

Effects of freeze-thaw cycle on mechanical properties of saline soil and Duncan-Chang model

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Abstract. In order to study the mechanical properties and change rules of undrained shear behavior of saline soil under the freeze-thaw cycles, an improved constitutive model reflecting the effects of freeze-thaw cycles was proposed based on the traditional Duncan-Chang model. The saline soil in Qian'an County, western Jilin Province, was selected as the experimental object. Then, a set of freeze-thaw cycles (0, 1, 10, 30, 60, 90, 120) tests were conducted on the saline soil specimens, and conventional consolidated undrained triaxial shear tests were conducted on the saline soil specimens that underwent freeze-thaw cycles. The stress-strain relationship was obtained by the triaxial shear test. The model parameters have a corresponding regression relationship with the number of freeze-thaw cycles. Finally, based on the function expression of the model parameters, the modified Duncan-Chang model with the number of freeze-thaw cycles as the influence factor was established, whilst the calculation program of the modified model is compiled. Based on the test results, the stress-strain relationship of the saline soil specimen shows strain hardening. The shear strength gradually decreases with the increase of freeze-thaw cycle. The 10 freeze-thaw cycles are the turning point in the trend of changes of the mechanical properties of saline soils. The calculated and experimental stress-strain relationship are compared, and the comparison between the calculated value of the model and the experimental value showed that the two had a good consistency, which verified the validity of the modified Duncan-Chang model in reflecting the effects of the freeze-thaw cycle.

Keywords: Duncan-Chang model; freeze-thaw cycle; saline soil; stress-strain relationship; strain hardening

1. Introduction

In the construction and operation of engineering projects in cold regions, due to seasonal climate changes, shallow foundations and subgrade soils will be affected by repeated freeze-thaw cycles, leading to irreversible changes in engineering properties (Kong *et al.* 2022). Therefore, the freeze-thaw cycle of soil is the primary concerned issue in cold regions engineering (Cheng *et al.* 2021a, Han *et al.* 2023). The effect of temperature difference on saline soil is similar to that of freeze-thaw cycle (Bing *et al.*, 2006). The freeze-thaw cycle in cold regions occurs at least once a year, or even once a day, which can affect the physical, hydrological and mechanical properties of the soil (Liu *et al.* 2016). Yang *et al.* (2003) pointed out that the freeze-thaw cycle process is a process that the soil in an unstable state develops into a dynamic stable state, and repeated freeze-thaw cycles can cause the soil structure to transition to a new dynamically stable equilibrium state. In summary, freeze-thaw cycles have a significant impact on the properties of soil.

Qi *et al.* (2006) reviewed the impact of freeze-thaw processes on the physical and mechanical properties of

soils. Many researchers have researched the effect of the freeze-thaw cycle on soil mechanical properties (Xiang *et al.* 2022, Adeli Ghareh Viran and Binal 2018, Zhao *et al.* 2021). Konrad (1989) point out the freeze-thaw process can alter the structural connection and arrangement of soil particles, thereby altering the mechanical properties of soil. Bing *et al.* (2011) showed that the failure of saline soil that has not undergone freeze-thaw cycles is brittle and requires six freeze-thaw cycles to form a new equilibrium. Kamei *et al.* (2012) showed that the compressive strength of solidified soil decreases with increasing freeze-thaw cycles.

The first two cycles showed a significant decrease in compressive strength, followed by a subsequent decrease. Chang *et al.* (2014) proposed that the influence of confining pressure and freeze-thaw cycles on mechanical properties is stronger than the freezing temperature. Yang *et al.* (2015) found that the ultimate compressive strength of both seasonally frozen and permafrost soils decreases with increasing temperature. Wang *et al.* (2015) found that after 5 to 6 freeze-thaw cycles, the compressive strength of solidified soil decreased. Han *et al.* (2018a) pointed out that after a large number of freeze-thaw cycles, the strength will decline significantly.

Among them, the stress-strain relationship comprehensively reflects the soil deformation and strength characteristics. Thus, there have been many researches on the influence of freeze-thaw cycle on the stress-strain

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relationships ((Duncan 1970, Simonsen and Isacsson 2001, Simonsen *et al.* 2002)). In addition, Chang *et al.* (2015) selected a new normalization factor and established a normalization equation for the stress-strain characteristics of silty sand under different confining pressures and freeze-thaw cycles, and predicted the stress-strain relationship. By introducing constitutive theory and establishing a mathematical model, it is possible to further elucidate the changes in soil mechanical properties under freeze-thaw cycles. Therefore, establishing a constitutive model that can reflect the impact of freeze-thaw cycles is one of the important research directions in current permafrost engineering. The constitutive model of soil includes nonlinear elastic model and elastic-plastic model. The former mainly includes hyperbolic model, while the latter includes cam-clay model and elliptic-parabolic double-yielding surface model based on the classical yield surface theory, as well as non-yield surface theoretical model such as partial yield model and boundary surface theoretical model (Yao *et al.* 2012). On this basis, there are already some studies on the constitutive model of freeze-thaw cycle of soil (Cheng *et al.* 2021b; Dayarathne *et al.* 2022, Fang *et al.* 2019, Qiu *et al.* 2020). The experimental basis for the above studies is mostly the conventional consolidation drainage triaxial shear test of saturated soil. However, in fact, shallow soil is essentially undrained due to the over consolidation stress history and low permeability during the compaction process of cohesive soil foundation. Therefore, there is currently a lack of research on constitutive models regarding the impact of freeze-thaw cycles on soil in an undrained state.

Duncan-Chang hyperbolic model is the nonlinear variable elasticity model based on incremental generalization Hooke's law. It has simple form, clear physical meaning of model parameters, and is most widely and maturely applied in engineering applications. However, it can't reflect the dilatancy and central stress shadow. Many improvement methods have been proposed and some modified models have been established to describe the regular deformation characteristics of soil under the influence of different factors, in order to expand its applicability. Wang *et al.* (2010) defined a disturbance function using pore water pressure as a parameter and constructed the Duncan-Chang model to describe the undrained shear behavior of structural soil. Zhang *et al.* (2014) established a regression formula of the relationship between parameters of Duncan-Chang model and temperature and initial water content, and established a modified Duncan-Chang model that could reflect the influence of the above factors through the triaxial test of frozen silty clay. Liu *et al.* (2016) proposed a normalization factors based on the new limit deviatoric stress and damage amount of freeze-thaw cycle in hyperbola model, and established a predictive model for the stress-strain relationship of silty soil under freeze-thaw cycles. Hu *et al.* (2018) established a modified Duncan-Chang model based on the number of freeze-thaw cycles to reflect the shear behavior of silty clay. The above research results show that Duncan-Chang model is a flexible and improved constitutive model that can reflect the effects of various soil

properties, loads, and boundary conditions.

Although extensive research has been conducted on the changes in soil mechanical properties caused by freeze-thaw cycles, there has been little discussion on a large number of freeze-thaw cycles, and there has been little research on the constitutive models of saline soil under large freeze-thaw cycles. The severe soil salinization in the western region of Jilin Province has constrained project construction in the region and the soil has strong dispersibility (Zhang *et al.* 2015). The freeze-thaw process of saline soil is a complex process (Zhang *et al.* 2017), and repeated freeze-thaw effects can cause changes in the mechanical properties of saline soil, directly affecting the stability of the project. Therefore, it is necessary to study the mechanical properties of freeze-thaw cycles. The current paper focuses on the stress-strain relationship of remolded saline soil specimen in western Jilin Province. Saline soil specimens were prepared through mixing and use of astatic compaction method. Then the conventional consolidated undrained triaxial shear tests under different confining pressures (50, 100, 200, 300 kPa) were determined, to discuss the influence of the different freeze-thaw cycles (0, 1, 10, 30, 60, 90 and 120) on the stress-strain relationship. Finally, based on the analysis of the test results of the corresponding stress-strain curve, the function expression of the relation between the parameters of Duncan-Chang model and the number of freeze-thaw cycles was determined, and then a modified model which can reflect the freeze-thaw cycle effect of saline soil was proposed, and the rationality of the model was verified by the test results.

2. Materials and sample preparation

2.1 Experimental materials

The soil samples used in this study were collected at a depth of 40cm in Qian'an County, western Jilin Province (a seasonal frozen region in the northeast of China). The saline soil here is a type of structural behavior soil (Wang *et al.* 2016) and Qian'an is a typical distribution point. Under the combined action of leaching and evaporation, the salt content is the highest at 40 cm depth. Therefore, the experimental soil samples were taken from the saline soil at a depth of 40 cm in Qian'an County. The overall precipitation in this region is much smaller than the evaporation, which will inevitably lead to soil drying and salt migration upwards with water, ultimately resulting in salt enrichment. As salt accumulates toward the surface, it becomes increasingly salinized. The physical parameters (grain size distribution) of saline soil are shown in Fig. 1. Some basic physical properties are listed in Table 1. The saline soil is classified as lean clay (CL) based on the Unified Soil Classification System (USCS) (ASTM 2011).

The basic chemical properties of saline soil samples at a depth of 40 cm are shown in Table 2. It can be seen that the cations in soil are mainly sodium ions, while the anions are mainly bicarbonate ions and sulfate ions.

Table 1 List of some basic physical properties of natural saline soil

Soil type	Natural density(g/cm ³)	Specific gravity of solid Particles(g/cm ³)	Plastic limit (%)	Liquid limit (%)	Optimum water content (%)	Maximum dry density(g/cm ³)	Clay content (%)
CL	1.97	2.72	17.18	24.98	15.6	1.78	32.35

Table 2 Basic chemical properties

PH	Soluble salt content (%)	K ⁺ (mmol/kg)	Ca ²⁺ (mmol/kg)	Mg ²⁺ (mmol/kg)	Na ⁺ (mmol/kg)	SO ₄ ²⁻ (mmol/kg)	HCO ₃ ⁻ (mmol/kg)	Cl ⁻ (mmol/kg)
7	0.55	1.22	1.42	2.4	31.46	0.25	3.76	1.47

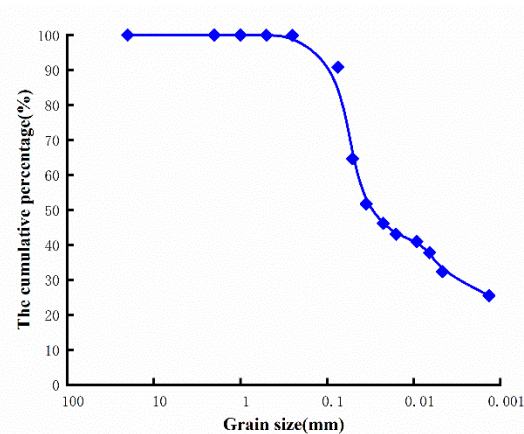


Fig. 1 Grain size distribution of natural saline soil

2.2 Specimen preparation

Remolded soil can be well applied under different experimental conditions (Costanzo *et al.* 2006). Dry the saline soil samples collected from the experimental site, and then prepare sufficient screened experimental soil through a 2 mm sieve. Add water according to the optimal moisture content in the saline soil, then mix it and let it stand for 24 hours to make the water mix evenly.

Transfer the material prepared above to the compaction mould and conduct compaction tests according to ASTM D-698 (ASTM 2011) to produce standard triaxial specimens with a height of 8cm and a diameter of 3.91 cm. Regarding the determination of sample compaction degree and moisture content: according to engineering requirements, the compaction degree should not be less than 85%, but if the compaction degree exceeds 95%, it will be difficult to compact. Therefore, a compaction degree of 90% is chosen between 85% and 95%. The optimum moisture content is 15.6%, so the selection of the moisture content is 15.6%. Then, using a molding machine, a standard triaxial sample with a diameter of 39.1mm and a height of 80mm was prepared. Compactness was controlled to 90% and the dry density was controlled to 1.603 g/cm³.

After the specimen is made, it is wrapped and sealed in plastic film. Fang *et al.* (2016) showed that using double-layer plastic film to wrap the sample can avoid water loss during freeze-thaw cycles and be used to simulate a closed system without external water supply. The initial saturation of the specimens is 60.88%, and the porosity is 0.70.

Table 3 Experimental scheme of the test

Moisture content, w/%	Degree of compaction/%	Confining pressure/KPa	Freeze-thaw cycles
15.6%	90%	50 100 200 300	0(FT0)
			1(FT1)
			10(FT10)
			30(FT30)
			60(FT60)
			90(FT90)
			120(FT120)

2.3 Experimental scheme

Select confining pressure and number of freeze-thaw cycles as experimental variables and conduct comprehensive tests on the two factors. This study conducted freeze-thaw cycle experiments using a simulation platform for rock and soil freeze-thaw tests in ultra-low temperature environments. Based on the actual seasonal average temperature of sampling points in winter and summer in Qian'an City, as well as the commonly used freeze-thaw cycle test conditions (Han *et al.* 2018b). When the freezing temperature is lower than -10°C, the strength decrease tends to stabilize, so the freezing temperature is chosen to be -20°C (Wang *et al.* 2020). Thawing temperature and room temperature 20°C. Therefore, the melting temperature was set to 20°C and the experimental freezing temperature was set to -20°C. In order to ensure complete thawing and freezing of the specimen, the freezing time is set to 12 hours, and the melting time is also set to 12 hours. A freeze-thaw cycle is to complete a freezing process and melting process, and a freeze-thaw cycle lasts for 24 hours. To simulate the different freeze-thaw cycles, the freeze-thaw cycles of specimens were set to 0, 1, 5, 10, 30, 60 and 120, and corresponding soil specimens were designated as FT0, FT1, FT10, FT30, FT60, FT90 and FT120, to simulate the different freeze-thaw cycles. The specimens are frozen for 12 hours in the freeze-thaw simulation platform, and then melted for 12 hours outside to complete a freeze-thaw cycle according to the design temperature. Finally, different freeze-thaw cycles were completed according to the experimental design. The specific experimental scheme is shown in Table 3.

The freeze-thaw cycle mainly affects the soil at a shallow depth. Roustaei *et al.* (2015) found that due to the over-consolidation stress history of compaction process and the instantaneous driving load, low-permeability silty clays

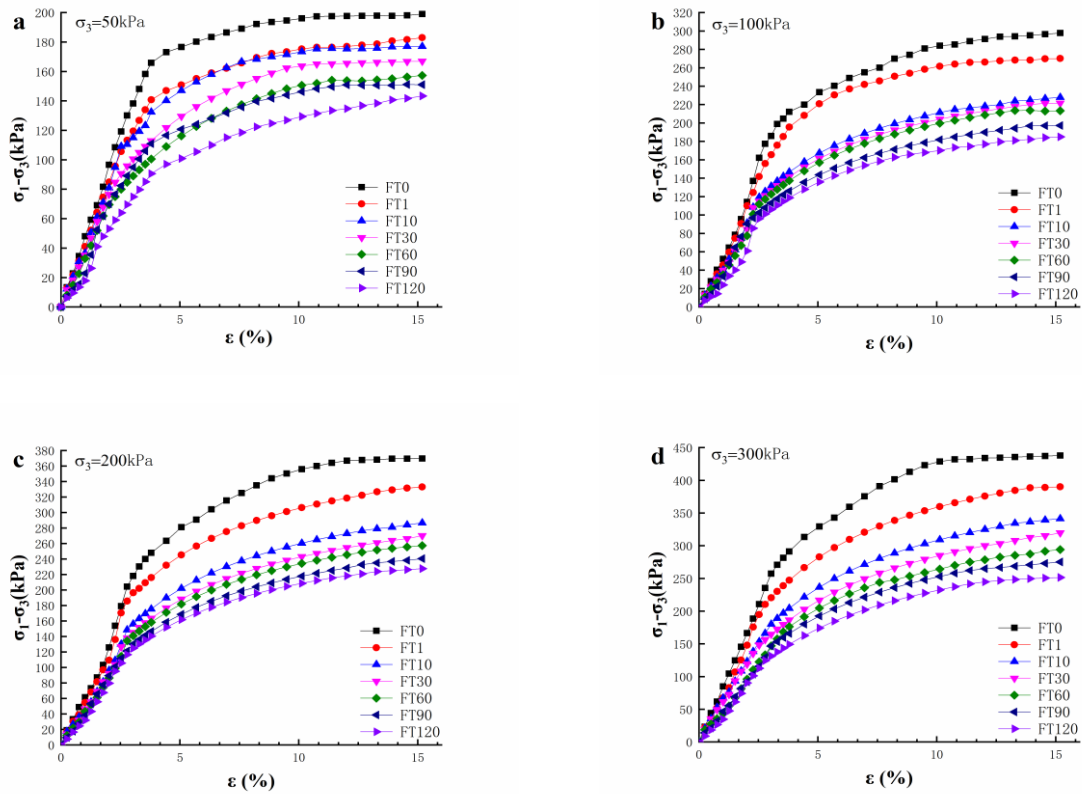


Fig. 2 The variation curve of stress-strain relationship with the number of freeze-thaw cycles under different consolidation confining pressures (a) 50 kPa, (b) 100 kPa, (c) 200 kPa and (d) 300 kPa

Table 4 Shear strength of specimens after different number of freeze-thaw cycles

Confining pressure/kPa	Freeze-thaw cycles						
	0	1	10	30	60	90	120
50	193.22	177.79	169.92	163.99	157.31	151.07	143.36
100	297.70	264.75	227.80	221.57	213.26	197.23	184.91
200	369.82	338.36	286.72	270.09	257.33	240.56	227.65
300	437.79	397.13	341.33	319.66	294.14	275.14	251.54

roadbeds usually do not have time to develop the process of drainage in the melting stage. Therefore, triaxial shear test is chosen as consolidated undrained triaxial shear test. The confining pressure is 50, 100, 200 and 300 kPa. The experiment was carried out on the Model TSZ-3 Strain Controlled Triaxial Test Apparatus (manufactured by Nanjing Soil Instrument Factory Co., Ltd., Nanjing, China), with an axial loading rate set at 0.6%/min and a controlled strain of 16%.

3. Results and discussions

3.1 Stress-strain relationship

The effects of salt expansion, pore water freezing and their migration during the freezing process contribute to the

rearrangement of saline soil aggregates and pore evolution, thereby affecting the interlocking force among soil particles and macroscopically affecting the mechanical behavior of saline soil. In triaxial shear tests, the relationship between the axial strain ε_l and the deviator stress ($\sigma_l - \sigma_3$) of soil specimens can be divided into three types: strain hardening, ideal elastic-plastic and strain softening. Fig. 2 shows the stress-strain relationship of saline soil under different freeze-thaw.

From the Fig. 2, it can be seen that freeze-thaw cycles have a significant impact on the mechanical properties of saline soil. This indicates that the shear strength of the saline soil generally decreased with increasing freeze-thaw cycles. Among them, in the first 10 freeze-thaw cycles, the decline rate is relatively fast, and then gradually slows down with the increase of freeze-thaw cycles, indicating that the 10 freeze-thaw cycles are the turning points of the

Table 5 shear strength indexes values of samples after freeze-thaw cycles

Shear strength index	Number of freeze-thaw cycles						
	0	1	10	30	60	90	120
c	61.0382	59.34404	58.3885	57.78776	57.6623	55.72821	54.94826
φ	17.39736	15.81456	13.63236	12.76081	11.71413	10.9372	9.901731

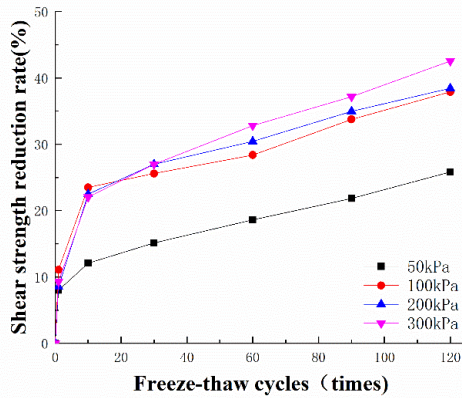


Fig. 3 Variation ratio of shear strength of specimens after freeze-thaw cycles

stress-strain relationship curve trend. In the initial stage of loading, the saline soil is in the stage of linear elastic deformation, and its strength increases rapidly with strain. After entering the stage of nonlinear deformation, the soil exhibits non ideal elastic-plastic deformation. Whenever the confining pressures are 50, 100, 200 and 300 kPa, the stress-strain relationship is strain-hardened. The plane position of the stress-strain curve decreases continuously with the increase of the number of freeze-thaw cycles, and the decrease amplitude gradually decreases, indicating that the freeze-thaw cycle had a continuous degradation effect that increased with the number of freeze-thaw cycles. However, the decline progressively slowed because the freeze-thaw cycles changed the characteristics of the saline soil, such as the connection and arrangement of particles and the stress history, thereby causing changes in the stress-strain characteristics after 10 freeze-thaw cycles. This is because after a certain number of freeze-thaw cycles, the formation of larger cracks slows down as the number of freeze-thaw cycles continues to increase, leading to a gradual weakening of the degradation effect.

3.2 Peak undrained shear strength

Regarding the determination of peak undrained shear strength: for the strain softening stress-strain relationship, the shear strength value is the local stress value at its peak point; For the strain hardening relationship, the shear strength value corresponds to the deviatoric stress value when the axial strain is 15%. The consolidated undrained triaxial compression test was conducted on soil samples after different freeze-thaw cycles, and the results are shown in Table 4. Then, the relationship between shear strength on saline soil and confining pressure and freeze-thaw cycles was analyzed.

According to the results in Table 4, the shear strength decreases gradually with the increase of freeze-thaw cycles, indicating that freeze-thaw cycles have a continuous degradation effect on saline soil structure. The peak undrained shear strength decreases with the increase of freeze-thaw cycles, which is a result of the deterioration of saline soil properties. During the freezing process, the change in shear strength mainly depends on two factors: on the one hand, the surface soil is first frozen during the freezing process of the sample. As the freezing process continues, the freezing front moves inward, and the moisture inside the sample moves outward. The decrease of internal moisture content increases the shear strength of soil specimen. On the other hand, during the soil freezing process, moisture transforms into ice volume expansion, which destroys the original structure of the soil skeleton and generates large pores. After soil melting, these large pores cannot be fully restored. Regardless of the number of freeze-thaw cycles, the peak undrained shear strength increases with the increase of confining pressure. The reason is that the confining pressure in the triaxial test can reduce the increased pore volume of the saline soil during freeze-thaw cycles and restore the strength level of the sample to a certain extent. Therefore, the confining pressure can inhibit the deterioration of freeze-thaw cycles.

Fig. 3 shows the variation ratio of shear strength of specimens under different confining pressures with the number of freeze-thaw cycles. When the confining pressures are 50, 100, 200 and 300 kPa, the maximum shear strength reduction rate was 25.81%, 37.89%, 38.44%, 42.54% respectively, which is all occurs under 120 freeze-thaw cycles. It also can be seen from the Fig. 3 that after 1 and 10 freeze-thaw cycles, the rate of reduction is relatively large. This indicates that the freeze-thaw cycle will weaken the strength of saline soil. After the first 10 freeze-thaw cycles, the shear strength decreased relatively, which is consistent with the above conclusion.

4. Parameter determination of Duncan-Chang model

The essence of the Duncan-Chang model is to apply the incremental method concept to approximate the nonlinear stress-strain curve. The corresponding calculation parameters include tangent deformation modulus E_t and tangent poisson's ratio μ_t or tangent bulk modulus B_t . The model parameters include cohesion c , internal friction angle φ , failure ratio R_f , initial tangential modulus, calculated constants K and n , and Duncan-Chang model constant G , F , D ($E-\mu$ model) or K_b , m ($E-B$ model). The physical meaning of model parameters is clear. Based on the consolidated

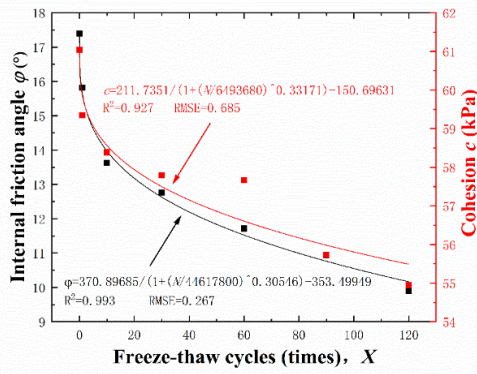


Fig. 4 Changes rules of shear strength index with the number of freeze-thaw cycles

undrained triaxial shear test, following the methods described in the literature (Qi *et al.* 2008, Wang *et al.* 2010, Zhang *et al.* 2014) with the number of freeze-thaw cycles X as the variable, the function expressions between the parameters of each model and the number of freeze-thaw cycles are determined, and a modified Duncan-Chang model considering the influence of freeze-thaw cycles is established.

4.1 Cohesion $c(X)$ and internal friction angle $\varphi(X)$

According to the stress path method, $(\sigma_1 + \sigma_3)/2$ is the horizontal axis and $(\sigma_1 - \sigma_3)/2$ is the vertical axis. Draw the Mohr stress circle and then draw the average straight line passing through each arch point, where σ_1 is the large principal stress, σ_3 is the small principal stress. Then calculate the internal friction angle and cohesion based on the linear slope and its intercept on the vertical axis

$$\varphi = \arcsin[\tan(\alpha)] \quad (1)$$

$$c = d/\cos(\varphi) \quad (2)$$

Among them, α is the slope of the average straight line, and d is the intercept of the average straight line on the vertical axis.

The shear strength indexes (c , φ) of specimens under different freeze-thaw cycles are shown in Table 5.

It can be seen from Table 5 that the values of cohesion c and internal friction angle φ for the specimen have decreased. At the same time, cohesion c changed from 0 to 6.1 kPa, while internal friction angle φ changed from 0° to 7.5° , resulting in a final decrease rate of 11.08% and 75.7%, respectively.

As the number of freeze-thaw cycles increases, the cohesion c and internal friction angle φ for the specimen gradually decreased. Therefore, the logistic function can be used to fit the regression relationship between them and the number of freeze-thaw cycles, i.e., Eq. (3).

$$c(X) = \frac{x_0 - A_2}{1 + (X/A_1)^p} + A_2 \quad (3)$$

Where: x_0 is the index value of unfrozen and thawing specimens and A_1 , A_2 , and p are the fitting parameters.

The fitting curves of cohesion c and internal friction angle φ are shown in Fig. 4. It can be seen from the Fig. 4 that as the number of freeze-thaw cycles increases, both cohesion c and internal friction angle φ gradually decrease, indicating that freeze-thaw cycles have a continuous weakening effect on the saline soil, where the decrease is faster under the first 10 freeze-thaw cycles and slower after 10 cycles, indicating that 10 freeze-thaw cycles are the turning point in the trend of cohesion c and internal friction angle φ . This is consistent with the previous changes and analysis of stress-strain relationship and shear strength.

According to the mole-coulomb limit equilibrium theory, the formula for calculating the shear strength $(\sigma_1 - \sigma_3)_f$ of specimens under different number of freeze-thaw cycles and confining pressures is

$$(\sigma_1 - \sigma_3)_f = \frac{2cc\cos(\varphi) + 2\sigma_3\sin(\varphi)}{1 - \sin(\varphi)} \quad (4)$$

4.2 Initial tangent modulus $E_t(X)$ and failure ratio $R_f(X)$

According to the concept of elastic modulus, tangent modulus is defined as

$$E_t = \frac{d\sigma_1}{d\varepsilon_1} \quad (5)$$

In the conventional triaxial shear test, σ_3 is a constant, $d\sigma_3=0$. Therefore, the tangent modulus can be directly obtained according to the stress-strain relationship in the vertical direction, as follows

$$E_t = \frac{d\sigma_1}{d\varepsilon_1} = \frac{d(\sigma_1 - \sigma_3)}{d\varepsilon_1} \quad (6)$$

Konder proposed that the stress-strain relationship of strain-hardening soils can be expressed by the following hyperbola. The equation is

$$q = (\sigma_1 - \sigma_3) = \frac{\varepsilon_1}{a + b\varepsilon_1} \quad (7)$$

Where: q is the deviatoric stress, a and b are experimental constants.

Due to $d\sigma_2 = d\sigma_3 = 0$, where σ_2 is the intermediate principal stress, the tangent deformation modulus can be defined as

$$E_t = \frac{\partial(\sigma_1 - \sigma_3)}{\partial\varepsilon_1} = \frac{a}{(a + b\varepsilon_1)^2} \quad (8)$$

When the strain is small, that is, at the beginning of loading, the specimen is in the elastic deformation stage, $\varepsilon_1=0$ and $E_t = E_i$, then the initial tangent modulus E_i is as follows

$$E_i = \left(\frac{\sigma}{\varepsilon_1}\right)_{\varepsilon_1 \rightarrow 0} = \frac{1}{a} \quad (9)$$

When the strain reaches infinity, the deviatoric stress corresponding to the asymptotic line of the ideal hyperbolic relation is the ultimate deviatoric stress, as shown below

$$(\sigma_1 - \sigma_3)_{ult} = (\sigma_1 - \sigma_3)_{\varepsilon_1 \rightarrow \infty} = \frac{1}{b} \quad (10)$$

The ultimate deviatoric stress is not easy to measure in experiments, but the ultimate deviatoric stress of soil can be determined. Therefore, in order to determine the ultimate deviatoric stress, the empirical failure ratio R_f is generally

Table 6 Values of a and b after different number of freeze-thaw cycles

Confining pressure/kPa	parameter	Number of freeze-thaw cycles						
		0	1	10	30	60	90	120
50	b	0.0043	0.0045	0.0047	0.0049	0.0052	0.0052	0.0056
	a	0.0113	0.012	0.0164	0.0175	0.0189	0.0205	0.024
	R ²	0.9827	0.9901	0.9831	0.9796	0.977	0.9524	0.9494
100	b	0.0026	0.0029	0.0035	0.0036	0.0036	0.004	0.0038
	a	0.01	0.0113	0.0155	0.0161	0.0171	0.0174	0.019
	R ²	0.9515	0.9538	0.9712	0.9658	0.9542	0.9466	0.9
200	b	0.0021	0.0023	0.0026	0.0027	0.0029	0.003	0.0032
	a	0.0092	0.0102	0.0133	0.0139	0.0145	0.0151	0.0174
	R ²	0.9496	0.9474	0.9673	0.9644	0.9558	0.9593	0.9392
300	b	0.0018	0.002	0.0022	0.0023	0.0024	0.0027	0.0029
	a	0.0071	0.0077	0.011	0.012	0.0132	0.0145	0.017
	R ²	0.9707	0.9567	0.9874	0.9912	0.9815	0.9664	0.943

Table 7 The values of the fitting parameters

Model parameters	Confining pressure/kPa	Fitting parameters				
		A_1	A_2	p	R^2	RMSE
E_i	50	4.036	4494.213	1.113	0.958	359.144
	100	2.097	5560.837	1.331	0.984	225.257
	200	2.745	6165.134	1.038	0.957	381.117
	300	3.649	6379.914	1.152	0.972	522.704
$(\sigma_1 - \sigma_3)_{ult}$	50	41.706	150.178	0.508	0.974	3.028
	100	1.822	260.759	1.168	0.963	9.301
	200	6.143	292.311	0.621	0.993	4.981
	300	2132.488	-173.452	0.313	0.986	8.622

Table 8 Values of R_f after freeze-thaw cycles

confining pressure/kPa	Number of freeze-thaw cycles						
	0	1	10	30	60	90	120
50 kPa	0.831	0.800	0.799	0.804	0.818	0.786	0.803
100 kPa	0.774	0.768	0.797	0.798	0.768	0.789	0.703
200 kPa	0.777	0.778	0.745	0.729	0.746	0.722	0.728
300k Pa	0.788	0.794	0.751	0.735	0.706	0.743	0.729
Total	3.170	3.140	3.092	3.066	3.038	3.039	2.963
Average	0.792	0.785	0.773	0.766	0.759	0.760	0.741

defined as follows

$$R_f = \frac{(\sigma_1 - \sigma_3)_f}{(\sigma_1 - \sigma_3)_{ult}} \quad (11)$$

For the hyperbola expressed in the above equation, a linear relationship can be obtained through coordinate transformation as follows

$$\frac{\varepsilon_1}{(\sigma_1 - \sigma_3)} = a + b\varepsilon_1 \quad (12)$$

The undetermined parameters a and b are determined by fitting the stress-strain relation obtained from triaxial shear test using the above formula. There is an approximate linear

relationship between $\varepsilon_1/(\sigma_1 - \sigma_3)$ and ε_1 . The linear fitting results of a and b are shown in Table 6.

According to the values of a and b in table 6, calculate the initial tangent modulus E_i and ultimate deviatoric stress $(\sigma_1 - \sigma_3)_{ult}$ using Eqs. (9) and (10). The results are shown in Figs. 5 and 6 respectively. As shown in Figs. 5 and 6, both E_i and $(\sigma_1 - \sigma_3)_{ult}$ show a gradually decreasing trend with the increase of freeze-thaw cycles. Similarly, the regression relationship between E_i and freeze-thaw cycles can be fitted using Logistic function. The regression relationship between $(\sigma_1 - \sigma_3)_{ult}$ and freeze-thaw cycles also can be fitted using Logistic function, namely, Eq. (3). The values of the fitting parameters are shown in Table 7.

Table 9 Values of K and n after different number of freeze-thaw cycles

parameter	The value of each parameter under different number of freeze-thaw cycles						
	0	1	10	30	60	90	120
lgK	2.001	1.962	1.827	1.803	1.773	1.749	1.690
K	100.194	91.654	67.195	63.527	59.353	56.079	49.012
n	0.233	0.224	0.215	0.206	0.203	0.197	0.190
R^2	0.812	0.707	0.849	0.931	0.981	0.977	0.858

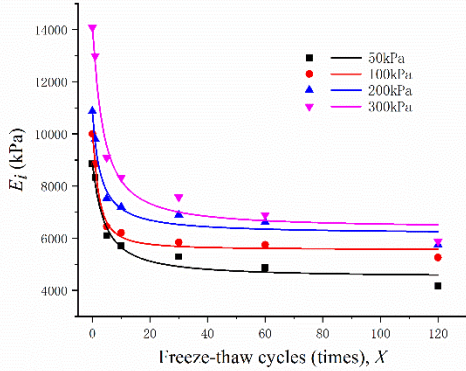


Fig. 5 Change rule of initial tangent modulus with the number of freeze-thaw cycles

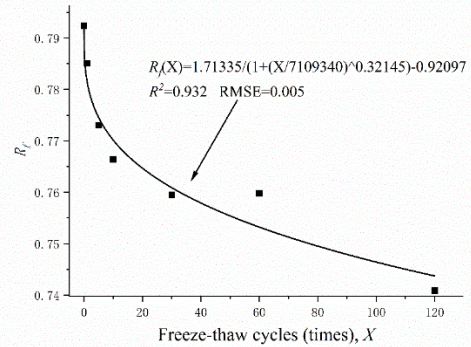


Fig. 7 Change rule of R_f with the number of freeze-thaw cycles

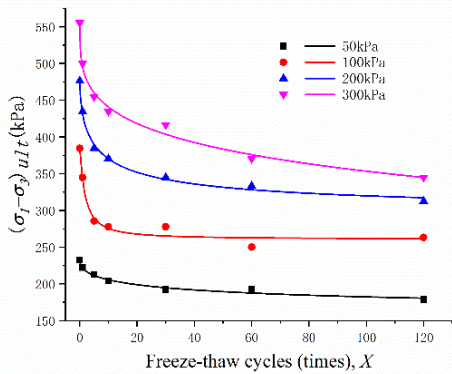


Fig. 6 Change rule of ultimate deviatoric stress with the number of freeze-thaw cycles

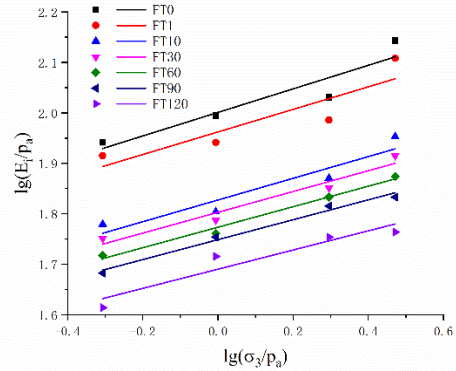


Fig. 8 Relation curves $lg(\sigma_3/p_a) - lg(E_i/p_a)$ of specimens after different number of freeze-thaw cycles

4.3 The parameters $K(X)$ and $n(X)$

The initial tangent modulus is a parameter related to the confining pressure, that is, the initial tangent modulus varies under different confining pressures. Janbu recommends using the following empirical relationships

$$E_i = K P_a \left(\frac{\sigma_3}{P_a} \right)^n \quad (13)$$

Where: K , n are all constants; P_a is the atmospheric pressure under standard conditions, equal to 101.3 kPa.

The ratio of actual deviatoric stress to the deviatoric stress at failure is defined as the stress level, and the formula is as follows

$$S_L = \frac{\sigma_1 - \sigma_3}{(\sigma_1 - \sigma_3)_f} \quad (14)$$

The tangent deformation modulus changes with the stress level, Substitute Eqs. (4) (11) (13) and (14) into Eq. (8) yields the following results

$$E_t = \left[1 - \frac{R_f (\sigma_1 - \sigma_3) (1 - \sin \varphi)}{2 c \cos \varphi + 2 \sigma_3 \sin \varphi} \right]^2 K P_a \left(\frac{\sigma_3}{P_a} \right)^n \quad (15)$$

Or abbreviated as

$$E_t = E_i (1 - R_f S_L)^2 \quad (16)$$

Based on the test results in Fig. 5, the relationship curve between $lg(\sigma_3/P_a)$ and $lg(E_i/P_a)$ was drawn, as shown in Fig. 8. From Fig. 8, it can be seen that the position of the fitting line decreases gradually with the increase of freeze-thaw

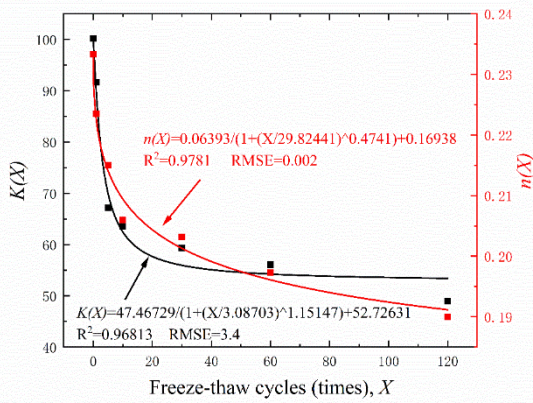


Fig. 9 Change rule of $K(X)$ and $n(X)$ with the number of freeze-thaw cycles

cycles, and the slope of the fitting line also changes accordingly. The values of K and n are shown in Table 9. $K(X)$ gradually decreases with the increase of freeze-thaw cycles. The logistic function can be used to fit their regression relationship with the number of freeze-thaw cycles, which is Eq. (3). At the same time, $n(X)$ decreases with the increase of freeze-thaw cycles. The regression relationship between $n(X)$ and the number of freeze-thaw cycle also can be fitted using Logistic function, namely, Eq. (3). The results are shown in Fig. 9.

4.4 Tangent poisson ratio

In the consolidated undrained triaxial shear test, the specimen volume remains constant, and therefore the test constants G , F , D or K_b , m cannot be obtained. According to the generalized Hooke law, when the volume strain is equal to 0, the Poisson ratio is set to 0.5. In this case, in order to guarantee the numerical calculation, it's usually set to 0.49 (Qi *et al.* 2008). Considering that different values of Poisson's ratio can affect the calculation results of the stress-strain relationship model, when the value of Poisson's ratio is between 0.49 and 0.499, corresponding calculations and comparisons of the stress-strain relationship were conducted. The results showed that the difference is very small. Therefore, this paper sets the poisson ratio to 0.5.

In summary, in order to determine the variation of tangential deformation modulus E_t with the number of freeze-thaw cycles during the consolidated undrained shear process of saline soil after different number of freeze-thaw cycles, the modified Duncan-Chang model with the number of freeze-thaw cycles as the influence factor includes five undetermined parameters, which can be determined by conventional triaxial shear test.

5. Modified Duncan-Chang model verification

The nonlinear increment form of the stress-strain relationship can be expressed as the generalized Hooke law matrix

$$\{d\sigma\} = [C^{et}]\{d\varepsilon\} \quad (17)$$

In the formula, the $d\sigma$ row and $d\varepsilon$ vector are stress increment column vectors and strain increment column vectors respectively, and C^{et} is nonlinear elastic stiffness matrix.

For the triaxial shear test, considering the axisymmetric problem, the stress and strain in the three-dimensional polar coordinate system are respectively

$$d\sigma = (d\sigma_\rho, d\sigma_z, d\tau_{\rho z}, d\sigma_\theta)^T \quad (18)$$

$$d\varepsilon = (d\varepsilon_\rho, d\varepsilon_z, d\gamma_{\rho z}, d\varepsilon_\theta)^T \quad (19)$$

Where, σ is normal stress; τ is shear stress; ε is normal strain; γ is partial strain; The subscript, ρ , z and θ are the coordinate variables in a cylindrical coordinate system.

The volume strain during the sample shearing process without drainage is as follows

$$\varepsilon_V = \varepsilon_\rho + \varepsilon_z + \varepsilon_\theta = 0 \quad (20)$$

Where, ε_ρ , ε_z and ε_θ is the strain of the direction of ρ , z and θ in the cylindrical coordinate system.

The nonlinear stiffness matrix C^{et} is as follows

$$C^{et} = \frac{E_t(1-v_t)}{(1+v_t)(1-2v_t)} \begin{bmatrix} 1 & d_1 & 0 & d_1 \\ d_1 & 1 & 0 & d_1 \\ 0 & 0 & d_2 & 0 \\ d_1 & d_1 & 0 & 1 \end{bmatrix} \quad (21)$$

Where, d_1 and d_2 are all constants; $d_1 = v_t/(1-v_t)$, $d_2 = (1-2v_t)/2(1-v_t)$.

According to the fitting function of the model parameters, the above modified Duncan-Chang model calculation program considering the effect of freeze-thaw cycles was developed in Excel spreadsheet. The comparison results of calculated values of models and measured values are shown in Fig. 10. As can be seen from Fig. 10, the calculated results of the model are basically similar to the experimental results. It is indicated that the modified Duncan-Chang model can reflect the variation law of the stress-strain relationship of saline soil under freeze-thaw cycles.

6. Conclusions

Based on the experimental works performed in this study on remolded saline soil (CL) under different freeze-thaw cycles (0, 1, 10, 30, 60, 90 and 120), the following major conclusions can be drawn:

- In this paper, the stress-strain curve of saline soil specimen exhibits strain hardening type. The shear strength decreases gradually with the increase of freeze-thaw cycles. Among them, the decline was faster under the first 10 freeze-thaw cycles, and then the decline gradually became slower as the number of freeze-thaw cycles increased, indicating that the 10 freeze-thaw cycles are the turning point in the trend of changes in the mechanical properties of saline soils.
- The regression analysis of experimental data shows that, as the number of freeze-thaw cycles increases, the shear strength indexes cohesion c , internal friction

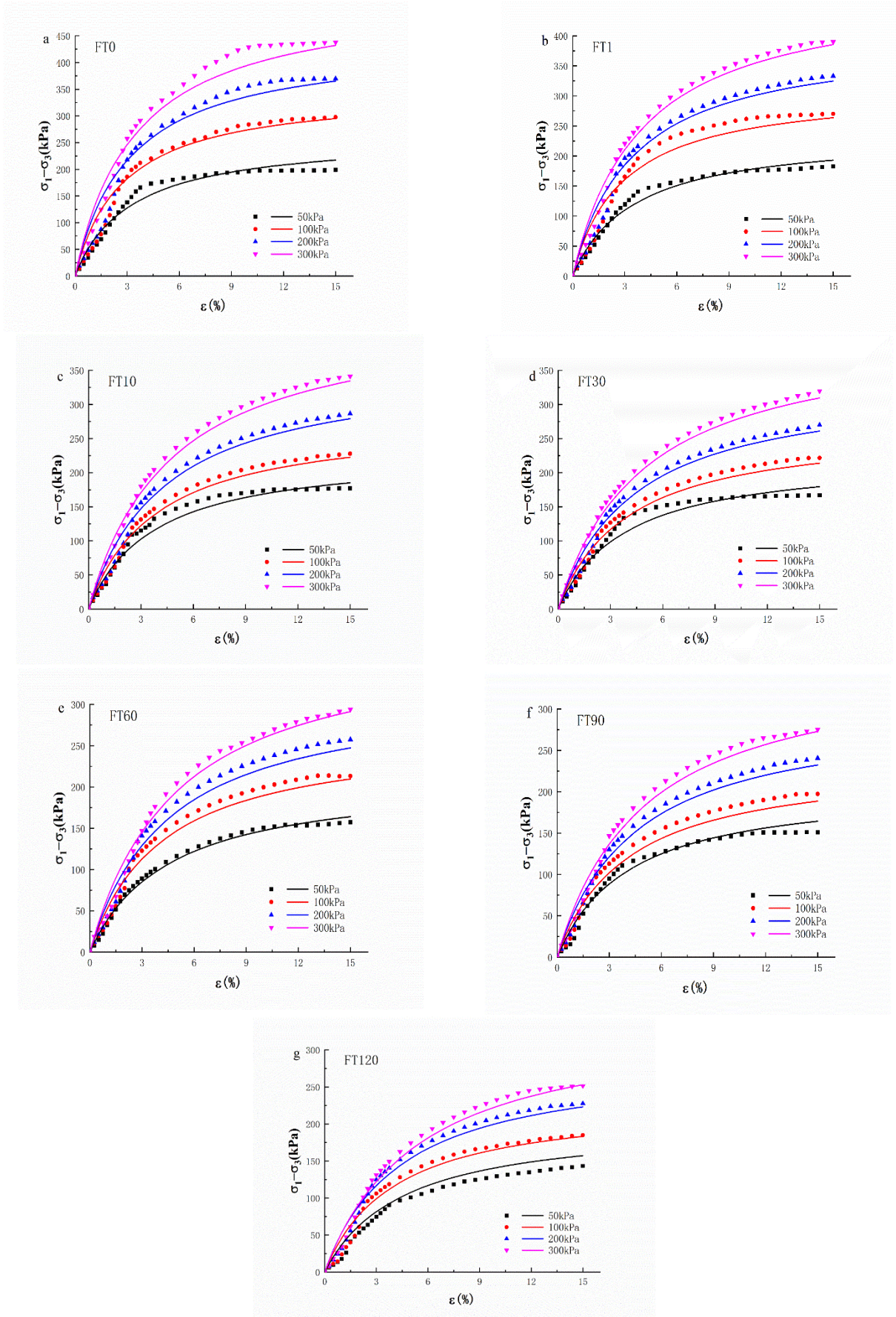


Fig. 10 Comparison between model calculation and experimental measurement of stress-strain relationship under different freeze-thaw cycles: (a) FT0, (b) FT1, (c) FT10, (d) FT30, (e) FT60, (f) FT90 and (g) FT120

angle φ , the empirical failure ratio R_f , K and n in the parameters of Duncan-Chang model show a gradually decreasing trend, which can be fitted with a Logistic function. On this basis, a modified Duncan-Chang model was established with the number of freeze-thaw cycles as the influence factor, including $c(X)$, $\varphi(X)$, $R_f(X)$, $K(X)$, and $n(X)$. In the meantime, the ultimate deviatoric stress $(\sigma_1 - \sigma_3)_{ult}$ and initial tangent modulus E_i gradually decreases with the increase of freeze-thaw cycles, which also can be fitted with a Logistic function.

- Based on the matrix form of the generalized Hooke law, the triaxial shear test process of cylinder specimens is regarded as an axisymmetric problem, and the matrix form of stress, strain and nonlinear elastic stiffness is established in a three-dimensional polar coordinates system. A calculation program was developed and the calculated values of the model were compared with the experimental values. The results showed good consistency between the two, verifying the effectiveness of the modified Duncan-Chang model in reflecting the freeze-thaw cycle effect.
- This paper aims to study the deformation and mechanical properties of remolded saline soil under degradation law of freeze-thaw cycles. In the future, research can be conducted on the deformation and mechanical properties of saline soil under different salt conditions under the influence of freeze-thaw cycles. On this basis, the modified model should be further developed in numerical calculation software to achieve stability evaluation of engineering construction.

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References

- Adeli Ghareh Viran, P. and Binal, A. (2018), "Effects of repeated freeze-thaw cycles on physico-mechanical properties of cohesive soils", *Arabian J. Geosci.*, **11**(11), 250. <https://doi.org/10.1007/s12517-018-3592-5>.
- ASTM (2011), Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System), D2487-11, *ASTM International, West Conshohocken, PA, 2011*. <https://doi.org/10.1520/D2487-11>.
- Bing, H. and He, P. (2011), "Experimental investigations on the influence of cyclical freezing and thawing on physical and mechanical properties of saline soil", *Environ. Earth Sci.*, **64**(2), 431-436. <https://doi.org/10.1007/s12665-010-0858-y>.
- Chang, D., Liu, J. and Li, X. (2015), "Normalized stress-strain behavior of silty sand under freeze-thaw cycles", *Rock Soil Mech.*, **36**(12), 3500-3505. <https://doi.org/10.16285/j.rsm.2015.12.021>.
- Chang, D., Liu, J., Li, X. and Yu, Q.. (2014), "Experiment study of effects of freezing-thawing cycles on mechanical properties of Qinghai-Tibet silty sand", *Chinese J. Rock Mech. Eng.*, **33**(7), 1496-1502. <https://doi.org/10.13722/j.cnki.jrme.2014.07.023>.
- Cheng, S., Wang, Q., Fu, H., Wang, J., Han, Y., Shen, J. and Lin, S. (2021b), "Effect of freeze-thaw cycles on the mechanical properties and constitutive model of saline soil", *Geomech. Eng.*, **27**(4), 309-322. <https://doi.org/10.12989/gae.2021.27.4.309>.
- Cheng, S., Wang, Q., Wang, N., Wang, J. and Han, Y. (2021a), "Study on mechanical properties of saline soil and evaluation of influencing factors", *J. Cold Reg. Eng.*, **35**(2), [https://doi.org/10.1061/\(ASCE\)CR.1943-5495.0000247](https://doi.org/10.1061/(ASCE)CR.1943-5495.0000247).
- Costanzo, D., Viggiani, G. and Tamagnini, C. (2006), "Directional response of a reconstituted fine-grained soil—Part I: experimental investigation", *Int. J. Numer. Anal. Method. Geomech.*, **30**(13), 1283-1301. <https://doi.org/10.1002/nag.526>.
- Dayarathne, R., Hawlader, B. and Phillips, R. (2022), "Centrifuge modelling of gas pipelines undergoing freeze-thaw cycles", *Can. Geotech. J.*, **59**(4), <https://doi.org/10.1139/cgj-2020-0482>.
- Duncan, J.M. (1970), "Nonlinear analysis of stress and strain in soils", *J. Soil Mech. Found. Division*, **96**(5), 1629-1653. <https://doi.org/10.1061/JSFEAQ.0001458>.
- Fang, Q.Y., Chai, S.X., Li, M. and Wei, L. (2016), "Influence of freezing-thawing cycles on compressive strength and deformation of solidified saline soil", *Chinese J. Rock Mech. Eng.*, **35**(5), 1041-1047. <https://doi.org/10.13722/j.cnki.jrme.2015.1078>.
- Fang, W., Jiang, N. and Luo, X. (2019), "Establishment of damage statistical constitutive model of loaded rock and method for determining its parameters under freeze-thaw condition", *Cold Reg. Sci. Technol.*, **160**, 31-38. <https://doi.org/10.1016/j.coldregions.2019.01.004>.
- Han, M., Peng, W., Ma, B., Yu, Q., Kasama, K., Furukawa, Z., Niu, C. and Wang, Q. (2023), "Micro-composition evolution of the undisturbed saline soil undergoing different freeze-thaw cycles", *Cold Reg. Sci. Technol.*, **210**, 103825. <https://doi.org/10.1016/j.coldregions.2023.103825>.
- Han, Y., Wang, Q., Kong, Y., Cheng, S., Wang, J. and Zhang, X. (2018b), "Experiments on the initial freezing point of dispersive saline soil", *Catena*, **171**, 681-690. <https://doi.org/10.1016/j.catena.2018.07.046>.
- Han, Y., Wang, Q., Wang, N., Wang, J., Zhang, X., Cheng, S. and Kong, Y. (2018a), "Effect of freeze-thaw cycles on shear strength of saline soil", *Cold Reg. Sci. Technol.*, **154**, 42-53. <https://doi.org/10.1016/j.coldregions.2018.06.002>.
- Hu, T., Liu, J., Chang, D., et al. (2018), "Influence of freeze-thaw cycling on mechanical properties of silty clay and Duncan-Chang constitutive model", *China J. Highway Transport*, **31**(2), 298-307. <https://doi.org/10.19721/j.cnki.1001-7372.2018.02.032>.
- Hui, B., Ping, H.E. and Cheng-song, Y. (2006), "Influence of sodium sulfate on soil frost heaving in an open system", *J. Glaciol. Geocryology*, **28**(1), 126-130. <https://doi.org/10.1016/j.clay.2006.09.007>.
- Kamei, T., Ahmed, A. and Shibi, T. (2012), "Effect of freeze-thaw cycles on durability and strength of very soft clay soil stabilised with recycled Bassanite", *Cold Reg. Sci. Technol.*, **82**, 124-129. <https://doi.org/10.1016/j.coldregions.2012.05.016>.
- Kong, F., Nie, L., Xu, Y., et al. (2022), "Effects of freeze-thaw cycles on the erodibility and microstructure of soda-saline loessal soil in Northeastern China", *Catena*, **209**, 105812. <https://doi.org/10.1016/j.catena.2021.105812>.
- Konrad, J.M. (1989), "Physical processes during freeze-thaw

- cycles in clayey silts”, *Cold Reg. Sci. Technol.*, **16**(3), 291-303. [https://doi.org/10.1016/0165-232X\(89\)90029-3](https://doi.org/10.1016/0165-232X(89)90029-3).
- Liu, J., Chang, D. and Yu, Q. (2016), “Influence of freeze-thaw cycles on mechanical properties of a silty sand”, *Eng. Geol.*, **210**, 23-32. <https://doi.org/10.1016/j.enggeo.2016.05.019>.
- Qi, J., Luan, M., Wang, Z., et al. (2008), “Study on undrained shear behavior and hyperbolic stress-strain relationship of saturated clays”, *Rock Soil Mech.*, **8**, 2277-2282. <https://doi.org/10.16285/j.rsm.2008.08.051>.
- Qi, J., Vermeer, P.A. and Cheng, G. (2006), “A review of the influence of freeze-thaw cycles on soil geotechnical properties”, *Permafrost & Periglacial Processes*, **17**(3), 245-252. <https://doi.org/10.1002/ppp.559>.
- Qiu, W.L., Teng, F. and Pan, S.S. (2020), “Damage constitutive model of concrete under repeated load after seawater freeze-thaw cycles”, *Constr. Build. Mater.*, **236**(5), 117560. <https://doi.org/10.1016/j.conbuildmat.2019.117560>.
- Roustaeci, M., Eslami, A. and Ghazavi, M. (2015), “Effects of freeze-thaw cycles on a fiber reinforced fine grained soil in relation to geotechnical parameters”, *Cold Reg. Sci. Technol.*, **120**, 127-137. [doi:https://doi.org/10.1016/j.coldregions.2015.09.011](https://doi.org/10.1016/j.coldregions.2015.09.011).
- Simonsen, E. and Isacsson, U. (2001), “Soil behavior during freezing and thawing using variable and constant confining pressure triaxial tests”, *Can. Geotech. J.*, **38**(4), 863-875. <https://doi.org/10.1139/t01-007>.
- Simonsen, E., Janoo Vincent, C. and Isacsson, U. (2002), “Resilient properties of unbound road materials during seasonal frost conditions”, *J. Cold Reg. Eng.*, **16**(1), 28-50. [https://doi.org/10.1061/\(ASCE\)0887-381X\(2002\)16:1\(28\)](https://doi.org/10.1061/(ASCE)0887-381X(2002)16:1(28)).
- Wang, J., Ding, G.Y., Pan, L.Y., Cai, Y.Q. and Gao, Y.F. (2010), “Study of mechanics behavior and constitutive model of cemented soil under static triaxial tests”, *Rock Soil Mech.*, **31**(5), 1407-1412. <https://doi.org/10.16285/j.rsm.2010.05.043>.
- Wang, Q., Kong, Y., Zhang, X., Ruan, T. and Chen, Y. (2016), “Mechanical effect of pre-consolidation pressure of structural behavior soil”, *J. Southwest Jiaotong Univ.*, **51**(5), 987-994. <https://doi.org/10.3969/j.issn.0258-2724.2016.05.023>.
- Wang, Q., Qi, J., Wang, S., Xu, J. and Yang, Y. (2020), “Effect of freeze-thaw on freezing point of a saline loess”, *Cold Reg. Sci. Technol.*, **170**, 102922. <https://doi.org/10.1016/j.coldregions.2019.102922>.
- Wang, T.I., Liu, Y.J., Yan, H. and Xu, L. (2015), “An experimental study on the mechanical properties of silty soils under repeated freeze-thaw cycles”, *Cold Reg. Sci. Technol.*, **112**, 51-65. <https://doi.org/10.1016/j.coldregions.2015.01.004>.
- Xiang, B., Liu, E. and Yang, L. (2022), “Influences of freezing-thawing actions on mechanical properties of soils and stress and deformation of soil slope in cold regions”, *Scientific Reports*, **12**(1), 5387. <https://doi.org/10.1038/s41598-022-09379-3>.
- Yang, C.S., He, P., Cheng, G.D., Zhu, Y.L. and Zhao, S.P. (2003), “Testing study on influence of freezing and thawing on dry density and water content of soil”, *Chinese J. Rock Mech. Eng.*, **2**, 2695-2699. <https://doi.org/10.3321/j.issn:1000-6915.2003.z2.033>.
- Yang, Z., Still, B. and Ge, X. (2015), “Mechanical properties of seasonally frozen and permafrost soils at high strain rate”, *Cold Reg. Sci. Technol.*, **113**, 12-19. <https://doi.org/10.1016/j.coldregions.2015.02.008>.
- Yao, Y., Zhang, B. and Zhu, J. (2012), “Behaviors, constitutive models and numerical simulation of soils”, *China Civil Eng. J.*, **45**(3), 127-150. <http://doi.org/10.15951/j.tmgxcb.2012.03.001>.
- Zhang, X., Liu, J. and Zhang, Y. (2014), “The experimental research on constitutive relationship of frozen silty clay based on the Duncan-Chang model”, *Chinese J. Solid Mech.*, **35**(2), 150-159. <https://doi.org/10.19636/j.cnki.cjrm42-1250/o3.2014.02.006>.
- Zhang, X., Wang, Q., Li, P., et al. (2015), “Research on soil dispersion of Qian’an soil forest”, *J. Northeastern Univ. Nat. Sci.*, **36**(11), 1643-1647. <https://doi.org/10.3969/j.issn.1005-3026.2015.11.027>.
- Zhang, X., Wang, Q., Wang, G., Wang, W., Chen, H. and Zhang, Z. (2017), “A study on the coupled model of hydrothermal-salt for saturated freezing salinized soil”, *Math. Probl. Eng.*, **12**. <https://doi.org/10.1155/2017/4918461>.
- Zhao, G.-t., Han, Z., Zou, W.-l., et al. (2021), “Evolution of mechanical behaviours of an expansive soil during drying-wetting, freeze-thaw, and drying-wetting-freeze-thaw cycles”, *Bull. Eng. Geol. Environ.*, **80**(10), 8109-8121. <https://doi.org/10.1007/s10064-021-02417-w>.

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