Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-6, Issue-11, November 2024
DOI: 10.53469/jrse.2024.06(11).05

# Study on the Influencing Factors of Shear Strength of Carbonate Saline Soil based on Ring Shear Test

**Jinsheng Zhang, Yan Xu***

College of Construction Engineering, Jilin University, Changchun, Jilin 130012, China
**Corresponding Author, 471348028@qq.com*

**Abstract:** ***The Songnen Plain, situated in the northeastern region of China, is a typical seasonal permafrost zone with extensive carbonate saline soil. Physical parameters and environmental conditions are important factors influencing the mechanical properties of shallow carbonate saline soil. In this study, the effects of dry density (1.35g/cm$^3$, 1.40g/cm$^3$, 1.45g/cm$^3$, 1.50g/cm$^3$), salt content (0.5%, 1.0%, 1.5%), and freeze-thaw cycles (0, 1, 3, 5, 10, 15) on the shear strength of carbonate saline soil were systematically investigated through ring shear tests. The test results conclusively demonstrate that the shear strength of carbonate saline soils exhibits a positive correlation with the dry density. When the dry density increases from 1.35g/cm$^3$ to 1.50g/cm$^3$, the increase range of the shear strength of samples is between 5.0% and 11.3%. The impact on the shear strength of carbonate saline soils is relatively insignificant when the salt content changes in the range of 0.5% to 1.5%, with the shear strength of the soil fluctuating within the range of 1.8% to 3.2%. The freeze-thaw cycles lead to a progressive decay in the shear strength of carbonate saline soils, and the shear strength of the soils attains a relatively stable state after 5 freeze-thaw cycles. After 15 freeze-thaw cycles, the shear strength of carbonate saline soil diminishes by 15.2%. This study can provide scientific references for slope stability analysis and landslide control in regions with carbonate saline soil distribution.***

**Keywords:** Carbonate saline soil, Ring shear test, Shear strength, Dry density, Freeze-thaw cycle**.**

## 1. Introduction

Large areas of carbonate saline soil are distributed in the Songnen Plain in northeastern China. Shallow landslides and mudflows are prevalent geological hazards in this area, which are intrinsically related to the unique characteristics of carbonate saline soil and the local climatic conditions [1]. The Songnen Plain is a characteristic seasonal permafrost region, where shallow soils experience structural and strength deterioration upon repeated freeze-thaw cycles [2]. Meanwhile, due to the presence of soluble salt ions in saline soils, it will lead to changes in the shape, size, and connectivity of soil particles, which in turn has a profound impact on the soil strength [3]. Collectively, these factors may potentially trigger the occurrence of geological hazards such as landslides. Therefore, in-depth research on the mechanical properties of carbonate saline soil is of utmost significance for infrastructure construction and the prevention and control of geological hazards like landslides and mudflows in the Songnen Plain region.

Soil shear strength is an important index for the study of slope stability. It plays a pivotal role in elucidating landslide initiation conditions and mechanisms. The ring shear apparatus was initially utilized by Bishop et al. [5] in 1971 to study the shear strength of soils. Subsequently, Bromhead [6] and Sassa et al. [7] have made improvements to the ring shear instrument. Currently, ring shear has emerged as a commonly adopted method for investigating the shear strength of soil. Bi et al. [8] used a fully automatic ring shear instrument to investigate the variation rule of shear strength of remodeled loess under the conditions of different water content, dry density and shear rate. Xue et al. [9] took saturated chloride salted loess as the research object, and through the ring shear test and scanning electron microscope test, they found that the presence of soluble salt components affects the microstructure of the soil, and with the increase of salt content, the number of internal agglomerates in the soil increases, and the number of fine pores decreases, which then has an effect on the residual strength of the soil. Tiwari et al. [10] and Yao et al. [11] studied saturated chloride saline soils and found that the residual shear strength of saline soils increases with increasing salt concentration in the pore fluid. Xu et al. [14] found that sulfate solution concentration is an important factor affecting the shear strength of loess. The loess specimens with high sulfate content develop more medium-sized pores and a looser structure. Kong et al. [2] found that the freeze-thaw cycling process alters the microstructure of the soil and has a cumulative deteriorating effect on the soil shear strength. By summarizing the results of existing studies, it is found that dry density, salt content and freeze-thaw cycles are important factors in controlling the shear strength of saline soils, but the current research is mostly on saturated sulfate soils and chloride soils, and there are fewer studies on unsaturated carbonate saline soils.

In this study, the shallow carbonate saline soil in Songyuan area was taken as the research object, and the positive stress level of the soil in the range of 2-3 m was simulated by setting 50 kPa positive stress. The effects of dry density, salt content, and freeze-thaw cycles on the mechanical strength of carbonate saline soil were investigated using a fully automated servo-controlled ring shear. The research results provide a certain reference basis for the control of shallow slopes in the distribution area of carbonate impregnated soil.

## 2. Test Materials and Methods

### 2.1 Test Materials

The carbonate saline soil utilized in the experiment was procured from Qian'an County, Jilin Province, China. The depth of soil extraction range from 0.5 to 0.6 meters. The basic physical indexes of the soil samples are shown in Table 1. The soil particle size distribution curve is shown in Figure 1. The soluble salt ions in the soil were determined by ion chromatography and titration, and it was revealed that the cations were mainly dominated by $Na^+$ and the anions were mainly dominated by $HCO_3^-$. The soil samples for the test were subjected to salt washing, air drying, grinding, and sieving procedures. Subsequently, the test soil was formulated in accordance with the mass percentage of each component as per the test protocol. After the formulation was completed, the samples were placed in a sealed bag for 48 hours to ensure the uniform distribution of moisture and salt. The test program is detailed in Table 2. Sodium bicarbonate was used as the soluble salt component in the soil samples in this study. During the experiment, in order to try to make the test results consistent with the actual situation, the water content of each specimen was controlled as the natural water content, and four dry density levels of 1.35g/cm$^3$, 1.40g/cm$^3$, 1.45g/cm$^3$, 1.50g/cm$^3$ were selected on the basis of the natural dry density. Considering that the salt content of carbonate saline soils in Songyuan area is usually under 1.5% [7], three salt content levels of 0.5%, 1.0%, and 1.5% were selected. Calculated and analyzed meteorological data of Qian'an County, it was concluded that the average temperature difference of early spring in Qian'an County in the past ten years was about 14°C, so the freeze-thaw cycle temperature was selected to be -14°C to 14°C. After the sample loading was completed, the shear box was sealed with plastic wrap and placed in a freezer at -14°C for 12 hours for freezing, and then the shear box was transferred to a thermostat at 14°C for 12 hours for thawing, and the above process is considered to be a complete freeze-thaw cycle.

**Table 1:** Basic physical properties of the test soil

| Natural density(g/cm$^3$) | Natural dry density(g/cm$^3$) | Natural water content(%) | Liquid limit water content(%) | Plastic limit water content(%) | Particle size distribution(%) | | |
|---|---|---|---|---|---|---|---|
| | | | | | ≤2μm | 2-50μm | ≥50μm |
| 1.59 | 1.41 | 12.84 | 32.00 | 19.30 | 8.11 | 78.89 | 13.00 |

**Table 2:** Test program

| (1) Salt content SC (%) | (2) Dry density $\rho_d$ (g/cm$^3$) | (3) Freeze-thaw cycle FTC (times) |
|---|---|---|
| (4) 0.5 | (5) 1.35, 1.40, 1.45, 1.50 | (6) 0 |
| (7) 1.0 | (8) 1.35, 1.40, 1.45, 1.50 | (9) 0 |
| (10) 1.5 | (11) 1.35, 1.40, 1.45, 1.50 | (12) 0 |
| (13) 0.5 | (14) 1.40 | (15) 0, 1, 3, 5, 10, 15 |

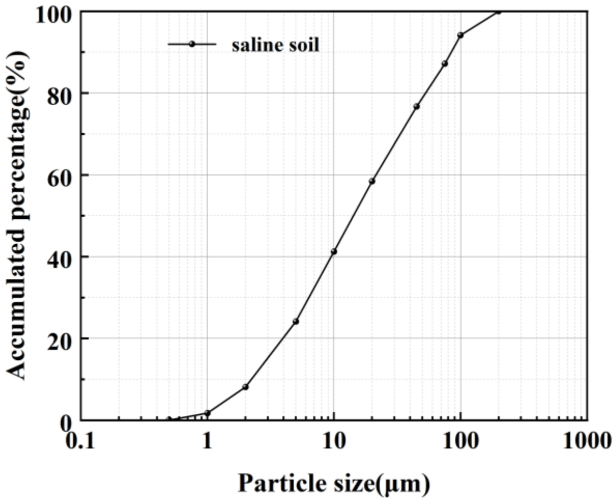


**Figure 1:** Particle size distribution curve of carbonate saline soil

### 2.2 Test Apparatus

The apparatus used in this test is the TT-RSA-10F fully automatic servo-controlled ring shear apparatus, as shown in Figure 2. The TT-RSA-10F ring shear utilizes a pneumatic loading mechanism to apply a vertical load to the soil through the upper pressurized plate. The lower shear box of the ring shear can be rotated in both left and right directions under the drive of a servo motor, and the specimen inside the box is sheared under the action of six convex teeth distributed on the upper pressurized plate. The shear box has an outer diameter of 100 mm, an inner diameter of 60 mm and a height of 20 mm. the shear speed of the instrument is in the range of 0.001-130°/min and the maximum torque that can be applied is 200 N-M.

**Figure 2:** TT-RSA-10F Automatic Servo-Controlled Ring Shear apparatus

### 2.3 Test Process

The static soil is loaded into the shear box in two installments, and the soil sample is compacted using the moid matched with the instrument, until the soil sample is flush with the upper surface of the shear box, and the specimen surface is leveled using a mold. After the soil sample is loaded, the sample used to investigate the influence of salt content and dry density can be directly fixed on the ring shear apparatus for testing. The sample used to investigate the effects of freeze-thaw cycling, after the completion of loading the sample for a certain number of freeze-thaw cycles, and then ring shear test. The test was conducted at a shear rate of 0.5 mm/min until a shear steady state was reached.

## 3. Results and Discussion

### 3.1 Effect of Dry Density on Soil Shear Strength

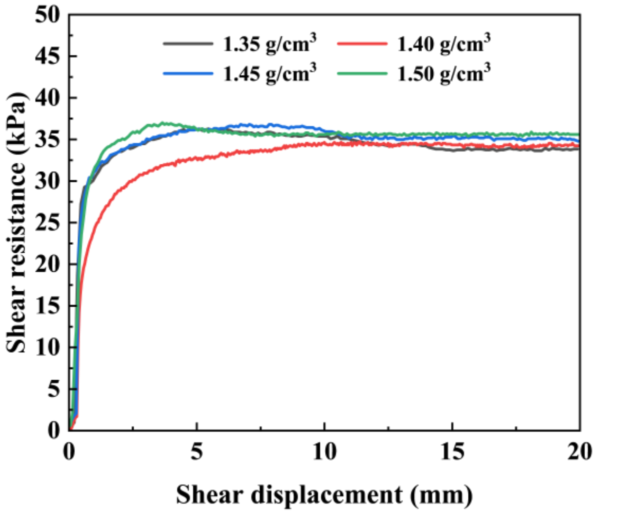


**Figure 3:** Stress-strain relationship for different dry density specimens at 0.5% salt content

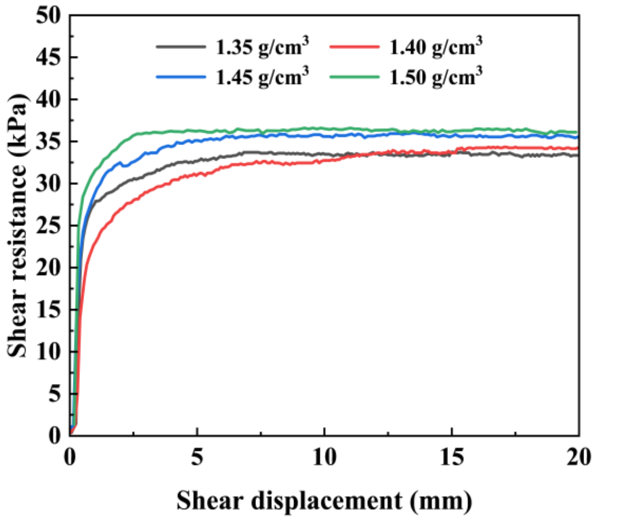


**Figure 4:** Stress-strain relationship for different dry density specimens at 1.0% salt content

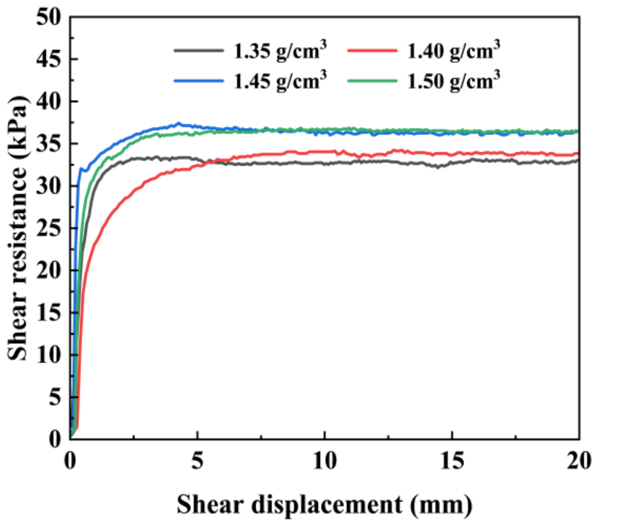


**Figure 5:** Stress-strain relationship of specimens with different dry densities at 1.5% salt content

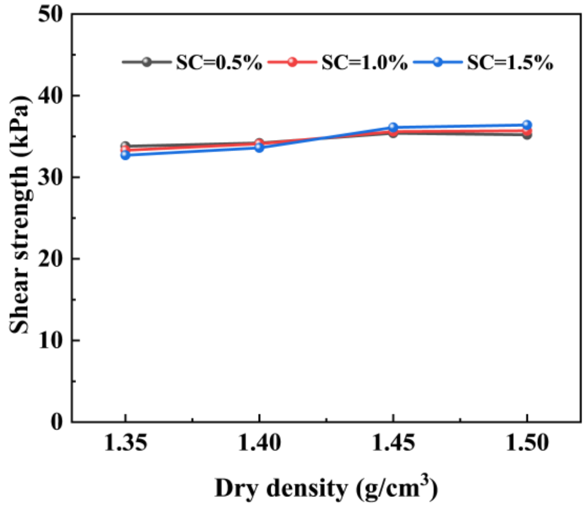


**Figure 6:** Shear strength of specimens with different salt content and different dry densities

Figures 3 to 5 show the variation of soil shear strength with dry density at three salt content levels of 0.5%, 1.0%, and 1.5%, respectively, for a specimen moisture content of 12.8%. It can be discerned from the graph that, with the increase of shear displacement, the average shear stress of the specimens under different conditions exhibits a similar trend, i.e., it increases rapidly in the initial stage, and the rate of increase decelerates when it reaches a certain value until it stabilizes. The test results show that the shear strength of carbonate saline soil augmentation with the increase of dry density. As the dry density increased from 1.35 g/cm$^3$ to 1.50 g/cm$^3$, the shear strength of the specimens for the three salt content levels augmented from 33.8 kPa, 33.3 kPa, and 32.7 kPa to 35.5 kPa, 36.1 kPa, and 36.4 kPa, corresponding to an increase of 5.0%, 8.4%, and 11.3%, respectively. This result was mainly due to the fact that when the water content of the soil is consistent, with the increase of the initial dry density, the pore ratio of the soil decreases, the degree of soil densification increases, the linkage between soil particles is enhanced, and when the soil is subjected to external forces, it will show a stronger resistance [8].

### 3.2 Effect of Salt Content on Soil Shear Strength

Previous research findings have indicated that alterations in salt content and salt types can influence the mechanical strength of the soil [11,13]. This implies the indispensability of researching the impact of salt content on soil mechanical properties for different types of saline soil. In this study, the effect of three carbonate content levels of 0.5%, 1.0%, and 1.5% on the shear strength of soil was investigated, and the results of the tests are shown in Figure3 to 6. With the increase of salt content from 0.5% to 1.5%, the soil shear strength decreased from 33.8 kPa and 34.2 kPa to 32.7 kPa and 33.6 kPa for the specimens with dry densities of 1.35 g/cm$^3$ and 1.40 g/cm$^3$, respectively, representing a decrease of 3.2% and 1.8% for each. In contrast, the soil shear strength increased from 35.4 kPa and 35.5 kPa to 36.1 kPa and 36.4 kPa for the specimens with dry densities of 1.45 g/cm$^3$ and 1.50 g/cm$^3$, respectively, representing an increase of 2.0% and 2.5% each. It is evident that when the salt content is varies within the range of 0.5% to 1.5%, the effect on the soil shear strength is relatively minor, and the numerical variation is within 4.0%. The experimental results indicate that for soil samples with a moisture content of

12.8%, the influence of salt content within the range of 0.5% to 1.5% on the shear strength of the soil is not significant.

### 3.3 Effect of Freeze-thaw Cycles on Soil Shear Strength

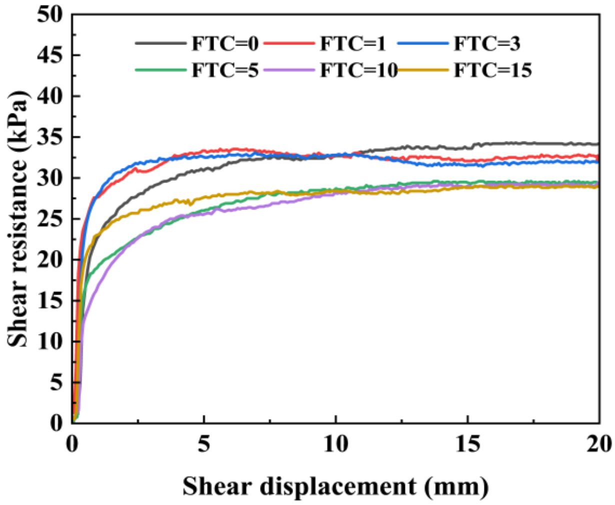


**Figure 7:** Stress-strain relationship of specimens with different freeze-thaw cycles

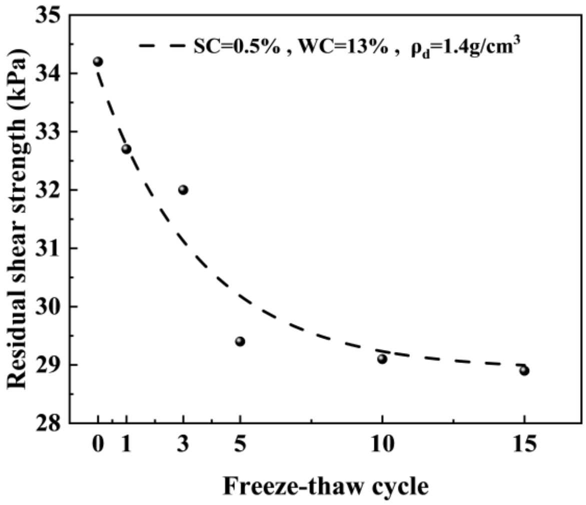


**Figure 8:** Shear strength of specimens with different numbers of freeze-thaw cycles

The freeze-thaw cycle is a crucial factor contributing to the deterioration of the structural strength of shallow soils. During the freeze-thaw cycling process, the phase change and transportation of pore water within the soil lead to an expansion in the pore space inside the soil and change the contact form of soil particles, which will lead to the strength damage of the soil. The test results in Figures 7 and 8 show that the shear strength of the specimens deteriorates significantly under the action of freeze-thaw cycles. The overall presentation decreases with the increase in the number of freeze-thaw cycles and exhibits decelerated deterioration. As the number of freeze-thaw cycles increased from 0 to 15, the soil shear strength decreased from 34.2 kPa to 28.9 kPa, which is a decrease of 15.2%. According to the results in the figure, it can be observed that when the number of freeze-thaw cycles is less than 5 times, the deterioration of soil shear strength by freeze-thaw cycles is more obvious, but when the number of freeze-thaw cycles exceeds 5 times, the deterioration of soil shear strength by freeze-thaw cycles becomes less obvious.

The underlying reason for this phenomenon is that the free water and sodium bicarbonate within the soil undergo phase changes during the freezing process. The transformation of free water from liquid to solid and the crystallization of sodium bicarbonate lead to volume expansion. Under the constraints of the surrounding soil particles, frost-heaving and salt-expansion forces are generated, resulting in an enlargement of the internal pore size and the destruction of the original cementing effect between soil particles. Meanwhile, during the freeze - thaw process, the temperature differential between the intra- and extra- soil environments induces the migration of salts driven by moisture. During the freezing phase, the moisture within the soil mass migrates towards the soil surface, thereby augmenting the surface detritus. Upon thawing, the ice crystals within the pores undergo melting and the sodium bicarbonate crystals dissolve anew, resulting in the release of freeze-(salt) expansion forces. Subsequently, under the influence of gravity, the moisture and salts migrate inwards within the soil matrix. The freeze-thaw process engenders the redistribution of internal pores, moisture, and salts within the soil. Under the freeze-thaw action, the soil experiences recurrent disturbed and continuous damaged, leading to a persistent reduction in shear resistance. After multiple freeze-thaw cycles, the internal pore distribution and particle arrangement within the soil gradually attain a state of stability, and the attenuation of the soil's shear strength also stabilizes progressively [2], [15].

## 4. Conclusion

This study focuses on shallow carbonate saline soil and investigates the effects of dry density, salt content, and freeze-thaw cycles on soil shear strength through ring shear tests. The main conclusion are as follows:

There exists a distinct positive correlation between the shear strength and dry density of carbonate saline soil. As the dry density increased from 1.35g/cm$^3$ to 1.50g/cm$^3$, the shear strength of soil samples with salt contents of 0.5%, 1.0%, and 1.5% increased by 5.0%, 8.4%, and 11.3%, respectively.

When the carbonate content varies within the range of 0.5% -1.5%, the effect on the shear strength of the soil is insignificant. The carbonate content increased from 0.5% to 1.5%, and the shear strength of the soil varied between 1.8% and 3.2%.

The freeze-thaw cycle has a cumulative weakening effect on the shear strength of carbonate saline soil. After 15 freeze-thaw cycles, the shear strength of the soil decreased by 15.2%. The threshold for the impact of freeze-thaw cycles on the shear strength of the soil was about 5 cycles. After 5 freeze-thaw cycles, the shear strength of the soil gradually stabilizes.

## References

[1] Jiang J, Wang G, Ji Y, et al.. The Impact of Meteorological Conditions on Agricultural Production in Songyuan City and Countermeasures. Contemporary Farm Machinery, 2024, (04):93+95.

[2] Kong F, Nie L, Xu Y, et al.. Effects of freeze-thaw cycles on the erodibility and microstructure of soda-saline loessal soil in Northeastern China. CATENA, 2022, 209: 105812.
[3] Shen J, Wang Q, Chen Y, et al.. Experimental investigation into the salinity effect on the physicomechanical properties of carbonate saline soil. Journal of Rock Mechanics and Geotechnical Engineering, 2024, 16(5): 1883-1895.
[4] Getahun E, Qi S, Guo S, et al.. Characteristics of grain size distribution and the shear strength analysis of Chenjiaba long runout coseismic landslide. Journal of Mountain Science, 2019, 16(9): 2110-2125.
[5] Bishop AW, Green GE, Garga VK, et al... A new ring shear apparatus and its application to the measurement of residual strength. Géotechnique, 1971, 21(4): 273-328.
[6] Bromhead E. A simple ring shear apparatus. Ground Engineering, 1979, 12(5).
[7] Wang F, Sassa K. Relationship between grain crushing and excess pore pressure generation by sandy soils in ring shear tests. Journal of natural disaster science ,2000,22(2): 87-96.
[8] Bi Q, Fan X, Dong W. Shear Strength Characteristics of Remolded Loess by Ring Shear Apparatus. Journal of Water Resources and Architectural Engineering, 2022,20(05):96-101.
[9] Xue C, Wang X, Liu K. Effect of Soaking Time and Salt Concentration on Mechanical Characteristics of Slip Zone Soil of Loess Landslides. Water, 2020, 12(12), 3465.
[10] Tiwari B, Tuladhar G R, Marui H. Variation in Residual Shear Strength of the Soil with the Salinity of Pore Fluid. Journal of Geotechnical and Geoenvironmental Engineering, 2005, 131(12): 1445-1456.
[11] Yao C, Chen P, Ma T, et al.. Physicochemical effect on shear strength characteristics of clayey soils based on ring-shear experiment. Canadian Geotechnical Journal, 2020, 57(12): 1820-1831.
[12] Wang J, Wang Q, Kong Y, et al.. Analysis of the pore structure characteristics of freeze-thawed saline soil with different salinities based on mercury intrusion porosimetry [J]. Environmental Earth Sciences, 2020, 79(7).
[13] Zhang F, Wang G, Kamai T, et al.. Effect of pore-water chemistry on undrained shear behaviour of saturated loess. Quarterly Journal of Engineering Geology and Hydrogeology, 2014, 47(3): 201-210.
[14] Xu J, Li Y, Ren, C, et al.. Damage of saline intact loess after dry-wet and its interpretation based on SEM and NMR. Soils Found, 2020, 60, 911-928.
[15] Bao W, Wu Q, Wu Q, et al.. Mechanical properties of Ili salinized loess under freeze-thaw conditions. Chinese Journal of Rock Mechanics and Engineering, 2024, 43(07): 1775-1787.