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Effect of Temperature on the Strength Characteristics of Unsaturated Silty Clay in Seasonal Frozen Region

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ABSTRACT

The strength characteristics of unsaturated silty clay after the cooling and single freeze-thaw cycle were studied by using Global Digital Systems Ltd. (GDS) triaxial test system after controlling initial matric suction. The results demonstrate that, the initial matrix suction and freezing process can strengthen the shear strength of the soil, which makes the stress-strain curve of the soil show certain strain hardening characteristics at different temperatures. when the temperature is negative (including 0°C), the curve has a flat transition section whose strength does not change with deformation, and the flat transition section becomes shorter as the temperature and confining pressure decrease. The strength of the soil at negative temperature and the speed at which it reaches its peak value are much greater than those of the soil after positive temperature and single freeze-thaw cycle, and the contribution of confining pressure to the strength decreases with the decrease of temperature. The effect of temperature change (15°C to -15°C) on soil strength is mainly reflected in the total cohesion, and the effect of freeze-thaw on the effective internal friction angle is more significant. The strength and deformation characteristics of soil under the freezing process and freeze-thaw cycle are determined by the initial matric suction, the form of connection between soil particles, the migration of unfrozen water, and the degree of water-ice phase transformation.

1. Introduction

The distribution area of permafrost and seasonal frozen soil regions accounts for approximately 23% of the world's total land area (Zhou et al., 2018), and most of the mid-high latitudes both in the northern and southern hemispheres are seasonally frozen region (Ma and Wang, 2014). Due to human activities and global warming, some parts of permafrost regions are also in a state of summer-thawing and winter-freezing, and the phenomenon of freezing-thawing is becoming more pronounced (Zhang et al., 2018; Zhang et al., 2019a), so the distribution of such seasonally frozen regions also expands. The soil in these areas undergoes freeze-thaw cycles due to day-night temperature difference and seasonal changes, the internal structure of the soil continues to be changed with periodic freezing and thawing. At the same time, due to the influence of climate conditions such as precipitation, sunshine, temperature changes, and the alternation of dry and wet conditions, the soil is generally in an unsaturated state: unsaturated soils different from saturated soils not only in terms of stress, strain, strength, seepage, and other properties, but also from other different types of soils.

In recent years, scholars have studied the strength characteristics of different kinds of seasonal frozen soils under the action of temperature from different perspectives, using different theories and methods, and certain research achievements have been obtained. In the study of freeze-thaw cycles, the changes in shear strength, cohesion, and internal friction angle of silty sand (Liu et al., 2016), clay soil (Firoozi et al., 2015; Orakoglu and Liu, 2017), loess (Xu et al., 2018; Zhou et al., 2018), expansive soil (Hotineanu et al., 2015; Tang et al., 2018; Wang et al., 2018), saline soil (Zhang et al., 2019b) and other soils, under different freeze-thaw cycles were revealed, mainly by controlling the different drainage conditions and the temperature during conventional triaxial shear test, direct shear test, unconfined compression test, and other such methods. The strength of soil will decrease due to the effects of a freeze-thaw cycle, and the

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strength tends to be stable after a certain number of cycles: the results of such research have basically reached consensus. Most of the soil in the seasonal frozen region is in the unsaturated state before the freeze-thaw cycle, and its unsaturated characteristics before the freeze-thaw have a great influence on its properties after freeze-thaw. At present, the research on the unsaturated properties of seasonal frozen soils mostly uses the initial moisture content as a parameter to analyze and discuss the strength characteristics of saline soil (Zhang et al., 2017), loess (Tian et al., 2016), silt soil (Yan et al., 2019) and clay soil (Liu et al., 2018a, 2018b) under a certain negative temperature and freeze-thaw condition, but failed to compare and analyze the results under different positive temperature, negative temperature and freeze-thaw temperature. On the other hand, the test mainly adopts the separate method of temperature control and strength test (Du et al., 2016b; Aksenov et al., 2018; Liu et al., 2018a), which cannot meet the stress conditions in the actual environment of soil at a certain depth freezing under constant pressure. Secondly, the unsaturated characteristics of the soil are mostly expressed by water content or saturation (Niu et al., 2016; Du et al., 2016a), and the initial matrix suction is not measured and controlled. Before the freeze-thaw action, the effect of basic parameters of unsaturated soil on soil strength was seldom considered or clarified, that is, the effect of initial matric suction on soil strength. In fact, for unsaturated seasonal frozen soil, before different freezing temperatures and freeze-thaw effects, there must be an initial matrix suction in the soil. The existence of the initial matrix suction will change the effect of temperature on soil strength. At present, through constant initial matrix suction, the research on the change of soil strength characteristics under different temperatures and freeze-thaw conditions is rarely involved.

The silt content in silty clay is relatively high, which has certain capillary phenomenon and water sensitivity characteristics. Its unsaturated characteristics are easy to change with the different moisture conditions of the soil, resulting in physical and mechanical properties of soil are easily changed when affected by seasonal temperature, therefore, the unsaturated silty clay in a typical seasonal frozen area (Changchun, China) is taken as the research object. Aiming at the shortcomings of the above studies, a temperature-controlled GDS triaxial apparatus was used to control the matric suction of soil samples, the samples were frozen and thawed under constant pressure and sheared at constant temperature. On the basis of simulating the real environment of soil samples to the greatest possible extent, the strength characteristics of soil samples after different negative temperatures and a single freeze-thaw cycle were studied to provide guidance to those working with unsaturated seasonally frozen soils and the selection of relevant parameters for engineering construction thereon.

2. Soil Properties

The silty clay was sampled from Changchun (China), which is the typical seasonal freeze region and also the crossing point of the "China-Mongolia-Russia economic corridor" in "One Belt, One Road" construction plan, located at 43°47'16" N and 125°24'18" E (Fig. 1). According to ASTM standard (ASTM D1587-08, 2012; ASTM D2113-08, 2013), soil samples were taken through thin-walled tube, with a depth of 5.4 m – 6.0 m. In order to ensure that the soil samples were in the "same state" to the greatest extent, the spacing of adjacent boreholes is 1 m, and the soil samples are taken out in a cylindrical shape of 10 cm × 20 cm, which is sealed, transported and stored according to the provisions of standard (ASTM D4220-95, 2007). The soil sample was yellowish-brown and in a plastic state. Due to the standard freezing depth of 1.7 m in Changchun, the soil has not undergone the freeze-thaw process in a natural state.

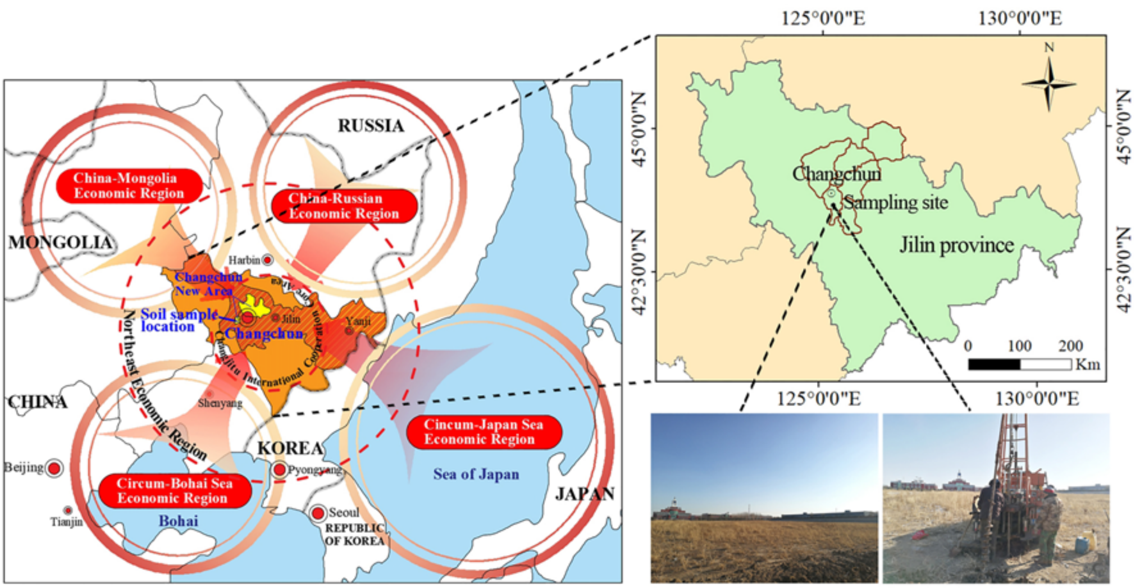


Fig. 1. Soil Sample Location and Site — The Crossing Point of the "China-Mongolia-Russia Economic Corridor" in China's "One Belt, One Road" Construction Plan

Table 1. Physico-Mechanical Properties of Silty Clay

Soil depth (m)	Soil sample number	Moisture content ω (%)	Saturation S_r (%)	Natural density ρ (g/cm^3)	Plastic limit ω_p (%)	Liquidity index I_L	Plasticity index I_p	Coefficient of compressibility $\alpha_{1\text{-}2}$ (MPa^{-1})
5.4 – 6.0	1	26.8	81.9	1.89	24.0	0.19	14.7	0.34
	2	25.9	86.2	1.88	20.4	0.39	14.2	0.35
	3	25.8	86.3	1.88	22.5	0.23	14.2	0.36
	4	26.0	87.5	1.89	21.9	0.28	14.7	0.36
	5	25.7	86.1	1.88	22.4	0.23	14.3	0.35

Table 2. Mineral Composition of Undisturbed Soil Samples

Mineral content ω(B)/10^{-2}							
Qtz	Kfs	Pl	Py	I/S	Ill	Kln	Chl
48.0	5.4	15.3	0.2	24.9	3.8	1.2	1.2

Note: Qtz: Quartz, Kfs: Kfeldspar, Pl: Plagioclase, Py: Pyrite, I/S: Illite/Smectite mixed laye, Ill: Illite, Kln: Kaolinite, C: Chlorite

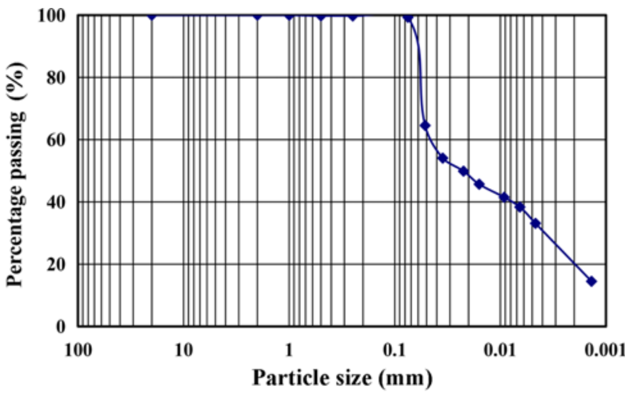


Fig. 2. Particle Size Distribution of Natural Silty Clay

The basic physical and mechanical indices are listed in Table 1, the mineral composition content of undisturbed soil samples is summarised in Table 2, and the particle size distribution curve is as shown in Fig. 2. According to the analysis, the soil is a medium-compressive silty clay, with primary minerals as its main component with other secondary minerals present, the degree of weathering is low, the content of illite and the massive mixed layer with strong hydrophilicity is 28.7%, which indicates that the soil has strong hydrophilicity. The grain size distribution of the soil sample, silt (0.005 – 0.075 mm) was 65.16% of the grain size group, and clay (< 0.005 mm) content was 34.14%. The content of silt (0.005 – 0.075 mm) is relatively high. When there are capillary pores in the soil, capillary phenomena are significant, the permeability is high, and flow paths are long, and soil would be more affected by the negative temperature.

3. Experimental Apparatus and Plan

3.1 Experiment Apparatus

The GDS unsaturated soil triaxial test system is used in this study. This system consists of three parts: a controller (providing and controlling axial pressure, confining pressure, pore air pressure, pore water pressure and temperature), triaxial double pressure chamber test equipment (including a load frame), and data acquisition system (including a data acquisition board, sensor and computer), as is shown in Fig. 3. The controller and data acquisition board are connected to the triaxial double pressure chamber test equipment. In the process of experiment, the controller provides four-dimensional stress path for the soil sampling in the triaxial double pressure chamber test equipment, and then the data is collected and converted by the acquisition

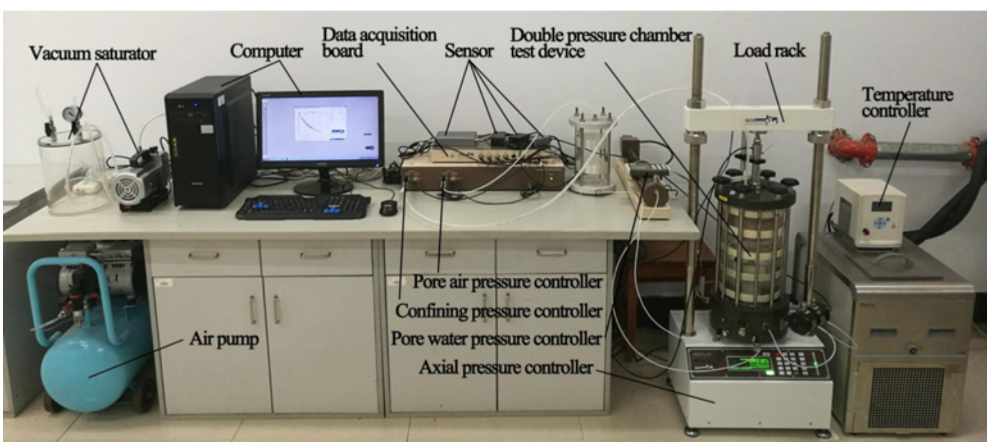


Fig. 3. GDS Unsaturated Soil Triaxial Test System

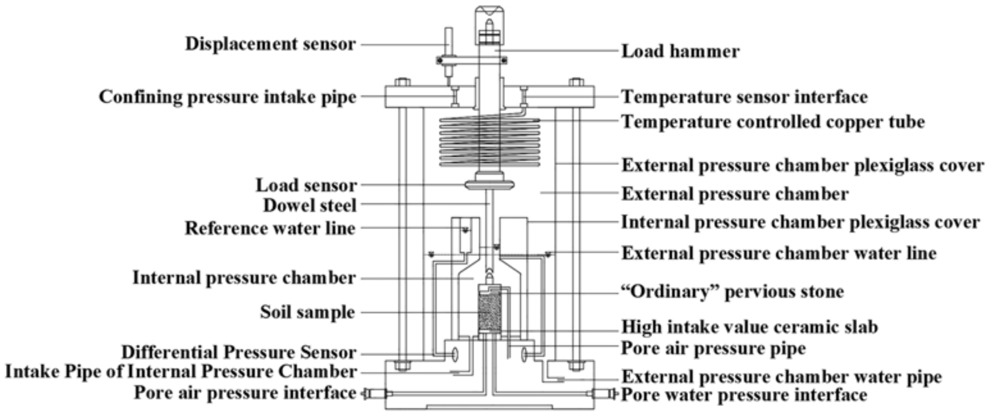
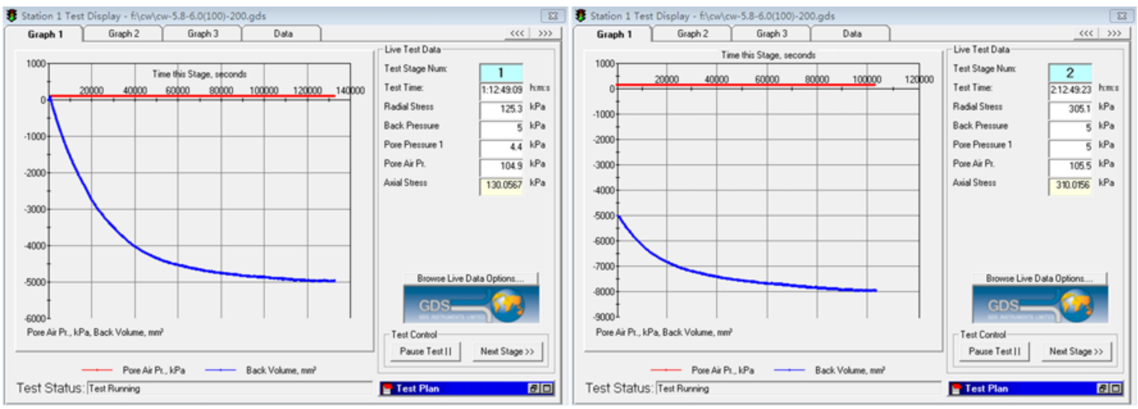


Fig. 4. Triaxial Double Pressure Chamber Test Equipment for GDS Unsaturated Soil



(a) (b)

Fig. 5. Completion of Constant-Suction Balance and Constant-Suction Consolidation (matric suction is 100 kPa): (a) Constant-Suction Balance, (b)Constant-Suction Consolidation

board.

The whole experimental procedure includes five parts: preparation of air-free water, saturation of ceramic plate, sample installation and disassembly, computer software control experiment, and data processing. Cylindrical soil sample (38 mm × 76 mm) was installed in the internal pressure chamber, in which the confining pressure, pore water pressure, pore air pressure, axial force, temperature, and sample volume change could all be measured and controlled (Fig. 4). The computer control process includes three stages: a constant-suction balance, constant-suction consolidation, and constant-suction shear. The main purpose of the constant-suction balance stage is to impose matric suction to the soil sample and soil state transformed from saturated into unsaturated. In the constant-suction consolidation stage, the samples were drained and consolidated under the specified pressure with constant suction. In the stage of constant-suction balance and constant-suction consolidation, the completion is determined by observing the change of back pressure volume. When the back pressure volume is essentially constant, it means that the balance or consolidation is completed, as shown in Fig. 5. When triaxial shear test was carried out under negative temperature condition, it was necessary to replace the air-free water by liquid anti-freeze in the pressure chamber after the sample matric suction became constant and consolidation completed. The confining pressure controller ensured the specified confining pressure on the sample through the anti-freeze, and then opened the temperature controller, transferred and controlled the temperature through the copper tube. The shear experiment can be carried out when the temperature reached a certain negative value and remained a constant state for 24 hours. In the frozen-thaw process, it shall be frozen for 12 hours and thawed for 12 hours. The sample was frozen under constant pressure and sheared at constant temperature, which can better simulate in situ conditions.

3.2 Experiment Plan

Soil sample was conducted to be vacuum-saturated before the experiment started, and then the dehydration process was simulated by controlling matric suction using GDS unsaturated soil triaxial test equipment. Based on the previous monitoring data of the void ratio changing with the matric suction (0 kPa, 50 kPa, 100 kPa, 150 kPa, 200 kPa) at different net confining pressures during the constant-suction consolidation stage, the curve of void ratio changing with matric suction drawn is shown in Fig. 6 (Chen et al., 2019). It can be seen from Fig. 6 that at normal atmospheric temperature, when the matrix suction is greater than 100 kPa, the void ratio tends to be stable gradually. At this time,

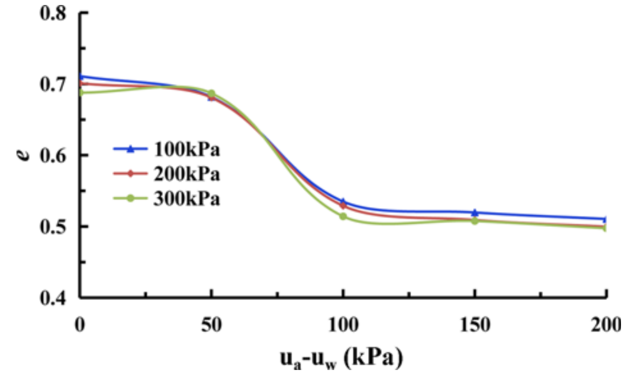


Fig. 6. Variation Curve of Void Ratio with Matric Suction at Different Confining Pressures

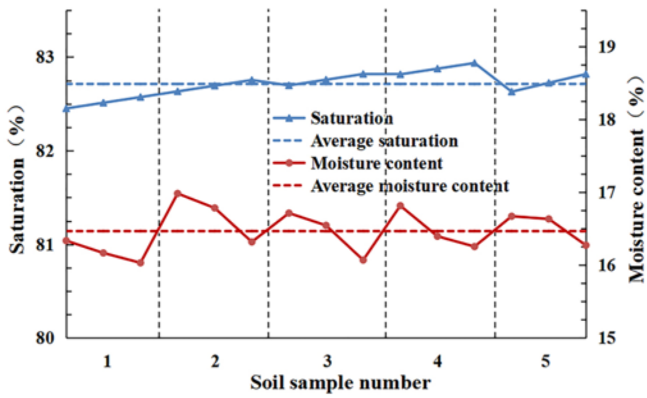


Fig. 7. Soil Saturation and Moisture Content at Constant Initial Matric Suction

the effect of the adsorption strength generated by the matric suction on the soil structure is relatively small. Therefore, matric suction of 100 kPa was used as the benchmark to minimize the influence of the change of matrix suction on the soil structure during the freezing process. When the matrix suction is 100 kPa, the average void ratio of the soil sample used in the research is 0.5039, and the saturation and water content of the soil sample were shown in Fig. 7, wherein the average water content is 16.46%, and the average saturation is 82.71%. Referred to the ASTM standard (ASTM D2580-03a, 2007) and previous experience, the net confining pressure of the test was controlled as 100 kPa, 200 kPa and 300 kPa, respectively, and the shear rate was 0.05%/min. Because there are many temporary engineering with the characteristics of deep, large and wide in the seasonal frozen area, such as deep foundation pit engineering, foundation engineering, etc., the excavation depth is often below the frozen depth. For engineering that can be completed in one temperature change period, the soil under the frozen depth often undergoes only one freeze-thaw action. At the same time, the study shows

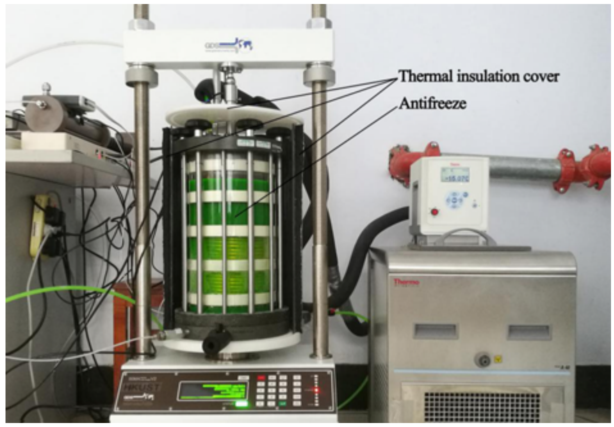


Fig. 8. The Equipment of Triaxial Shear Test at Negative Temperature (initial matric suction 100 kPa and temperature -15°C)

that the influence of one-time freezing and thawing on soil properties is more significant, and the influence of freezing and thawing on soil properties decreases with the increase of freezing and thawing times (Wang et al., 2007; Wang et al., 2015; Liu et al., 2016; Wang et al., 2019; Xu et al., 2019), so the study of unsaturated soil is conducted with single freeze-thaw cycle. At the constant-suction consolidation stage, the matric suction is constant and kept at 100 kPa, the net confining pressure reaches the pre-specified value and consolidation is completed, based on the monthly average temperature of a certain year in Changchun City (Table 3), when the temperature is constant at 15°C, 0°C, -5°C, -15°C, and 15° to -15°C to 15°C (single freeze-thaw cycle), the strength characteristics of this unsaturated silty clay were studied. Based on the conventional triaxial shear test, the soil sample was first constant-suction consolidation, then frozen, and the final shear test is shown in Fig. 8.

4. Analysis of Experimental Results

4.1 Effect of Confining Pressure and Temperature Changes on Deformation and Strength Characteristics of Soil Samples

The peak strength results of the samples at different net confining pressures and temperatures are shown in Table 4. As can be seen from Table 4, when the temperature is constant, the peak strength of soil increases gradually with the increase of net confining pressure. When the confining pressure is constant, the peak strength of soil increases continuously with the decrease of temperature. When the confining pressure changes in a certain range (100 – 200 kPa, 200 – 300 kPa, 100 – 300 kPa), the increasing extent of the peak strength of the soil decreases significantly with the decrease of temperature. It shows that the increase of confining pressure and the decrease of temperature can improve the

Table 3. Monthly Average Temperature of Changchun in Recent Year

Month	1	2	3	4	5	6	7	8	9	10	11	12
Monthly mean temperature (°C)	-15	-11	-2.5	8	15.5	20.5	23.5	22	15.5	7.5	-3	-12

Table 4. Experimental Results: Peak Strength of Soil Samples under Different Confining Pressure and Temperature

Temperature (°C) \ Confining pressure (kPa) \ Peak	100	200	300	100 – 200	200 – 300	100 – 300
15	364.734	527.369	692.960	162.635	165.591	328.226
0	1,146.135	1,251.714	1,416.236	105.579	164.522	270.101
-5	2,641.344	2,651.063	2,712.833	9.719	61.77	71.489
-15	4,851.589	4,858.924	4,897.563	7.335	38.639	45.974
15 – -15 – 15	231.721	303.008	383.224	71.287	80.216	151.503

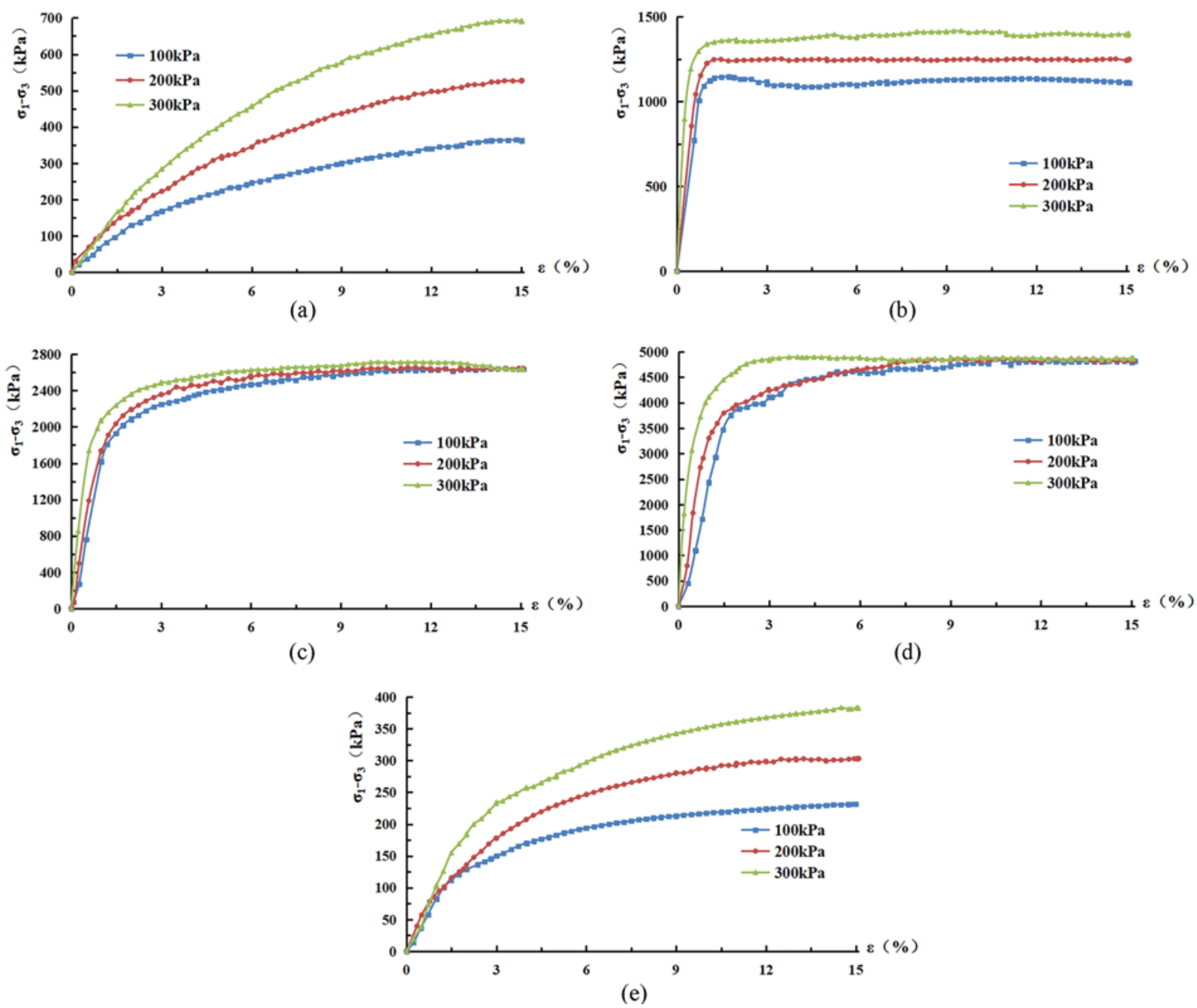


Fig. 9. Deviatoric Stress-Strain Curve under the Influence of Net Confining Pressure: (a) 15°C, (b) 0°C, (c) -5°C, (d) -15°C, (e) 15°C – -15°C – 15°C

strength of unsaturated soil, but with the decrease of temperature, the contribution of confining pressure to soil strength decreases.

The deviatoric stress-strain curves of the soil samples at the same temperature and different net confining pressures are shown in Figs. 9(a) – 9(e). It can be seen from the figure that the soils all show certain hardening characteristics, and the strain hardening characteristics of the soils are more obvious after positive temperature and single freeze-thaw action. When the temperature is negative (including 0°C), the stress-strain curve has a flat transition section with different lengths, which becomes shorter when the temperature and confining pressure decrease.

It can be seen from the analysis that after the positive temperature (15°C) and single freeze-thaw cycle, with the increase of confining pressure, the cohesive and interlocking force between soil particles increases after consolidation, which increases the peak strength at failure under shear. Due to the effect of matric

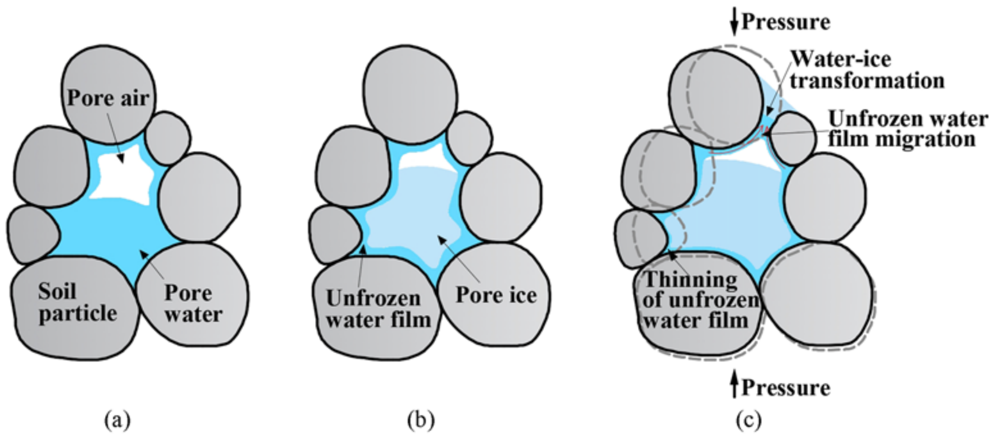


Fig. 10. Water Ice Phase Transition in the Triaxial Shear Process at Negative Temperatures: (a) Unfrozen, (b) Frozen, (c) Frozen Shear

suction, there is always some adsorption strength in the soil (Morgenstern, 1981), which strengthens the shear resistance of the soil, and makes the shear process show some hardening characteristics. The lower the temperature, the less the unfrozen water content, the higher the degree of water-ice phase change in the pores, the greater the force on the soil particles , so that when the temperature decreases, the contribution of the confining pressure to the strength decreases. With the decrease of temperature, soil freezes, and the bond between soil particles changes from a water-cement connection to a frozen connection. With the change of the connection form, the structure is strengthened and the strength is increased, the stress increased rapidly before the strain reached 1.5%. At constant negative temperature condition, with the increasing pressure on the soil specimen during shear process, the freezing point of unfrozen water in the pore of the compression zone decreases (Liu et al., 2017), and the unfrozen water in the pore migrates along the displacement path of soil particles and then accumulated. At the accumulation place of the unfrozen water (where damage occurs), water-ice phase transformation happened at all times (Fig. 10), the loss of soil strength exactly offset the soil strength increased by water-ice phase transformation, so the stress-strain curve shows a relatively flat transition section. The critical state of water-ice phase transformation occurs at 0ºC, and the rate of water-ice phase transformation is relatively slow, so the increased strength is less than or equal to the loss of the soil strength, slight softening occurred locally and the transition section on the curve becomes longer but not straight. With decreasing temperature, the rate of water-ice phase transformation increases, the increased strength exceed or equal to the loss of the soil strength, the length of the flat transition section on the strain curve is shorter but straighter. At the same negative temperature, with the increase of confining pressure, the freezing point of unfrozen water in the pore of the compression zone decreases, the rate of water-ice phase transformation decreases, so the increased strength is less than or equal to the loss of the soil strength, which makes the flat transition section of the stress-strain curve longer.

The deviatoric stress-strain curves of the soil samples at the same net confining pressures and different temperature are shown in Figs. 11(a) – 11(c). It can be seen from the figure that with the temperature decreases, the strength of the soil samples increases continuously. At negative temperatures (including 0ºC), the strength of the soil and the rate at which it reaches its peak value are much greater than those at positive temperatures and after single freeze-thaw cycle. The strength of soil is the lowest after single freeze-thaw cycle, which indicates that freeze-thaw action will reduce the strength of unsaturated soil.

According to the analysis, the forms of soil connection change with the decreasing of temperature, and the frozen connection increases the soil strength. When the confining pressure is constant, the lower the temperature, the higher the degree of phase transformation the faster the rate of water-ice transformation, and the greater the soil strength increase. After a freeze-thaw cycle, there are micro-cracks formed in the soil due to the water-ice phase transformation of occurring during the freezing process, which reduces the strength of the soil under shear.

4.2 Soil Shear Strength Parameters

Based on the experimental data obtained, the Mohr-Coulomb stress circle and failure envelope of the same matric suction at different temperatures were plotted (Fig. 12). The total cohesion (c'') and effective internal friction angle (φ') can be obtained (Table 4). The total cohesion consists of three parts: effective cohesion between soil particles, apparent cohesion caused by matric suction (Zhang et al., 2012), and ice cohesion caused by water-ice phase transformation.

From the Mohr-Coulomb strength curve (Fig. 12), with the decreasing of temperature, the influence of confining pressure on soil strength decreased gradually, and the failure envelope of shear strength gradually tends to be horizontal. From the experimental data in Table 5, When the temperature decreased from 15°C to -15°C, the total cohesion of the soil increased by 18.57 – 37.11 times, and the extent of increase also increasing trend. Meanwhile, the effective internal friction angle decreased by 0.17 – 0.32 times. It can be seen that the change of the total cohesion is more significant when the temperature is reduced.

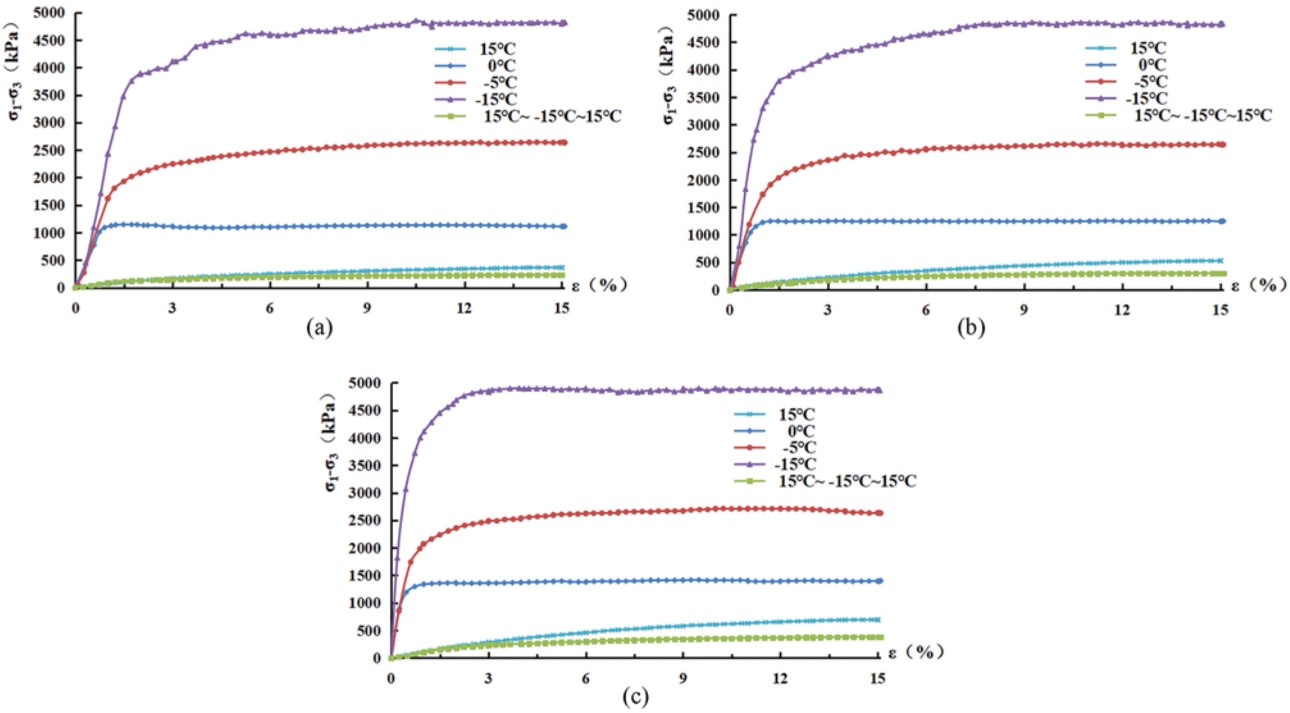


Fig. 11. Deviatoric Stress-Strain Curve under the Influence of Different Temperatures: (a) $\sigma_3 - u_a$ = 100 kPa, (b) $\sigma_3 - u_a$ = 200 kPa, (c) $\sigma_3 - u_a$ = 300 kPa

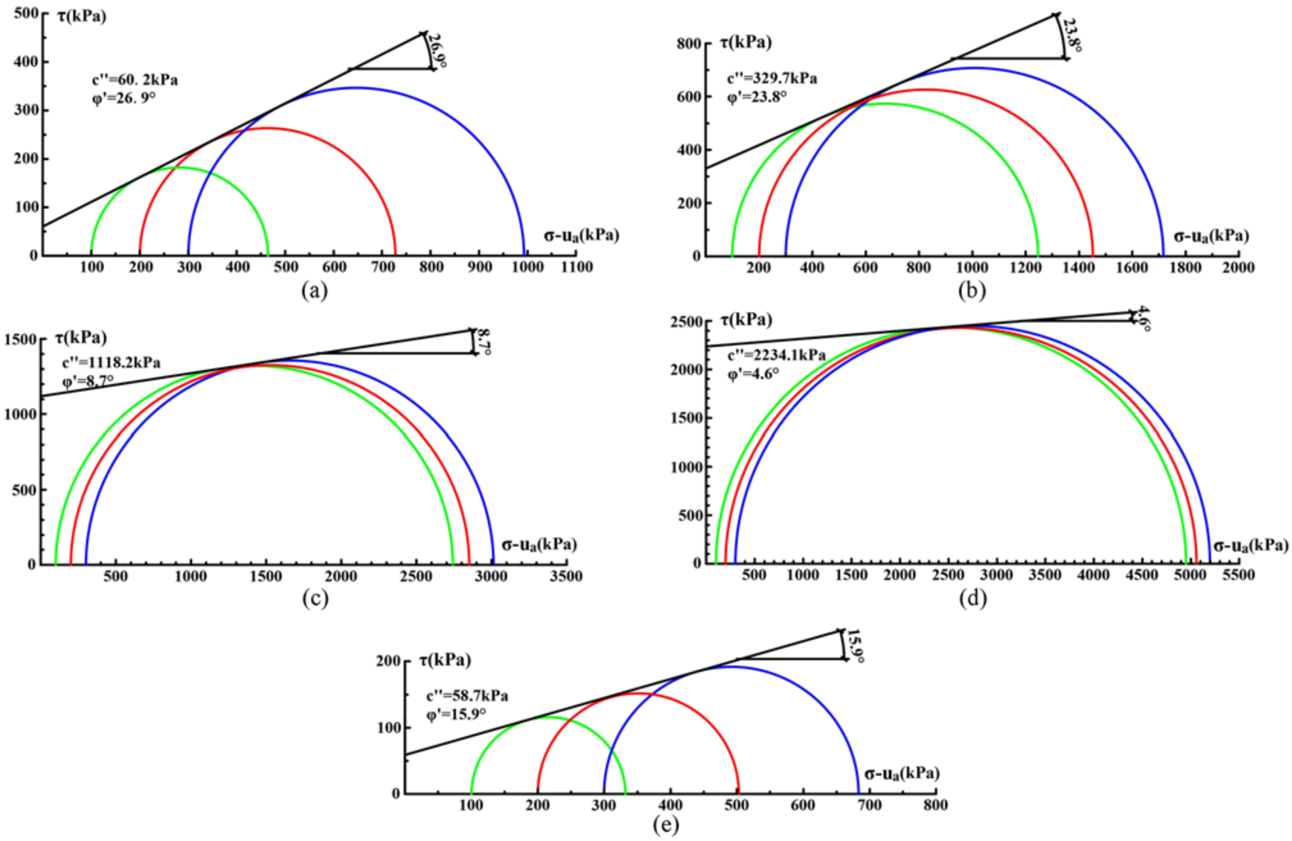


Fig. 12. Mohr's Circle of Stress at Different Temperatures: (a) 15°C, (b) 0°C, (c) -5°C, (d) -15°C, (e) 15°C – -15°C – 15°C

After single freeze-thaw cycle, both the total cohesion and effective internal friction angle of the soil decreased, indicating that even if there is still matric suction in the soil after freezing and thawing, freezing and thawing also weaken the strength of the soil. At negative temperature, the effective internal friction angle of the soil is lower than that after freeze-thaw, which

Table 5. Triaxial Shear Test Results of Unsaturated Soils at Different Temperatures

Soil sample number	Matric suction $u_a - u_w$ (kPa)	Temperature (°C)	Net confining pressure $\sigma_3 - u_a$ (kPa)	Deviatoric stress $\sigma_1 - \sigma_3$ (kPa)	Total cohesion c'' (kPa)	Effective internal friction angle φ' (°)
1 – 1	100	15	100	364.734	60.2	26.9
1 – 2			200	527.369		
1 – 3			300	692.960		
2 – 1		0	100	1,146.135	329.7	23.8
2 – 2			200	1,251.714		
2 – 3			300	1,416.236		
3 – 1		-5	100	2,641.344	1,118.2	8.7
3 – 2			200	2,651.063		
3 – 3			300	2,712.833		
4 – 1		-15	100	4,851.589	2,234.1	4.6
4 – 2			200	4,858.924		
4 – 3			300	4,897.563		
5 – 1		15 – -15 – 15	100	231.721	58.7	15.9
5 – 2			200	303.008		
5 – 3			300	383.224		

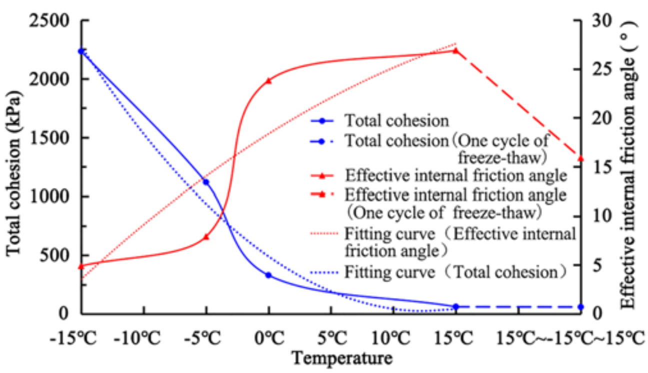


Fig. 13. Total Cohesion (left) and Effective Internal Friction Angle (right) versus Temperature

indicates that the strength of the soil under negative temperature is mainly provided by the total cohesion.

According to the analysis, under constant negative temperature, the connection form transformed from water-cement connection into frozen connection, which increased the bond strength between particles. In the shear test, the unfrozen water migrates and accumulates at the failure surface under the action of pressure, and water-ice phase transformation occurs simultaneously, at this time, the apparent cohesion generated by the matric suction is combined with the ice cohesion generated by water-ice phase transformation (Liu et al., 2019), resulting in a significant increase in total cohesion. However, when water ice transformation occurs in pores, the action of isolated ice crystals in macropores on soil particle skeleton increases, which reduces the embedding and interlocking between soil particles (Yan et al., 2019). At the same time, due to the presence of ice crystals and the lubrication function of unfrozen water in micro-cracks, the effective friction angle decreases.

Changes of total cohesion and effective internal friction angle with temperature are shown in Fig. 13. As can be seen from the figure, the total cohesive gradually increases with the decrease of temperature, and changes sharply below 0°C, while the effective internal friction angle varies greatly from 0°C to -5°C, and the positive and negative temperature ranges are gradually stable, and the relationship between them and temperature is non-linear. After a single freeze-thaw action, the change of the total cohesion of the soil is relatively small, and the effective internal friction angle is significantly reduced, which can indicate that the freeze-thaw effect has a more significant effect on the effective internal friction angle.

Table 6. Relationships between Strength Parameters and Temperature

Strength parameter	Functional relationship	Correlation coefficient
Total cohesion	$c'' = 2.9624t^2 - 74.475t + 490.67$	0.9787
Effective internal friction angle	$\varphi' = -0.0148t^2 + 0.8063\,t + 18.765$	0.8363

Note: t is temperature (°C); c'' is the total cohesion (kPa); φ' is the effective internal friction angle (°).

Fitting the relationship between temperature and total cohesion and effective internal friction angle, the formulae in Table 6 are obtained.

According to the correlation coefficient, the fitting effect between the total cohesion and the temperature is good, while the fitting effect between the effective internal friction angle and the temperature is relatively poor, suggesting that the influence law of temperature on the total cohesion is strong, while the influence law on the effective internal friction angle is not obvious.

5. Conclusions

Control the initial matrix suction, simulate the actual temperature change environment, and conduct experimental research on unsaturated silty clay in the seasonal frozen region under different temperatures and single freeze-thaw conditions. Analyze the deformation and strength characteristics of the soil during the cooling process and after the completion of the freeze-thaw cycle. The main conclusions were as follows:

1. Due to the influence of negative temperature and matric suction, the stress-strain curve of each soil sample showed certain characteristics of strain hardening. Under the condition of constant negative temperature, due to the migration and phase change of unfrozen water during the shear process, the stress-strain curve has a flat transition section that becomes shorter as the temperature and confining pressure decrease.
2. The strengthening effect of confining pressure on soil properties is affected by temperature. With the decrease of freezing temperature, the decrease of unfrozen water content in the soil pores, the degree of water-ice phase transformation increases, and the force on soil particles increases, resulting in the contribution of confining pressure to soil strength decreases.
3. When the temperature decreases, the soil strength is mainly provided by the total cohesion. The effect of freeze-thaw on the total cohesion of the soil is not significant, and the effect on the effective internal friction angle is more significant. The total cohesion of the soil changes significantly below 0ºC, while the effective internal friction angle only changes significantly from 0ºC to -5ºC, and the change is small in the positive and negative temperature ranges.

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