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Original Research

Experiment Study of Salt-Frost Heave on Saline Silt under the Effects of Freeze-Thaw Cycles

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Abstract

Multiple freeze-thaw cycle experiments were performed to determine the in-*situ* deformation of salt-frost heave of sulfate saline silt under long-term freeze-thaw conditions. For the determination of *in-situ* salt-frost heave of saline silt by removing the effect of water-salt migration due to temperature gradients, the in-situ salt-frost heave apparatus was designed to achieve a uniform cooling effect. The influence laws of four main factors, such as salt content, water content, initial dry density, and load, on the residual pore ratio of sulfate saline silt under the effects of freeze-thaw cycles have been analyzed. It has been found that sulfate saline silt with different initial pore ratios will eventually reach the same and stable residual pore ratio after multiple freeze-thaw cycles, independent of the initial compactness of the soil. At the water content was 16%, the residual pore ratio increased, then decreased and then increased again as the salt content increased. At the salt content was 3%, the residual pore ratio decreased linearly with the increase of water content. As the load became greater, the residual porosity ratio decreased. The accumulation effect of salt-freezing heave of residual saline silt could be effectively reduced at a water content of 16%, a salt content of 3%, and a load greater than 12.5 kPa. During multiple freeze-thaw cycles, the relationship between salt-frost heave deformation and pore ratio conforms to a linear negative correlation, and there was a positive correlation between the magnitude of accumulative salt-frost heave deformation and the magnitude of single salt-frost heave deformation. The equation of residual pore ratio with salt content, water content and load as parameters has been given in this paper. Using this equation, the prediction of accumulative deformation of salt-frost heave

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under long-term freeze-thaw conditions in residual sulfate saline silt in the seasonal permafrost region can be realized.

Keywords: saline silt, salt-frost heave, freeze-thaw cycles, salt precipitation

Introduction

The structural connections and arrangements between soil particles are altered by freeze-thaw phenomena that occur with fluctuations in ambient temperature, and this alteration has a strong effect on the physical and mechanical properties of the soil. Research have shown that freeze-thaw cycles increases the pore ratio of dense soil while it reduces the pore ratio of loose soil. The pore ratio of dense soil and loose soil will tend to a stable value after the freeze-thaw cycles, which is called the residual pore ratio [1]. Loose silt, low-density clay and normally consolidated remodeled soil are compacted during the freeze-thaw cycles, resulting in increased modulus and strength and reinforced structural properties [2]. However, for strongly superconsolidated remodeled soil, the structure is weakened by the freeze-thaw cycles [3]. A large number of experiments have shown that the weakening effect of freeze-thaw cycles on soil structure is widespread. The cement structure between soil particles is gradually destroyed by repeated freezing and thawing and the particles are rearranged. During the freeze-thaw cycles the soil structure becomes looser and looser and the cohesive force is continuously reduced, what is more, the pore ratio of the soil body is continuously increased, and the soil deformation is accumulative [4-7]. Electron microscopy, CT, and MIP have been used to observe the microstructure of soil after freeze-thaw action. The mechanism of the effect of freeze-thaw cycles on soil structure has been studied by many researchers at the microscopic level, and the results show that (1) freeze-thaw cycles cause crushing and agglomerating behavior of soil, and the soil particles tend to homogenize [6, 8], (2) freeze-thaw cycles will induce a decreasing in the number of small pores and an increasing in the number of large pores [9] ,(3) with the increase in the number of freeze-thaw, some overhead pores consisting of large and medium pores appear in the soil samples [10-11], (4) the existence of salt in the soil affects the connection form of the soil skeleton [12-13].

The accumulation of deformation disappears with the increase of the number of freeze-thaw cycles, so that the soil structure and mechanical properties gradually stabilize. The structure of the soil at stabilization is influenced by the combined action of water, salt, heat and force, and is the end point of the structural development of the soil under the effects of freeze-thaw cycles. The pore ratio of soil in stable equilibrium structure is the residual pore ratio. The residual pore ratio is an important index to characterize the limit capacity of pore development of soil with certain water, salt, heat and force conditions under the action of freeze-thaw cycles, which is important for predicting the long-term accumulative salt-frost heave deformation of soil and assessing the current salt-frost heave development of soil.

Many researchers have suggested that water migration and the growth of ice lenses are the root cause of frost heave [14-15], while for residual saline silt regions there is no significant development of ice lens, but salt expansion and frost heave hazards are still serious [16-17]. This phenomenon indicates that in-situ salt expansion and frost heave caused by long-term freezing-thawing cycles cannot be ignored. Existing investigations mainly focus on the mechanism of frost heave caused by water migration, and lack a systematic analysis of the deformation patterns of salt-frost heave in residual saline silt regions in the northwest under long-term frost heave conditions. In this paper, multiple freeze-thaw cycle experiments have been performed and the in-situ deformation of salt-frost heave in sulfate saline silt under long-term freeze-thaw conditions has been determined. The effect of four main factors, including salt content, water content, initial dry density and load, on the residual pore ratio of sulfate saline silt under freeze-thaw cycles was analyzed, and the mechanism of the accumulative *in-situ* deformation of salt-frost heave in saline silt under freeze-thaw cycles was analyzed. The results are of positive significance for the in-depth understanding of the mechanism of in-situ deformation generation of salt-frost heave in residual sulfate saline silt under the action of freeze-thaw cycles, and can also provide reference for the prediction of long-term accumulative deformation of residual sulfate saline silt in seasonal permafrost areas in northwest China, and the assessment of the development and prevention of salt-frost heave hazard.

Materials and Methods

Materials and Experimental Methods

Materials and Sample Preparation

The experimental soil was collected from Lanzhou. The soil has been washed by pure water to remove salt (6 times), dried, crushed, sieved (2 mm) and then sealed and stored. The physical property index of the soil is shown in Table 1. Anhydrous sodium sulfate had been dissolved in distilled water and prepared into a certain concentration of sodium sulfate solution at room temperature (20±2ºC), which was mixed well with dry soil and prepared into soil samples.

Table 1. Physical properties of soil.

Relative density (g/cm^3)	Liquid limit W_L/%	Plastic limit W_p/%	Plasticity index I_p	Coefficient of uniformity $C_u = d_{60}/d_{10}$
2.69	26.8	17.6	9	6.87

Table 2. Contents of soluble salts in soil.

Anion content (mg/kg)				Cation content (mg/kg)			Soluble salt concentration (mg/kg)
CO_3^{2-}	HCO_3^-	SO_4^{2-}	Cl^-	Ca^{2+}	Mg^{2+}	$K^+ + Na^+$	
16	232	337	36	108	26	111	761

Experimental Apparatus

The experiment was conducted using a homemade in-situ salt-frost heave apparatus. The structure of the apparatus is shown in Fig. 1. The soil samples were 8 cm in diameter and 2 cm in height. Salt expansion deformation was measured by YWD-50 displacement sensor with a sensitivity of 200 με/mm. The loading device was WG single lever medium pressure consolidation instrument, and the temperature control used DL2010 high precision low temperature bath with a temperature control range of -20ºC~100ºC and an accuracy of ±0.1ºC. For the determination of in-situ salt-frost heave of saline silt by removing the effect of water-salt migration due to temperature gradients, the in-situ salt-frost heave apparatus was designed with two measures to achieve a uniform cooling effect. First, the inner barrel of the specimen was made of stainless steel with good thermal conductivity, using the inner barrel to cool down from the side and bottom of the specimen at the same time. Second, the specimens were designed as cylinders with a height of 2 cm and a diameter of 8 cm. Due to the small thickness of the specimen and the ability to cool down from the side and bottom simultaneously, there was no obvious temperature gradient inside the specimen during the cooling process.

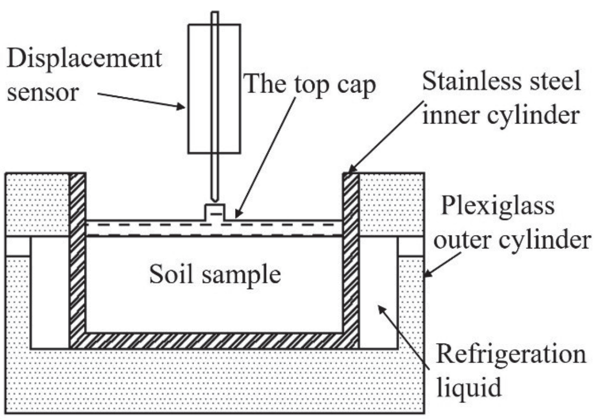

Fig. 1. Schematic diagram of salt-frost heave apparatus.

Experiment Design

(1) Freeze-thaw cycle experimental condition control

The temperature in the experiment was controlled by a high-precision low temperature cold bath. The measured temperature-time variation curve in the center of the soil sample under single freeze-thaw in this experiment is shown in Fig. 2 (the actual temperature in the soil sample was measured by a PT100 temperature sensor, and the temperature measurement position was the center of the soil sample).

(2) Variables control

The controlled variable method was adopted for this experiment, and the main influencing factors studied were salt content, water content, initial void ratio, and load. The specific covariate controls are shown in Table 3.

Experiment Results and Analysis

Residual Void Ratio of Saline Silt

The salt-frost heave deformation of saline silt under multiple freeze-thaw action was accumulative, which

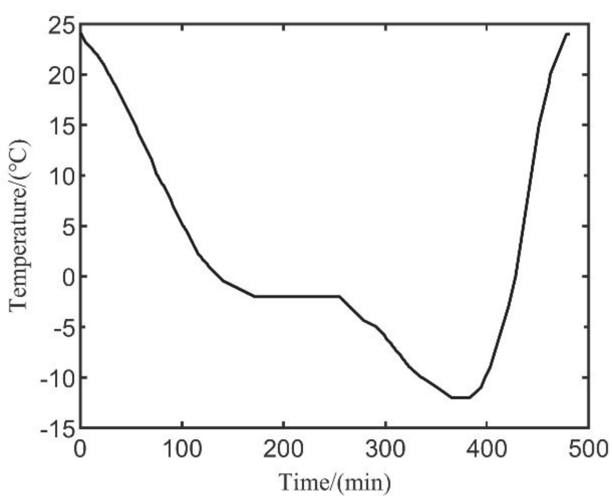

Fig. 2. Temperature change curve during freeze-thaw process.

Table 3. Freeze-thaw cycle experimental parameters control table.

Number	Salt content %	Water content %	Initial void ratio	Load kPa
1#	3	16	0.4	0
2#	3	16	0.51	0
3#	3	16	0.66	0
4#	3	10	0.51	0
5#	3	12	0.51	0
6#	3	14	0.51	0
7#	3	16	0.51	0
8#	3	18	0.51	0
9#	3	20	0.51	0
10#	0.8	16	0.51	0
11#	1	16	0.51	0
12#	1.2	16	0.51	0
13#	1.6	16	0.51	0
14#	2	16	0.51	0
15#	3	16	0.51	12.5
16#	3	16	0.51	25
17#	3	16	0.51	50
18#	3	16	0.51	75
19#	3	16	0.51	100
20#	3	16	0.51	125

Note: Soil samples to which loads were applied were exposed to freeze-thaw experiments after deformation stabilization.

meant that the volume of saline silt gradually increased with the number of freeze-thaw cycles. Viklander defined the residual void ratio as the void ratio of the soil when it reaches the stable state [1]. The data of soil samples 1#, 2# and 3# showed that the residual void ratio of residual saline silt was also not affected by the initial degree of compactness of the soil samples.

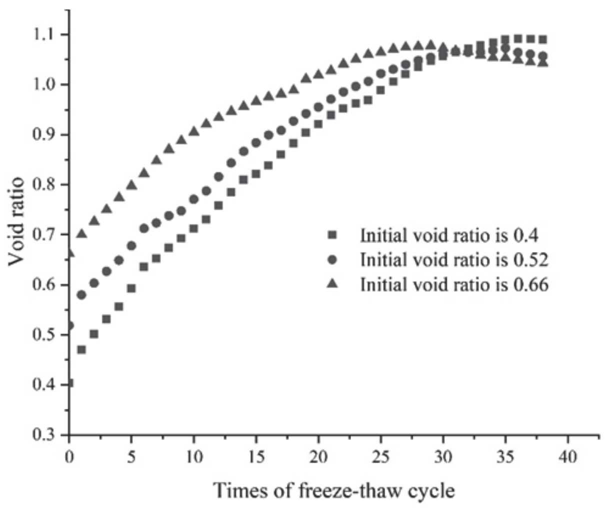

Fig. 3. Void ratio change curves of soil samples with different initial void ratios under long-term freeze-thaw cycles.

The variation curves of void ratio with increasing number of freeze-thaw cycles for sulfate saline silt with the same salt content (3%) and water content (16%) but different initial void ratios under multiple freeze-thaw cycles are given in Fig. 3. Fig. 3 shows that the void ratio of the soil gradually increases with the increase of the number of freeze-thaw cycles under the action of multiple freeze-thaw cycles, and stabilizes after reaching 30 freeze-thaw cycles. The residual sulfate saline silt with different initial void ratios will eventually reach the same and stable residual void ratio under multiple freeze-thaw cycles, and the residual void ratio is not affected by the initial compactness of the soil.

The ultimate body strain generated by saline silt under the action of long-term freeze-thaw cycles can be calculated from the soil void ratio e and the residual void ratio e_{res}:

$$\Delta\varepsilon_v = \frac{e_{res} - e}{1+e} \tag{1}$$

If the void ratio and residual void ratio of the soil are known, the following equation can be used to calculate the accumulative volume deformation ΔV_a of residual type sulfate saline silt under long-term freeze-thaw conditions.

$$\Delta V_a = V_s \Delta\varepsilon_v \tag{2}$$

where V_s is the initial volume of saline silt.

The effects of water and salt migration within the soil were not considered in the above equations. Therefore, the applicability of the above equations is limited in the surroundings with water recharge and significant water-salt migration. However, for the residual sulfate saline silt foundation without water recharge in the dry zone, which is less affected by water-salt migration, the above equation has a greater practical value. It is of great practical engineering significance to predict the ultimate volume deformation of saline silt foundation under the action of long-term freeze-thaw cycles by using the ultimate volume strain obtained from the residual porosity ratio.

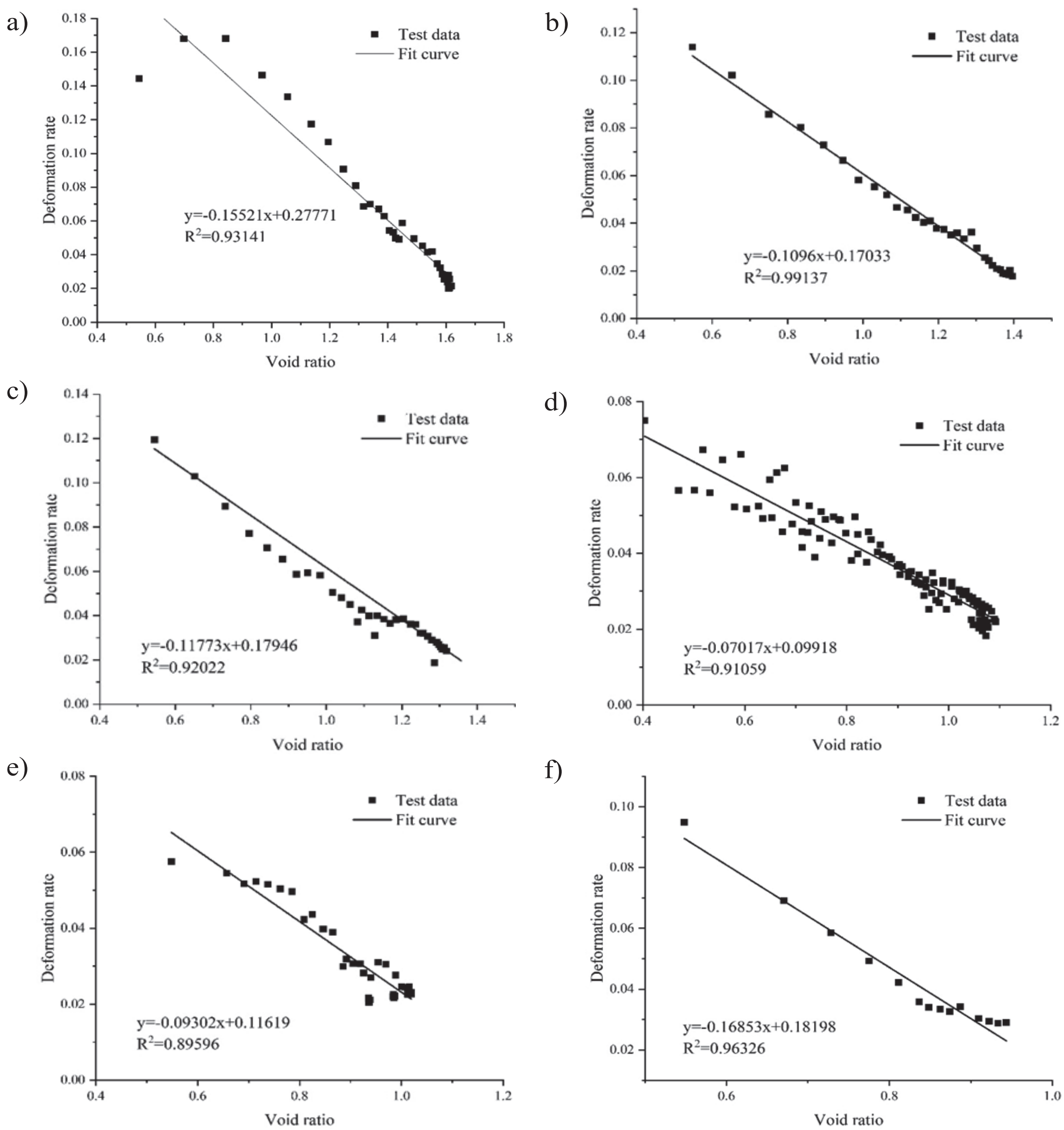

Fig. 4. Variation of salt-frost heave deformation of soil samples with void ratio under different water content conditions; a)Water content 10% and salt content 3%, b) Water content 12% and salt content 3%, c) Water content 14% and salt content 3%, d) Water content 16% and salt content 3%, e) Water content 18% and salt content 3%, f) Water content 20% and salt content 3%.

Porosity Ratio and Salt-Frost Heave

A set of soil sample void ratio and the corresponding salt-frost heave deformation and thawing deformation data can be obtained for each freeze-thaw test of soil samples. Since the void ratio of soil sample increases gradually with the increase of freeze-thawing times, the data of salt-frost heave deformation of soil sample with the change of void ratio can be obtained through multiple freeze-thawing experiments, as shown in Fig. 4. From Fig. 4, it can be noticed that with the increase of the number of freeze-thaw cycles, the void ratio of soil samples gradually increases, and the salt-frost heave deformation then decreases. The relationship between salt-frost heave deformation and void ratio is in line with the linear negative correlation. This indicates that in porous materials, the smaller the pore volume, the greater the crystallization deformation when the crystallization volume is constant. If the soil porosity ratio is known, the prediction of single salt-frost heave deformation can be achieved by using the equations of porosity ratio and deformation rate obtained from the fitting. However, some researchers controlled the porosity of the soil by changing the sand grading, and the data showed that there was no obvious linear relationship between the porosity ratio and crystalline deformation [18-19]. The pore structure of porous materials refers to the size, distribution and connectivity of pores, while the porosity can only reflect the size of the total pore volume of porous materials and does not completely reflect the pore structure of porous materials. Therefore, it cannot be simply said that there is necessarily a linear negative correlation between salt-frost deformation and void ratio in saline silt. Combined with the experimental conditions of this experiment, the following conclusion can be drawn: under the same soil, different degree of compactness, there is a linear negative correlation between salt-frost heave deformation and void ratio.

The residual deformation is the difference between salt-frost heave deformation and thawing deformation. Fig. 5 gives the change curves of salt-frost heave deformation and thawing deformation of specimens 1#, 2# and 3# with the increasing void ratio. It can be seen that when the void ratio is small, there is a large residual deformation of the specimens, and when the void ratio reaches the residual void ratio, the residual deformation of the specimens disappears. Since the residual deformation of the specimen originates from the change of soil structure by the freeze-thaw process of saline silt, the soil structure also tends to stabilize and reach a stable equilibrium structure when the soil void ratio reaches the residual void ratio.

Many researchers have used advanced means to observe the microstructure of soil after freeze-thaw, and the results show that repeated freeze-thaw causes a gradual disruption of the cementation structure between soil particles, the clumps in the soil undergo splitting and agglomeration, the particles are rearranged, and the presence of salt in the soil also affects the connection form of the soil skeleton. As the times of freezing and thawing increased, the number of large pores gradually increased, and some overhead pores consisting of large and medium pores appeared in the soil samples [10-11]. Combined with the previous research results, the process of structural development and shelf pore formation in saline silt under the action of freeze-thaw cycles was analyzed here. During the cooling process, water-salt crystallization generated a large crystallization force at the contact location of soil particles, which led to soil fragmentation and pore enlargement, and then salt-frost heave was formed. Salt crystals bonded fine soil particles and develop continuously during salt precipitation, forming soil-salt bound particles, and the size and arrangement of soil agglomerates were changed. During the warming process, some of the salt crystals dissolved, resulting in the soil skeleton formed during the cooling process losing some of the support of the salt crystals, and the pore volume in the soil decreases, resulting in thawing deformation. However, due to the internal frictional resistance, cohesion and matrix suction within the soil body, and the presence of some incompletely dissolved materials such as salt crystals existed in the soil agglomerates, the soil agglomerates not being able to recover their original position. As the result, the unrecoverable residual deformation appears, and an overhead structure will be easily formed as shown in Fig. 6 [16]. The overhead structure cannot be developed infinitely. When the void ratio of the soil reached the residual void ratio, the overhead structure stopped developing and forms an equilibrium structure that tends to be stable. Therefore, the salt expansion of saline silt under multiple freeze-thaw cycles was accumulative, and the accumulative salt expansion decreased with the enlarging pores, and the accumulative deformation will

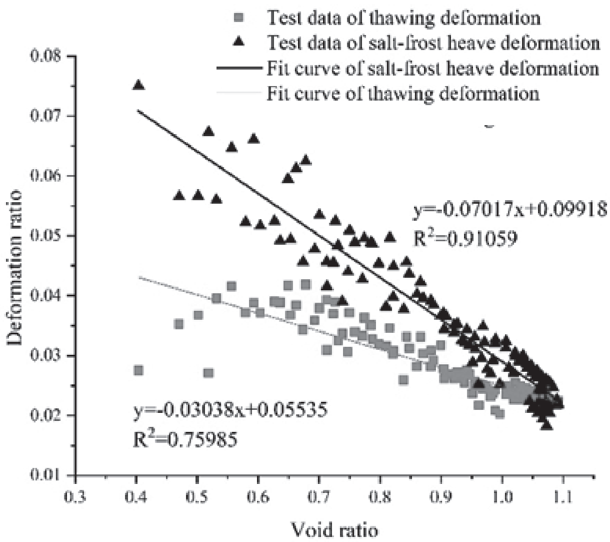

Fig. 5. Salt-frost heave deformation, thawing deformation and void ratio relationship curve.

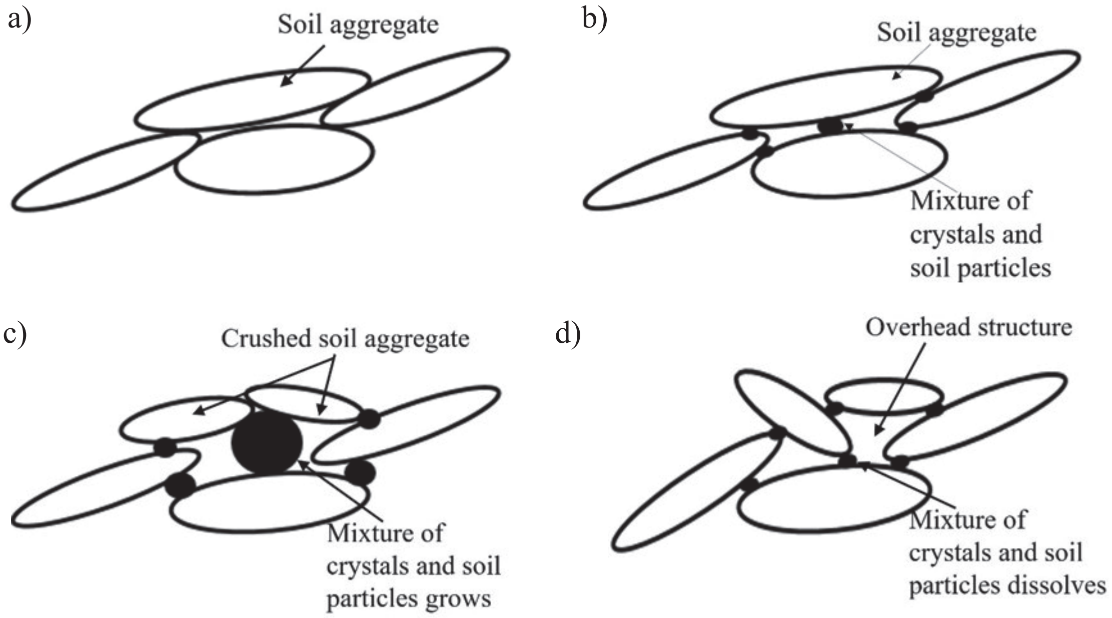

Fig. 6. Schematic diagram of soil overhead structure formation during freeze-thaw cycles; a) initial soil structure, b) Crystallization precipitation during the cooling process, c) Soil agglomerate fragmentation during cooling process, d) Overhead structure of soil after warming and thawing.

disappeared when the soil void ratio have reached the residual void ratio.

Effects of Salt Content on Residual Void Ratio

The phase change of water and salt inside the soil during the freeze-thaw cycle is the motive force that drives the continuous development of the soil structure and the salt content has a significant effect on the amount of salt-freeze heave deformation during a single cooling of the soil. The variation process of the void ratio of residual saline silt with different salt contents under long-term freeze-thaw cycles could be obtained from the data of specimens 2# and 10# to 14#, which is given by Fig. 7. It can be gained that the void ratio of the specimens with different salt contents gradually increases with the increase of the number of freeze-thaw cycles, and gradually stabilizes after 30 cycles.

According to the data in Fig. 7, the average value of the last three void ratios of the specimens was taken as the residual void ratio, and the relationship between the residual void ratio and the salt content can be obtained, as shown in Fig. 8. It can be observed that as the salt content increases, the residual void ratio increases, then decreases and then increases again. Since the starting

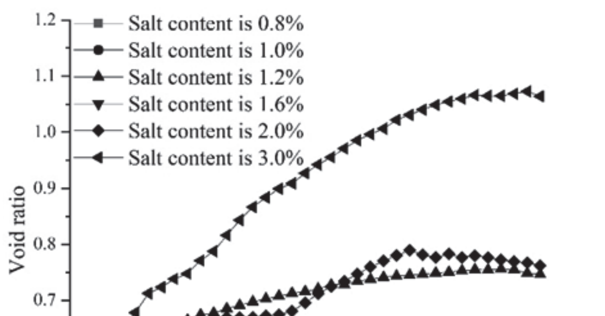

Fig.7. Changing curve of void ratio of specimens with different salt content under the effect of freeze-thaw cycles.

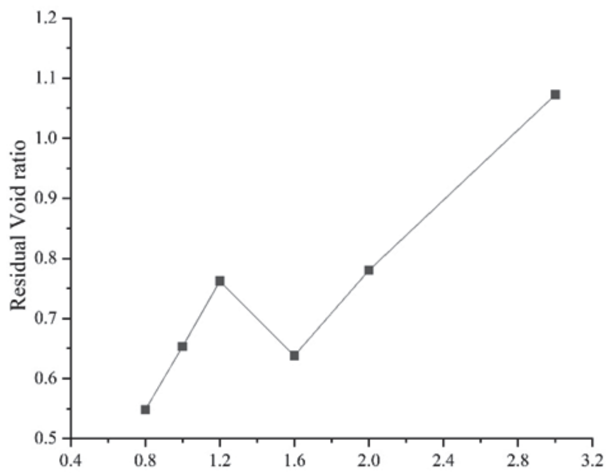

Fig. 8. Salt content and residual void ratio relationship curve.

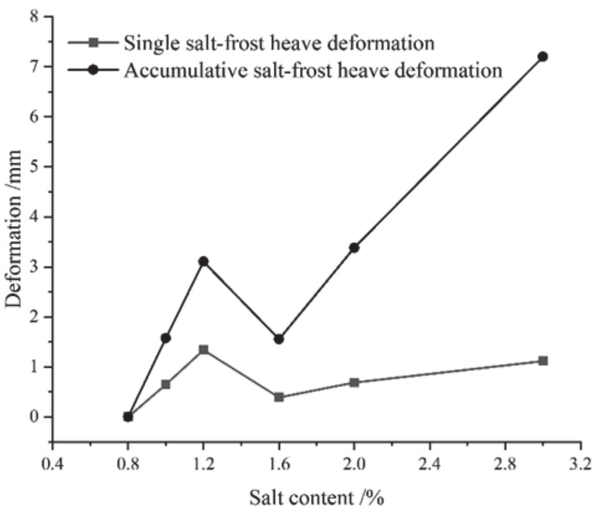

Fig. 9. Salt content and single and accumulative deformation relationship curve.

void ratio of the above specimens is 0.51, and the single salt-frost deformation of the specimens at the void ratio of 0.51 can be obtained, the residual void ratio and accumulative deformation of the specimens change with increasing salt content in the same way as the single salt-frost deformation, as shown in Fig. 9. This indicates that there is a strong correlation between the magnitude of accumulative salt-frost heave deformation and the magnitude of single salt-frost heave deformation.

The relationship curves between single salt-frost heave deformation and accumulative salt-frost heave deformation have been fitted in Fig. 10. It can be noted that there is an obvious linear positive correlation between single salt-frost deformation and accumulative salt-frost deformation, and the relationship equation between the two at salt content ≤1.2% is significantly different from that at salt content >1.2%. From the research findings of our group, the conclusion that salt crystals start to precipitate before freezing in saline silt when the salt content is greater than 1.2% can be reached [20]. Therefore, when salt crystals start to precipitate before freezing of saline silt, the relationship between single salt-frost heave deformation and accumulative salt-frost heave deformation changes abruptly. This indicates that the salt precipitation before the onset of freezing causes a significant change in the crystalline deformation mechanism of saline silt.

Effects of Water Content on Residual Void Ratio

The variation of water content not only affects the water-salt phase variation under the action of freeze-thaw cycles, but also affects the structural strength of the soil, which will have an effect on the residual void ratio of the soil. From the experimental data of specimens 2# and 4# to 8#, the void ratio variation curves of residual saline silt with different water contents under long-term freeze-thaw cycles can been obtained, as shown in Fig. 11. According to the data in Fig. 11, the average value of the last 3 times of void ratio of the specimen was taken as the residual void ratio, and the relationship between residual void ratio and water content can be obtained as shown in Fig. 12. What can be reached from Fig. 12 is that the residual void ratio decreases linearly as the water content increases. This means that the greater the water content, the smaller the accumulative deformation of saline silt under long-term freeze-thaw action. What can evidently be observed is that unlike permafrost frost deformation which requires a large amount of water recharge for its generation, saline silt produce

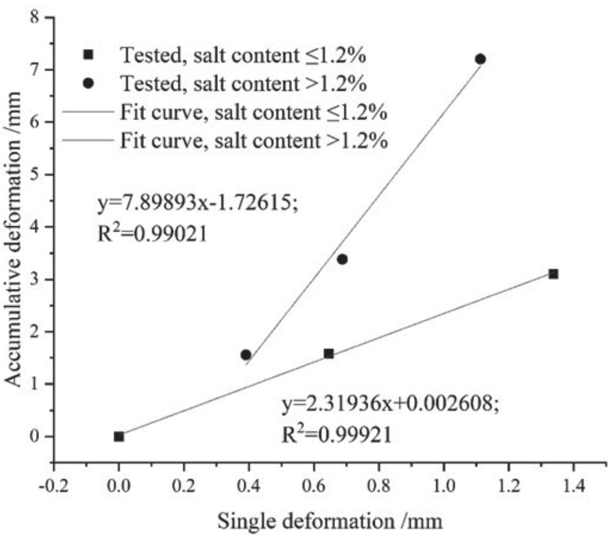

Fig. 10. Single deformation and accumulative deformation relationship curve.

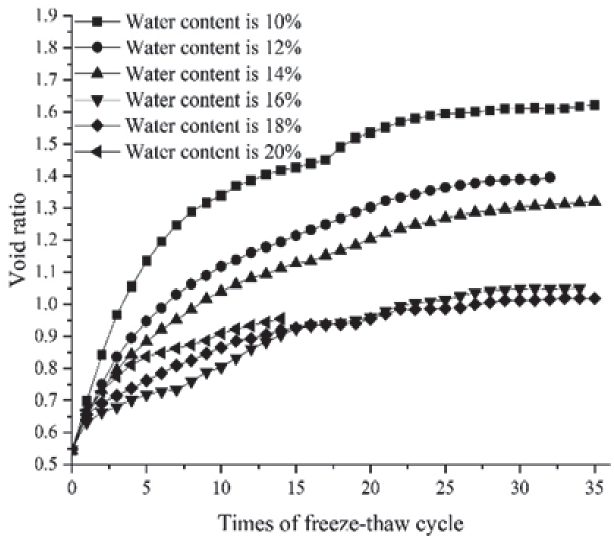

Fig. 11. Void ratio change curve of specimens with different water content under freeze-thaw cycles.

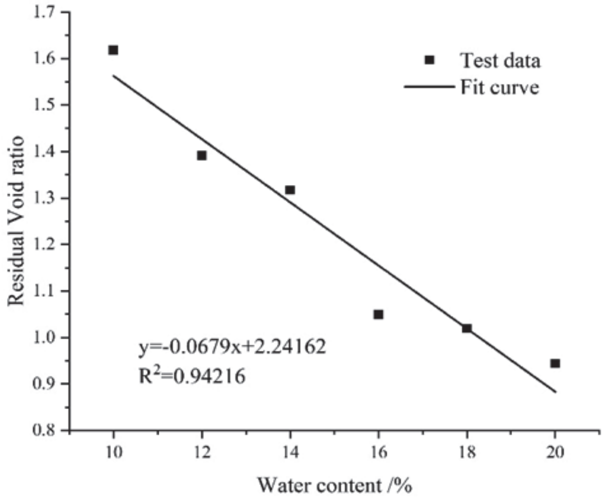

Fig. 12. Relationship between water content and residual void ratio.

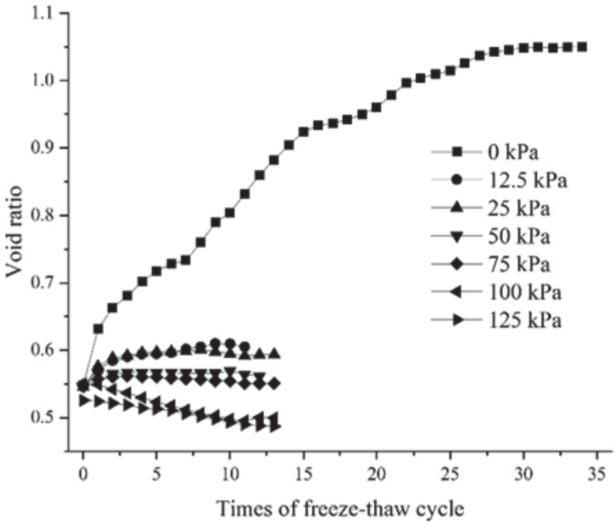

Fig. 13. Void ratio variation curves of specimens under different loads under freeze-thaw cycles.

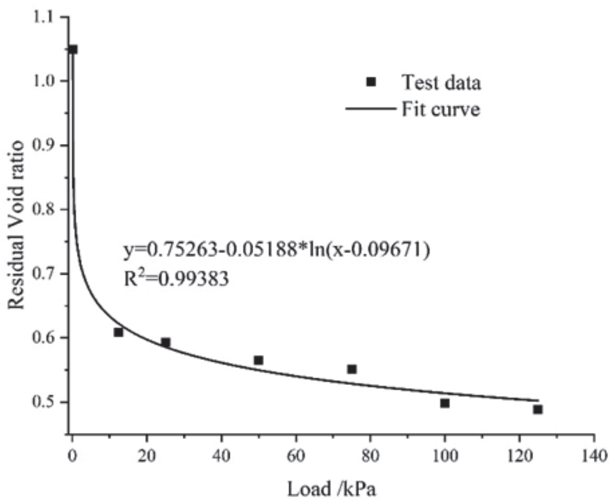

Fig. 14. Relationship curve between load and residual void ratio.

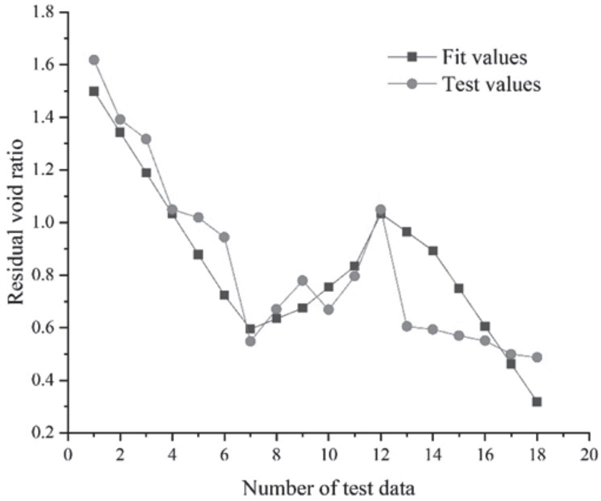

Fig. 15. Curves of fitted and experimental values of residual void ratio.

a larger accumulative deformation of salt frost heave in the presence of a small amount of water.

Effects of Load on Residual Void Ratio

The effect of cooling rate on salt-frost heave deformation during freeze-thaw cycles was neglected, and the residual void ratio e_{res} was considered as a function of salt content s (%), water content w (%) and load p (kPa). To dimensionless the above parameters, let s` = s/100, w` = w /100, and p` = p/1atm. The software SPSS 21.0 was used to perform a nonlinear regression analysis of the experimental data so that the equation for the residual void ratio e_{res} was obtained:

$$e_{res} = 1.678\text{-}0.0775\omega`+0.1994s`-0.576p` \quad (3)$$

The correlation coefficient of Eq. (3) is 0.7925.

The residual void ratio e_{res} calculated by Eq. (3) was compared with the experimental value to obtain as shown in Fig. 15, which shows that the deviation between the fitted and experimental values is small. The prediction of accumulative deformation of salt-frost heave under long-term freeze-thaw conditions of sulfate saline silt can be achieved using Eq. (1), Eq. (2) and Eq. (3). In order to ensure the reliability of the calculation results and provide scientific reference indexes for the engineering, the conditions of application of the above calculation equations are given here in combination with the conditions of this experiment: 1) the soil is sulfate saline silt; 2) there is no water recharge during the freeze-thaw process; 3) the water content of the soil remains constant during the freeze-thaw cycle. The above conditions are in good agreement with the actual engineering conditions of residual type sulfate saline silt in the seasonal permafrost area. Eq. (1), Eq. (2) and Eq. (3) can provide evaluation indexes for the actual engineering in the above areas to provide the salt-frost heave characteristics of the site under long-term freeze-thaw conditions.

Conclusions

The in-situ deformation data of salt-frost heave of sulfate saline silt under multiple freeze-thaw cycles have been obtained through multiple freeze-thaw experiments. By analyzing the effects of four main factors, including salt content, water content, initial dry density, and load on the residual void ratio of residual type sulfate saline silt, the mechanism of in-situ deformation accumulative generation of salt-frost heave in saline silt under the action of freeze-thaw cycles has been given. Moreover, the following conclusions have been obtained:

(1) Sulfate saline silt with the same initial void ratio eventually reach the same and stable residual void ratio under multiple freeze-thaw cycles, independently of the initial compactness of the soil. At 16% water content, the residual void ratio increases, then decreases and then increases with increasing salt content. At a salt content of 3%, the residual void ratio decreases linearly with increasing water content. The greater the load, the smaller the residual void ratio. At 16% water content and 3% salt content, when the load is greater than 12.5kPa, it can effectively reduce the salt-frost heave accretion of residual saline silt.

(2) With the increasing number of freeze-thaw cycles, the void ratio of soil samples gradually increases and the salt-frost heave deformation decreases. The deformation of salt-frost heave in this process is in line with the linear negative correlation with the void ratio, and there is a positive correlation between the magnitude of accumulative salt-frost heave deformation and the magnitude of single salt-frost heave deformation.

(3) The equation of residual void ratio with salt content, water content and load as parameters has been given by this paper. Using this formula, the prediction of accumulative deformation of salt-frost heave under long-term freeze-thaw conditions in residual type sulfate saline silt in the seasonal permafrost zone can be achieved.

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Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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