 \text{ km}^2$  of seasonal permafrost area, which are predominantly distributed in Northeast China, Northwest China, and Qinghai-Tibet Plateau [1]. Recently, with the

development of China's strategy of western development and revitalization of the northeast old industrial base, the infrastructure construction represented by high-speed railways and expressways will rapidly develop in the cold regions such as Northeast China and Northwest China, Central Asia, and Russia. In cold regions, the surface soil as the foundation undergoes a repeated freeze-thaw process, which changes the structure connection and arrangement of soil particles, further changing the physical-mechanical

property of soil. Furthermore, the long-term and repeated action of traffic load causes the mechanical properties of embankment soil to constantly evolve, which further aggravates the occurrence of a large area of embankment subsidence, slurry turning disease, slope collapse, lateral uplift, or shear crack extrusion caused by basement extrusion and seriously affects the long-term service performance of traffic engineering. Therefore, it is critical and imperative to investigate the influence of the repeated freeze and thaw process and long-term train loading on the accumulative deformation evolution of embankment soil.

Currently, the research results mainly focus on the effect of repeated freeze-thaw on the static characteristic of different types of soils [2–5]. Many researchers found that resilience modulus and shear strength of soil are reduced with an increase of repeated freeze-thaw times. Meanwhile, the compressibility of soil also affects the mechanical properties subjected to freeze-thaw cycle. The cohesive force of soil exhibiting large compactness reduced with the increase of repeated freeze-thaw, and the angle of internal friction increased or underwent insignificant changes [6–8]. However, Su et al. [9] found that the cohesive forces of soil exhibiting little compactness decrease after some freeze-thaw cycles, which is because fine-grained soils are sensitive to water and temperature and unsuitable for direct use as an engineering material. There are few studies on the dynamic properties of soil subjected to cyclic freeze-thaw under dynamic loads, including earthquake, traffic, and wave loads [10–14]. Based on the nonconsolidation and nondrainage dynamic triaxial test on Changchun silty clay, Dai et al. [15] found that the dynamic strength of silty clay after three repeated freeze-thaw cycles tended to be stable and did not change with confining pressure and freeze-thaw cycle times. The dynamic strength of fly ash soil subjected to repeated freeze-thaw also has the characteristics mentioned above [16]. After repeated freezing and thawing for 3–8 times, the dynamic modulus of fly ash soil and silty soil remained stable, among which the dynamic modulus of fly ash soil was higher than that of silty soil. Zhang [17] investigated the dynamic shear modulus and damping ratio of the silty soil of Natural Mabel Creek in Alaska subjected to repeated freeze-thaw. They observed that dynamic shear modulus of silty clay after cyclic freeze-thaw increased and the damping ratio remained unchanged at the shear strain less than 0.03%, but the damping ratio of the soil after cyclic freeze-thaw increased when it was greater than 0.03%. Based on freeze-thaw cycle tests on soils with three different plasticity indexes, the mechanical parameters of compacted embankment soil subjected to cyclic freeze-thaw were studied by Wang et al. [18]. They found that repeated freeze-thaw significantly affected the strength and deformation property of the soil. Many researchers studied the static strength of melted soil by considering the freezing temperature, melting temperature, and cyclic freeze-thaw times, while the investigation of the dynamic characteristics of melted soil has just begun. Comprehensive research on the accumulative deformation evolution of embankment silty clay subjected to repeated freeze-thaw is even less common.

Therefore, centering on the demand of transportation construction in cold region, the evolution law of  $\sigma_{\text{dec}}$  and  $\epsilon_p$  of Qinghai-Tibet silty clay subjected to cyclic freeze-thaw as important parameters of dynamic stability of subgrade was studied using a dynamic triaxial test. A constitutive model of permanent deformation is proposed, which considers cyclic freeze-thaw times and long-term traffic load. The research results provide significant scientific and application value for clarifying the development mechanism of accumulated deformation of roadbed soil and its role in treating roadbed diseases in traffic engineering in cold regions by providing guidance to local railroad and highway construction.

## 2. Test Scheme

*2.1. Soil Properties.* The particle distribution curve of the material used in this paper is shown in Figure 1, which was taken from the Qinghai-Tibet Railway in China. The physical characteristics of the soil are summarized in Table 1, such as the maximum dry density, plasticity index, and optimum water content.

*2.2. Test Equipment.* In this paper, the MTS-810 closed-loop servohydraulic material testing machine, equipped with automatic numerical control and data acquisition system, was used for the dynamic triaxial tests. The various indexes of the triaxial test machine are shown in [19]. A refrigerator equipped with an automatic temperature control system is used to freeze Qinghai-Tibet silty clay. The freezing temperature of the refrigerator is up to 30 °C, and the temperature accuracy is 0.1 °C.

*2.3. Test Programme.* According to the requirements of Railway Engineering Geotechnical Test Code (TB10102-2010), the silty clay samples were prepared in batches and the experimental procedures involved the following five steps. (1) Cylindrical soil specimens with a compressed dry density of 1.89 g/cm<sup>3</sup>, a diameter of 61.8 mm, and a height of 120 mm were prepared by the artificial freezing method. (2) To ensure uniform freezing of soil samples, the prepared soil specimen with rubber sleeve was placed in the refrigerator for 24 hours at −11°C. (3) The specimen was melted at a maximum temperature of 20°C for 18 h. The time of freezing and thawing was enough which had been proved by experiments [20]. (4) After 0, 1, 2, 4, and 6 repeated freeze-thaw cycles, the cylindrical soil specimen was placed in the triaxial test instrument chamber. (5) The tests were carried out by the undrained and unconsolidated loading method. The repeated cyclic loads of sinusoidal waveform with vibration frequency of 2 Hz were applied in the test, as shown in Figure 2. Figure 2 also shows definition of accumulative plastic strain using dynamic stress-strain relationship. It can be seen from the figure that the line of plastic strain of soil in each load cycle is the curve of  $\epsilon_p$  changing with the number of load vibration. Test termination criteria are 10,000 vibrations or 8% dynamic axial strain. Table 2 shows dynamic triaxial experiment conditions of each sample.

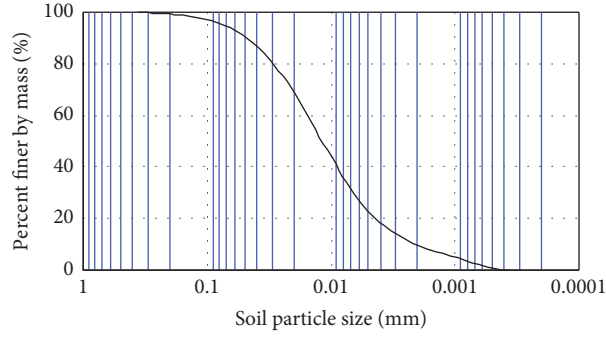


FIGURE 1: Particle analysis curve of Qinghai-Tibet silty clay.

TABLE 1: Physical properties of Qinghai-Tibet silty clay.

Maximum dry density	Liquid limit (%)	Plastic limit (%)	Optimum water content (%)	Saturated water content (%)	Plasticity index
1.89 g/cm <sup>3</sup>	26.1	17.3	12.35	17.45	8.8

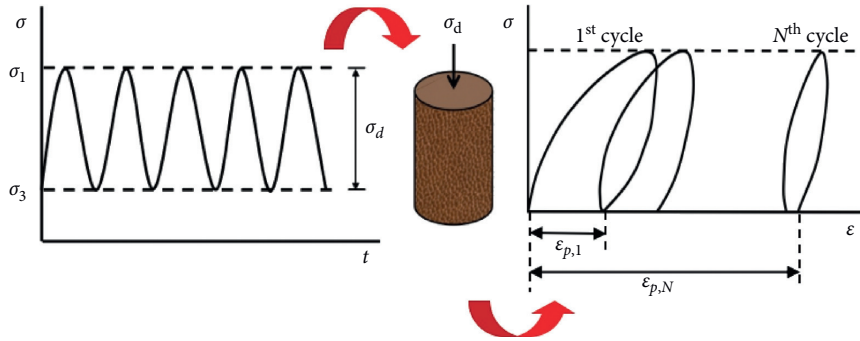


FIGURE 2: Axial strain of sample under long-term repeated cyclic loading.

TABLE 2: Dynamic triaxial test condition of thawed soil.

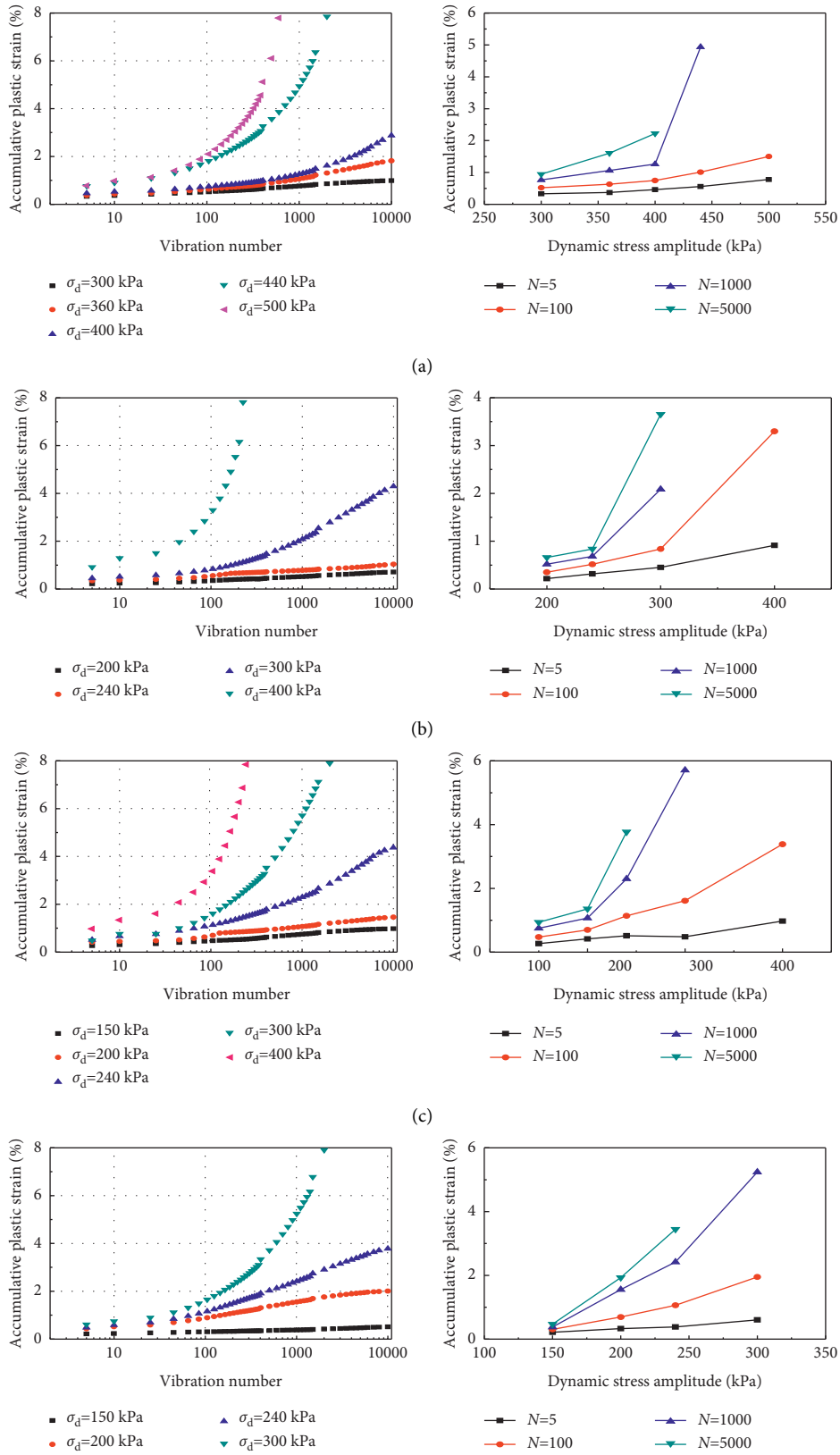
Water content (%)	Times of cyclic freeze-thaw ( $N_{cyc}$ )	Dynamic stress amplitude (kPa) ( $\sigma_d$ )
12.35	0	300, 360, 400, 440, 500
	1	200, 240, 300, 400
	2	150, 200, 240, 300, 400
	4	150, 200, 240, 300
	6	150, 180, 200, 240

### 3. Results and Discussion

**3.1. Effect of the Dynamic Stress Amplitude.** Figure 3 illustrates the influence of  $\sigma_d$  on  $\varepsilon_p$  of Qinghai-Tibet silty clay subjected to different number of repeated freeze-thaw cycles. It is clear that  $\varepsilon_p$  increases with increasing vibration numbers ( $N$ ). For all the tests, there is similar changing tendency of accumulative strain including initial creep stage, steady creep stage, and tertiary stage. During the initial creep stage, the accumulative strain increases at a rapid rate, while the strain rate gradually decreases until it reaches a minimum value. During the stable creep stage,  $\varepsilon_p$  develops at a constant rate. As expected, the accumulative plastic strain increased with the increase of  $\sigma_d$ . For the subgrade fill, there is a threshold value of dynamic stress. When the dynamic stress is greater than this value, the accumulative plastic strain of the soil will increase significantly until failure, which is called

failure type. When the dynamic stress is less than this value, the accumulative plastic strain of soil is small and tends to be stable, and the soil sample is elastic, which is called stable type.

Figure 3(b) shows that when  $\sigma_d$  is less than 200 kPa, the accumulative axial strain of silty clay gradually increases during the initial stage of vibration and tends to be stable with the increase of vibration numbers, which shows a stable type. When  $\sigma_d$  is greater than 400 kPa,  $\varepsilon_p$  of silty clay increases slowly at the initial stage of vibration, then starts to increase sharply, and quickly reaches failure which indicated a failure-type curve. After the turning point,  $\varepsilon_p$  of silty clay increases sharply and rapidly reaches the failure which indicated a failure type curve. Figure 3(b) also shows the relationship between  $\varepsilon_p$  of silty clay and  $\sigma_d$  under different vibration numbers. From the results obtained, when  $\sigma_d$  is 240 kPa,  $\varepsilon_p$  of silty clay linearly increases with  $\sigma_d$  at the



(d)  
FIGURE 3: Continued.

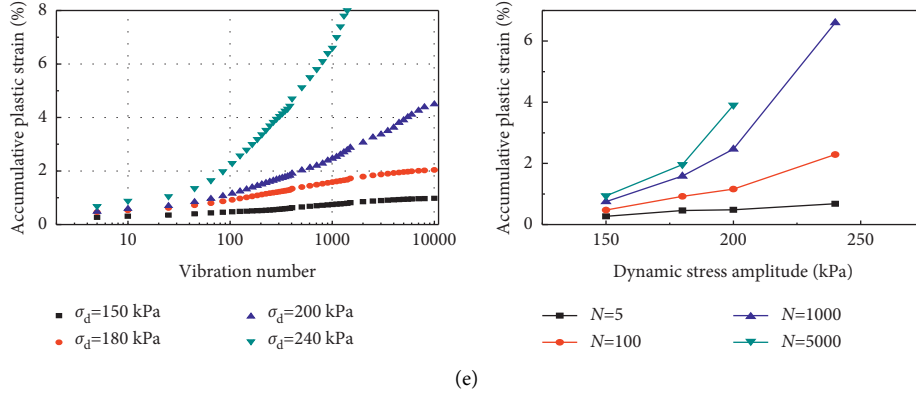


FIGURE 3: Effect of dynamic stress amplitude on the accumulative plastic strain after different number of freeze-thaw cycles ( $N_{cyc}$ ). (a)  $N_{cyc} = 0$ . (b)  $N_{cyc} = 1$ . (c)  $N_{cyc} = 2$ . (d)  $N_{cyc} = 4$ . (e)  $N_{cyc} = 6$ .

vibration number of 1000, indicating that the sample underwent stable deformation within the range of dynamic stress level and vibration numbers. When  $\sigma_d$  is greater than 240 kPa, the slope of the relationship curve between accumulative plastic strain and  $\sigma_d$  increases suddenly, indicating that the sample is damaged.

**3.2. Effect of the Number of Cyclic Freeze-Thaw.** Figure 4 gives the relationship between  $\varepsilon_p$  and vibration times of the Qinghai-Tibet Railway silty clay under different freeze-thaw times. Figure 4(b) shows that when  $\sigma_d$  was 300 kPa,  $\varepsilon_p$  of the silty clay is small for unfrozen soil, but the relationship curve between  $\varepsilon_p$  of soil subjected to two repeated freeze-thaw cycles and vibration numbers appeared as a turning point, sharply increasing and rapidly reaching failure. Figure 5 shows the relationship between  $N_{cyc}$  and  $\varepsilon_p$  of Qinghai-Tibet silty clay.  $\varepsilon_p$  of soil induced by train load is significantly affected by the repeated freeze-thaw process. When  $\sigma_d$  was 200 kPa, the accumulative plastic strain of the embankment soil exhibited an obvious increasing trend with the increase of cyclic freeze-thaw. When  $\sigma_d$  was increased to 300 kPa, the accumulative plastic strain showed an increasing trend during the first two times of freeze-thaw cycles, and then the accumulative plastic strain changed slightly with the increase in the subsequent freeze-thaw cycles, indicating that the failure form of silty clay gradually evolved from brittle failure to plastic failure.

**3.3. Effect of Freeze-Thaw Cycles on Critical Dynamic Stress.** One of important parameters for determining embankment stability is the critical dynamic stress ( $\sigma_{dcr}$ ). According to the fatigue test of cohesive soil, Heath et al. [21] defined the critical dynamic stress, which means that repeated dynamic stress greater than it will cause large permanent deformation of subgrade soil, and permanent deformation is small and terminated when repeated applied load is less than it, as shown in Figure 6.

Consequently, Figure 3(c) shows that  $\sigma_{dcr}$  of silt clay at freeze-thaw cycle  $N_{cyc} = 2$  was 200 kPa under certain test conditions. Based on this,  $\sigma_{dcr}$  of silty clay is 200 kPa

subjected to two freeze-thaw cycles. Figure 7 shows the influence of cyclic freeze-thaw on  $\sigma_{dcr}$  of Qinghai-Tibet silty clay. The  $x$  and  $y$  axes represent  $N_{cyc}$  and  $\sigma_d$ , respectively, and each point obtained from the above test is plotted in this coordinate. From Figure 6, the critical dynamic stress decreased with an increase in the number of freeze-thaw cycles, suggesting that  $N_{cyc}$  significantly influenced  $\sigma_{dcr}$ . Through regression analysis of  $\sigma_{dcr}$  subjected to repeated freeze-thaw, the fitting formula of  $\sigma_{dcr}$  of Qinghai-Tibet silty clay is obtained:

$$\sigma_{dcr} = 213.59 + 183.63 \times \exp\left(\frac{-N_{cyc}}{0.474}\right) R^2 = 0.98, \quad (1)$$

where  $N_{cyc}$  and  $\sigma_{dcr}$  represent the number of freeze-thaw cycles and the critical dynamic stress, respectively.

**3.4. Prediction Model for Accumulative Deformation of Thawed Soil.** This study adopted the Monismith model, which is simple and practical and conforms to equation (2). Based on this model, the evolution law of accumulated plastic strain of silty soil shown in Figure 3 was described by regression analysis. Parameters A and B of the Monismith model were obtained, respectively, as shown in Table 3.

$$\varepsilon_p = AN^B, \quad (2)$$

where  $\varepsilon_p$  is the accumulative plastic strain,  $N$  represents the vibration numbers, and A and B are the parameters. The correlation coefficient  $R^2$  under each test condition shown in Table 3 was mostly above 0.95, and the fitting effect was good.

To reduce the discretization of data points, the dynamic stress amplitude of each level was divided by the critical dynamic stress in the corresponding physical state. After normalization treatment, the dimensionless dynamic stress ratio  $S_{cr}$  was used to describe the magnitude of each level of dynamic stress. Equation (3) shows the stress ratio formula.

$$S_{cr} = \frac{\sigma_d}{\sigma_{dcr}} = \frac{q_d}{\sigma_{dcr}}. \quad (3)$$

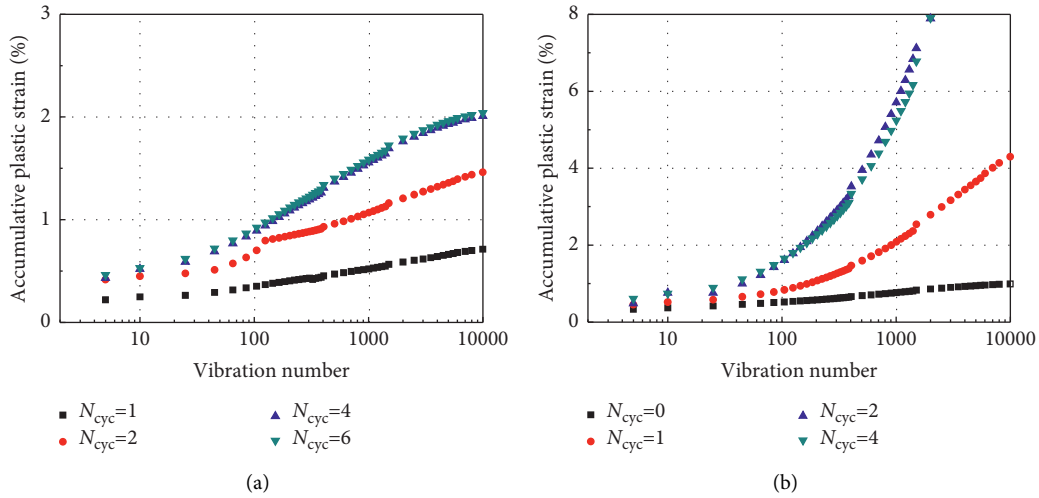


FIGURE 4: Relationship between the accumulative plastic strain and vibration numbers under different number of freeze-thaw cycles. (a)  $\sigma_d = 200$  kPa. (b)  $\sigma_d = 300$  kPa.

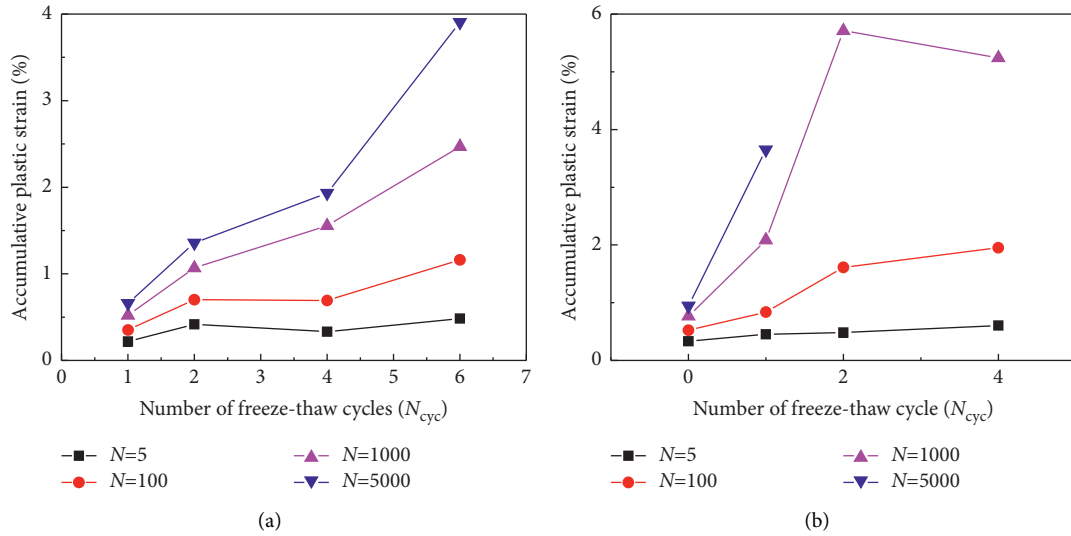


FIGURE 5: Relationship between the accumulative plastic strain and  $(N)_{cyc}$ . (a)  $\sigma_d = 200$  kPa. (b)  $\sigma_d = 300$  kPa.

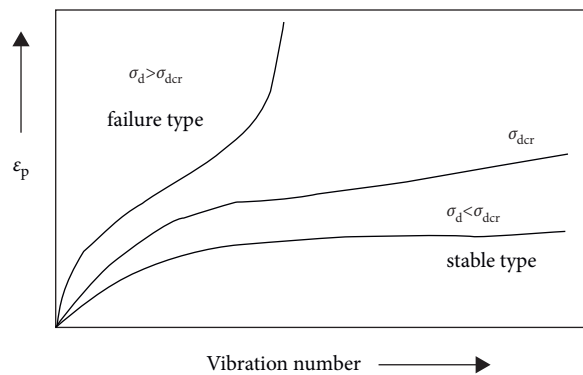


FIGURE 6: Schematic diagram of accumulative plastic strain development patterns.

Figure 8 shows that with an increase in the dynamic stress ratio, model parameters A and B also increased. Parameter A linearly increased with the stress ratio  $S_{cr}$ , and the fitting

formula can be expressed using equation (4). The exponent B of load times linearly increased with stress ratio  $S_{cr}$ , and the fitting formula can be expressed using equation (5).

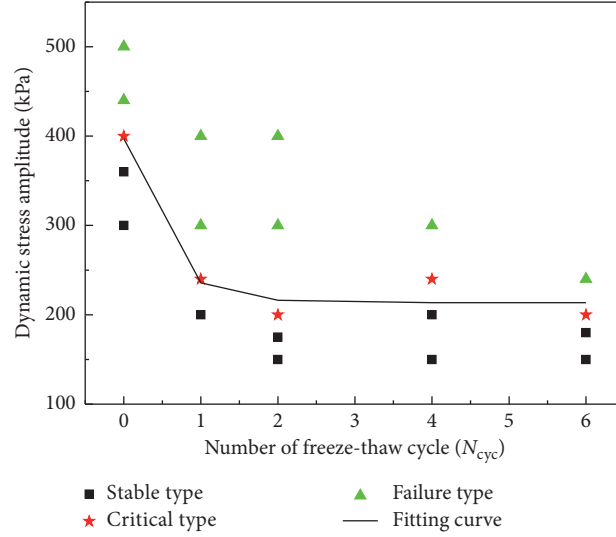


FIGURE 7: Relationship between the number of freeze-thaw cycles and threshold dynamic stress.

TABLE 3: Fitting parameters of the empirical model of dynamic permanent deformation of embankment soil under long-term train load.

$N_{cyc}$	$\sigma_d$ (kPa)	$S_{cr}$	A	B	$R^2$
0	300	0.75	0.0023	0.1514	0.995
	360	0.90	0.0026	0.201	0.997
	400	1.00	0.0031	0.156	0.993
	440	1.10	0.0042	0.171	0.995
	500	1.25	0.0043	0.159	0.997
1	200	0.83	0.0024	0.172	0.997
	240	1.00	0.0031	0.137	0.989
	300	1.25	0.0045	0.234	0.989
	400	1.67	0.0053	0.330	0.981
2	150	0.75	0.0019	0.199	0.998
	200	1.00	0.0029	0.186	0.992
	240	1.20	0.0029	0.304	0.997
	300	1.50	0.0037	0.351	0.975
4	400	2.00	0.0045	0.406	0.926
	150	0.63	0.0022	0.115	0.995
	200	0.83	0.0035	0.182	0.982
	240	1.00	0.0040	0.252	0.991
6	300	1.25	0.0038	0.341	0.988
	150	0.75	0.0026	0.173	0.980
	180	0.90	0.0032	0.178	0.964
	200	1.00	0.0032	0.298	0.996
	240	1.20	0.0028	0.361	0.995

$$A = 0.00103 + 0.00211S_{cr}R^2 = 0.78, \quad (4)$$

$$B = 0.00825 + 0.20837S_{cr}R^2 = 0.77. \quad (5)$$

The above analysis shows that the permanent deformation prediction formula of Qinghai-Tibet silty clay after cyclic freeze-thaw was as follows:

$$\varepsilon_p = AN^B = (0.00103 + 0.00211S_{cr})N^{(0.00825+0.20837S_{cr})}. \quad (6)$$

The above formula indicates that the accumulative plastic strain prediction model considers the comprehensive action of the freeze-thaw cycle and long-term train load.

Figure 9 compares the calculated and measured results of the accumulative plastic strain prediction model of Qinghai-Tibet silty clay considering repeated freeze-thaw cycles. The predicted permanent strain agrees well with the test results. The above model can be used for predicting the permanent deformation induced by the long-term action of traffic load. The model has important guiding significance for predicting

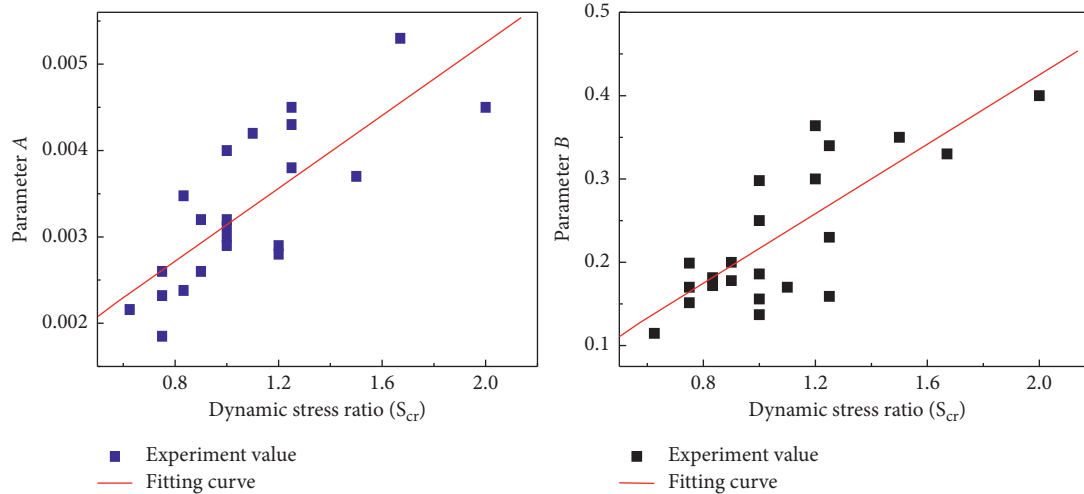


FIGURE 8: Parameters A and B vs. dynamic stress ratio  $S_{cr}$ .

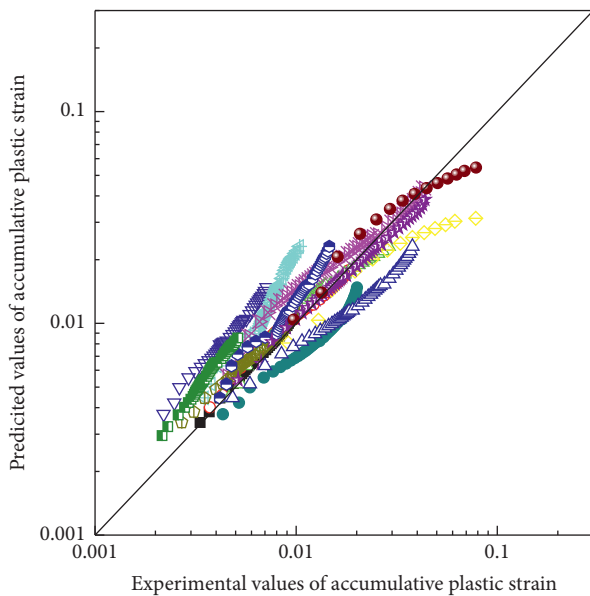


FIGURE 9: Comparison of predicted and experimental values of accumulative plastic strain.

the accumulative permanent deformation of permafrost embankment soil under freeze-thaw cycles and long-term train loads.

#### 4. Conclusions

The effect of cyclic freeze-thaw, train loads, and vibration numbers on the permanent settlement of silty clay widely distributed along the Qinghai-Tibet railroad was investigated. Prediction models for the critical dynamic stress and permanent deformation were presented by considering the freeze-thaw cycle and long-term train load. The main findings are summarized as follows:

- (1) The repeated freeze-thaw significantly influenced the accumulation of permanent deformation evolution and critical dynamic stress of Qinghai-Tibet silty

clay. When  $N_{cyc}$  was less than two,  $\epsilon_p$  of soil sharply increased with the vibrations, reaching a brittle failure. However, when  $N_{cyc}$  was six, the accumulative plastic strain of the silty clay gradually increased with the number of vibrations until it was destroyed, thus showing plastic failure. The failure form of the silty clay gradually evolved from brittle to plastic failure with an increase in the number of cyclic freeze-thaw.

- (2) A model for predicting the critical dynamic stress of silty clay subjected to cyclic freeze-thaw was established by using the multiple nonlinear regression method. The critical dynamic stress of soil after two repeated freeze-thaw cycles rapidly decreases and then changes little after the following freeze-thaw process.
- (3) Using the Monismith exponential model and normalizing the critical dynamic stress, a model for predicting the accumulative plastic strain of Qinghai-Tibet silty clay was established, which considers  $N_{cyc}$  and the long-term repeated cyclic load. The model has clear parameters and considers the influence of cyclic freeze-thaw, train loads, and vibration numbers on the accumulative plastic strain.

#### Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

#### Conflicts of Interest

The authors declare that they have no conflicts of interest.

#### Authors' Contributions

Lina Wang was responsible for methodology, investigation, resources, original draft preparation, and review and editing. Tianliang Wang supervised the study. Zhiyu Weng, Qiang



Liu, Guoyu Li, and Yingying Zhao were responsible for validation. All authors have read and agreed to the published version of the manuscript.

## Acknowledgments

This research was supported by the National Natural Science Foundation of China (Grant no. 52108346), State Key Laboratory Project of China (Grant nos. KF2020-12 and SKLFSE202019), Yunnan Science and Technology Department Basic Research Project of China (Grant no. 202101AT070253), and Jiangsu Planned Projects for Postdoctoral Research Funds (Grant no. 2021K534C).

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