Influence of Freeze-thaw on Lateral Pressure Coefficient at Rest of Lanzhou Loess

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Abstract: The influence of freeze-thaw on lateral pressure coefficient at rest of Lanzhou loess was studied by experiments. Unidirectional freeze-thaw device was used in the freeze-thaw test. Soil samples were frozen at different temperatures and thaw at a temperature of +20℃. K_0 compression, direct shear and lateral pressure coefficient at rest tests were carried out on freeze-thaw samples and unfrozen samples to investigate the regular behaviour of K_0 under freeze-thaw cycles. It is proved that the effect of the freeze-thaw action on the K_0 of the soil has a double effect: the lateral pressure coefficient at rest K_0 increases after freeze-thaw when the initial dry weight is small. When the initial dry weight of soil is large, the coefficient K_0 decreases after freeze-thaw. At the same time, the applicability of the empirical formula ($K_0 = 1 - sin\varphi$) is verified by the φ of soil before and after freeze-thaw obtained by direct shear test. The results show that the relationship between K_0 and φ of Lanzhou loess after freeze-thaw does not strictly follow the empirical relationship of thaw soil.

Keywords: Freeze-thaw Cycle; Lateral Pressure Coefficient at Rest; Collapsible Loess

1. Introduction

Freeze-thaw cycle, a commonly occurring weathering effect in cold zones, usually causes significant variations in the physic-mechanical characteristics of soils, thus affecting the safe operation of cold region projects[1-3]. K_0 is the proportion of effective horizontal stress to upright stress in the soil at its lateral limit conditions, and is an important mechanical parameter for calculating soil deformation and determining the lateral stress-strain state of the soil[4-6], which is mainly used in the safety design of retaining walls, pit excavation, slope stability and tunnelling projects[7-8].Therefore, in order to improve the safety of engineering facilities in cold areas, it is particularly crucial to conduct research on the effect of freeze-thaw cycles on coefficient K_0.

At present, there are numerous experimental and theoretical studies conducted on the coefficients K_0 of soils that have without freeze-thaw action. Li et al.[9]used the lateral deformation indicator method for the measurement of K_0 in shallow soils in Tianjin, and summarized the effects of soil clay content, plasticity index and effective internal friction angle φ on lateral pressure coefficient at rest. Jiang et al.[10] used a newly developed lateral pressure coefficient device to conduct experimental studies on two coarse-grained soil materials. The findings of the study revealed that the vertical stress had a significant effect on the soil samples, and all soil samples showed a upward tendency with the rising of vertical stress, and the decreasing trend was apparently weakened when the pressure was higher. Yao et al.[11]have derived a theoretical equation for the coefficient K_0 in permafrost based on a rate-dependent model, and in the course of the study, it was found that the empirical equation for the K_0 and φ in unfrozen soil is not fully applicable to permafrost. Uncuoglu E et al.[12]established an artificial neural networking with a model that can forecast cohesion *c* and the coefficient K_0 in cohesionless soils and derived an expression for the relationship between φ and K_0 in cohesionless soils. Zhao et al.[13] used triaxial tests to determine the coefficient K_0 of soil to study the variation law of soil under high pressure condition, and the results showed that the relationship between coefficient K_0 and pore ratio *e* was the closest. Hayashi H et al.[14]determined the coefficient K_0 based on consolidation tests and proposed a test equation to estimate it.Yao et al.[15]conducted tests using a new permafrost triaxial instrument and found that the main factor affecting permafrost is temperature. In Qiao et al.[16], the influence laws of deep lateral pressure distribution in under consolidated soil were numerically investigated and it was found that the equivalent $\boldsymbol{K_0}$ decrease with increasing overconsolidation rates. However, most existing studies are based on soils with no freeze-thaw action, which does not take into account any effect of freeze-thaw action on coefficient $\boldsymbol{K_0}$.

Based on the state of the art of the above-mentioned studies, this study uses the Lanzhou Loess, performs freeze and thaw cycles tests at different temperatures, and conducts lateral compressive stress tests on samples with and without freeze-thaw and cycling. The influence law of freeze-thaw action on $\boldsymbol{K_0}$ of soil under different dry weight conditions is further analysed.

2. Test Description

2.1. Soil PROPErties and SAMPLE PREPAration

The Lanzhou loess was selected as the test object, and its particle distribution curve is shown in Figure 1.

Four remodeled soil samples with different initial dry weights were prepared, and freeze-thaw and without freeze-thaw mechanical tests were performed on soil samples with the same initial dry weights, and soil samples have been prepared in the lab and subjected to freeze and thaw cycles. In which, the soil sample preparation process is approximately the same, please refer to the references [2] for the detailed steps, and Φ = 101 mm in diameter and h = 100 mm in height, the final size of the soil sample produced. Table 1 lists the relevant tests and the physical parameters of the required soil samples. In the table, the first group of soil samples is used for mechanical tests without freeze-thaw action; The second group of soil samples were subjected to freeze and thaw cycling on a freeze and thaw machine, and after each freeze and thaw cycle each soil sample was cut for mechanical examination, in addition, the small specimen size was 30 cm2 in cross-sectional area and 20 mm in height.

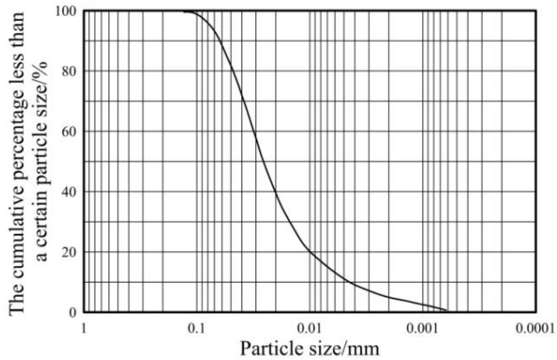

Figure 1. Grain size Distribution for the Lanzhou Loess

2.2. Freeze-THAW CYCLE TEsting

Freeze and thaw testing is performed in (Figure 2) a freeze and thaw tester which is run in a closed condition, with no external moisture added to any of its samples during a freeze and thaw cycle, with a thermostat temperature controlled at -1°C, an upper plate frozen, a temperature controlled at -10°C, and a lower plate temperature constant at -1°C. In order to thaw the soil sample, the temperature at the frozen end should be raised to +20°C. By monitoring the deformation of the soil sample during the test, the end of the freeze and thaw process is determined. When the test is finished the soil sample is cut, mechanically tested and compared with the soil sample in the same initial state.

2.3. Mechanical PARAMETER TESTing

To ensure that the present research results are more in accordance with the local soil characteristics, compression tests, direct shear tests and lateral pressure coefficient at rest tests were conducted on typical collapsible loess in Lanzhou area. Since the permeability of loess is large and the test period of standard consolidation test is long, this test determines the preconsolidation pressure of soil samples before and after freeze and thaw, using the rapid consolidation method. In this case, in the direct shear test, the strain-controlled direct shear meter (Figure 3) was used to obtain the strength parameters of the soil sample against shear before and after freeze-thaw, which are the cohesion c and the angle of internal friction $\boldsymbol{\varphi}$ .Four soil samples with different initial dry weights before and following freeze and thaw have been selected and placed on the direct shear instrument as necessary, and four vertical pressure levels of 50, 100, 200 and

300 kPa have been gradually applied to the samples, followed by uniform shearing at a shear rate of 0.8 mm per minute. When the measured shear stress readings gradually stabilize or have a sharp decline, indicating that the specimen has produced a shear broken; if the shear stress is no obvious peak or fallback point, then take the shear deformation of 4mm corresponding to the shear stress as the shear strength of the specimen. To make the sample under the absence of lateral pressure, axial pressure, lateral pressure and pressure under uniform control, so the JCY-type lateral pressure resting consolidation device (Figure 4) is selected to determine the lateral pressure resting of the soil sample before and after freeze and thaw. In the freeze-thaw and without freeze-thaw specimens were selected 1 specimen according to the requirements of installation, inspection and zeroing, etc. When loaded, the axial pressure was applied in steps of 100, 200 and 300 kPa, and then the vertical pressure and instrument readings were recorded at time intervals of 0.5, 1, 4, 9, 16, 25, 36 and 49 min. Read the pressure gauge at the above time interval and add the next level of axial pressure after the lateral pressure and compression deformation have stabilized.

Table 1. Physical Parameters of Tested Soil Samples and their Corresponding Testing

Sample number	Dry weight /KN·m^{-3}	freeze-thaw cold end temperature/℃	Mechanical testing
A_1 A_2~A_5 A_6	17.3	0℃ (without freeze-thaw)	Freeze-thaw cycle testing Compression and direct shear testing lateral pressure coefficient testing
A_7 A_8~A_{11} A_{12}		-10℃frozen, 20℃thaw	Freeze-thaw cycle testing Compression and direct shear testing lateral pressure coefficient testing
B_1 B_2~B_5 B_6	16.8	0℃ (without freeze-thaw)	Freeze-thaw cycle testing Compression and direct shear testing lateral pressure coefficient testing
B_7 B_8~B_{11} B_{12}		-10℃frozen, 20℃thaw	Freeze-thaw cycle testing Compression and direct shear testing lateral pressure coefficient testing
C_1 C_2~C_5 C_6	16.3	0℃ (without freeze-thaw)	Freeze-thaw cycle testing Compression and direct shear testing lateral pressure coefficient testing
C_7 C_8~C_{11} C_{12}		-10℃frozen, 20℃thaw	Freeze-thaw cycle testing Compression and direct shear testing lateral pressure coefficient testing
D_1 D_2~D_5 D_6	15.8	0℃ (without freeze-thaw)	Freeze-thaw cycle testing Compression and direct shear testing lateral pressure coefficient testing
D_7 D_8~D_{11} D_{12}		-10℃frozen, 20℃thaw	Freeze-thaw cycle testing Compression and direct shear testing lateral pressure coefficient testing

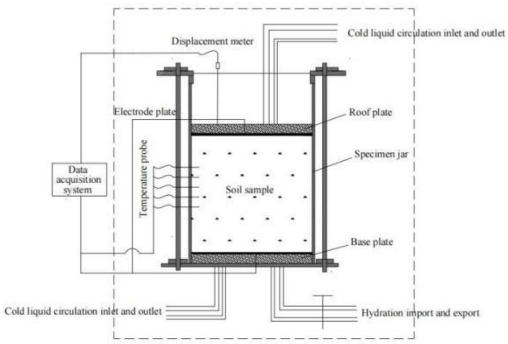

Figure 2. Schematic Diagram of Freeze-thaw Cycle Test Device

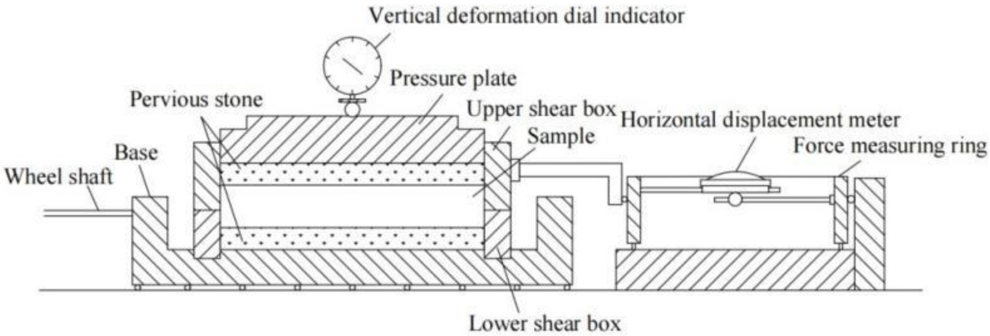

Figure 3. Strain Controlled Direct Shear Instrument

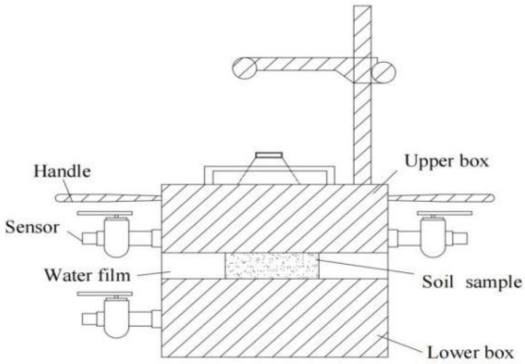

Figure 4. Coefficient of Resting Lateral Pressure Consolidator Oedometer

3. Analysis of The Test Results

3.1. Freeze-Thaw Time Course Curve

Dry weight is a key parameter that indicates whether the mechanical properties of the sample are altered by freeze-thaw. The influence of dry weight on the mechanical properties of the soil should be taken into account in the study of the change in the coefficient $\boldsymbol{K_0}$ in the soil before and after freeze and thaw.Figure 5 shows the freeze-thaw time course curves of four different dry weights of remodeled soils at the cold end of -10°C.From Figure 5, it is clear that the freeze capacity of the Lanzhou loess specimen is smaller than the thaw capacity when the dry weight is 15.8kN·m^{-3}, that is the dry weight gradually increases after freeze-thaw; the thaw capacity of the soil specimen is smaller than the frozen capacity after freeze and thaw when the dry weight is 16.3kN·m^{-3}, 16.8kN·m^{-3} and 17.3kN·m^{-3},that is, the volume of the soil sample is increasing and the dry weight is gradually decreasing, so freeze-thaw has a dual impact for soils with different dry weights, i.e., loose soils become more dense during freeze-thaw, while the opposite is true for dense soils, as shown in Figure 6.

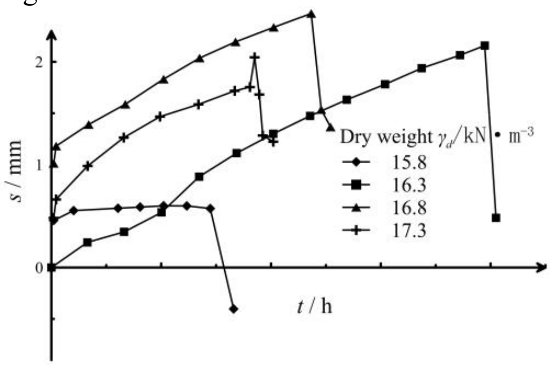

Figure 5. Freeze-thaw Duration Curve of Remolded under Freeze-thaw Cycles

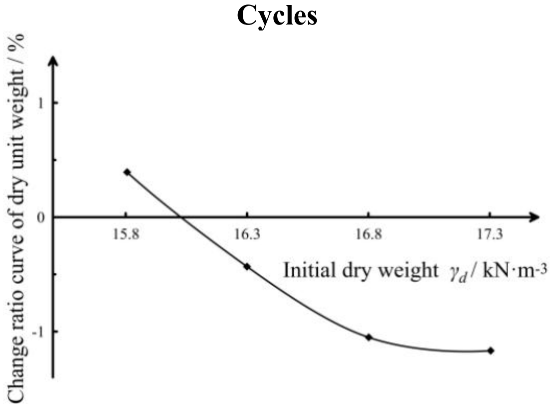

Figure 6. Change Ratio Curve of Dry Weight Sample under Different Dry Weight

3.2. Variation of MECHANICAL PARameters

Figure 7 and Figure 8 show the variation of c and φ for specimens of different dry weights after freeze-thaw at a temperature of -10°C at the frozen end. As can be seen from the figure, for the Lanzhou loess with dry weight greater than 16.8kN·m-3, the c decreases after freeze-thaw, while the φ increases. c increases and φ decreases for soil samples with dry weight less than 16.3kN·m-3 after freeze-thaw process. It can be seen that for soil samples with different dry weights, the effect of freeze-thaw on c and φ is twofold. During freeze and thaw testing, the original structure of the soil is destroyed, and the large soil particles are reduced in size, i.e., the larger pores in the soil gradually decrease, which leads to an increase in the contact points between the particles, the main reason for the increasing in φ.

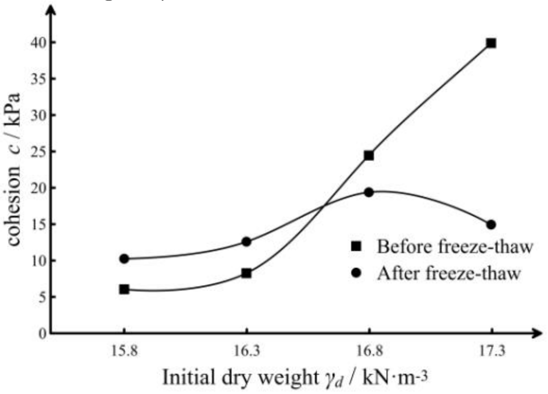

Figure 7. Influence of Different Dry Weight on Cohesion c

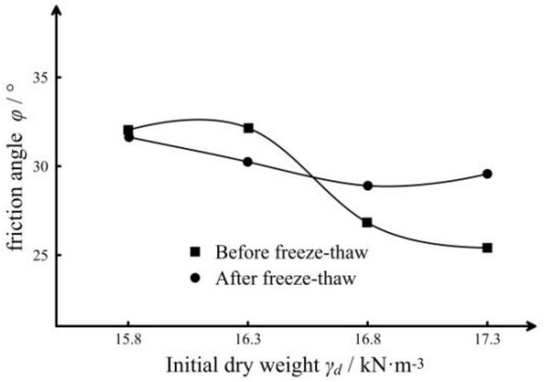

Figure 8. Influence of Different Weight on Friction Angle φ

Figure 9 depicts the variation graphs of the pre-consolidation pressure before and after freeze and thaw for soil samples with different initial dry weights at the freezing terminal temperature of -10℃. As shown in the figure, when the dry weight of the soil is larger ($\boldsymbol{\gamma_d}$ =16.8kN·m^{-3}, $\boldsymbol{\gamma_d}$ =17.3kN·m^{-3}), the pre-consolidation pressure of the Lanzhou loess sample decreases after freeze-thaw, and the range of variation is larger. When the dry weight of soil was 15.8kN·m^{-3} and 16.3kN·m^{-3}, the pre-consolidation pressure of soil samples increased after freeze-thaw. The magnitude is relatively small, This agrees well with Song et al.'s [2] Lanzhou Loess findings.

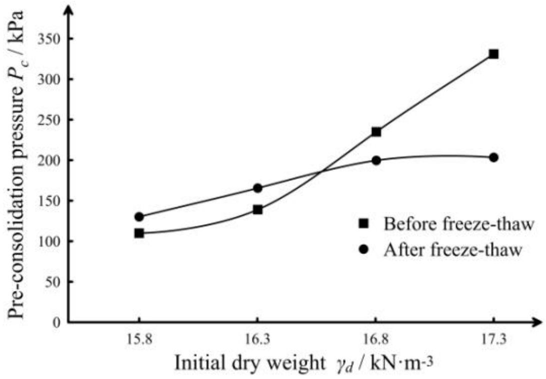

Figure 9. Influence of Different Dry Weight on Pre-consolidation Pressure P_c

Figure 10 shows the effect of freeze-thaw action on the coefficient K_0 of specimens with different initial dry weights at a frozen end temperature of -10°C. As shown in the figure, the effect of freeze-thaw process on the coefficient K_0 of soil samples continues to exhibit a dual effect. When the initial dry weight of the soil is less than 16.3kN·m^{-3}, the freeze-thaw process increases the coefficient K_0; when the initial dry weight of the soil is greater than 16.8kN·m^{-3}, the freeze-thaw action decreases the K_0.

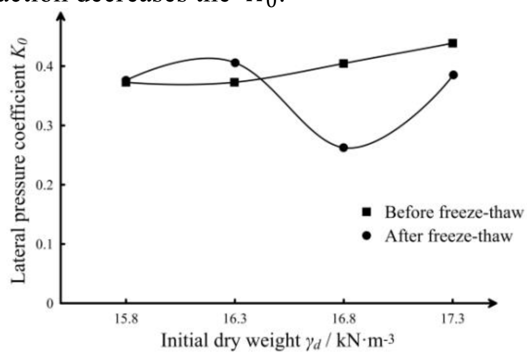

Figure 10. Influence of Different Dry Weights on K_0

When the initial dry weight is less than or greater than a certain value, the change trend of each index before and after freeze-thaw is different, and we call this value the critical dry weight. From Figure 7 to Figure 10, it can be seen that the critical dry weights corresponding to the four different indicators are different, as shown in Table 2 theoretically, the critical dry weight should be a certain value, however, the critical dry weight obtained from this test is not a certain value, but appears in the interval of 16.3 ~ 16.8 kN·m^{-3}. This result is mainly due to the random nature of the tests, which is mainly manifested in two aspects. On the one hand, local differences in soil structure are inevitable in the sample preparation process, and the test results may not be identical even for two specimens with the same initial dry weight; on the other hand, the influence of the instrumentation and specimens in the freeze-thaw process is also inevitable, and there are various randomness and uncertainty. Therefore, the critical dry weight obtained by using different mechanical indicators is not a constant value.

Table 2. The Critical Dry Weight Corresponding to each Index

Mechanical index	Critical dry weight γ_{d0}/kN·m^{-3}
c / kPa	16.6
φ / °	16.5
P_c / kPa	16.6
K_0	16.4

4. Discussion

4.1 Verification of $\mathbf{K_0}$ EQuation

At present, among the existing formulas for calculating the coefficient $\boldsymbol{K_0}$, the most commonly used one is the equation: $\boldsymbol{K_0 = 1 - sin\varphi}$, derived by Jaky [17] in 1948 through an experimental research. The applicability of this empirical formula in loess soils experiencing freeze-thaw has not been verified yet. Table 3 lists the $\boldsymbol{\varphi}$ before and after freeze and thaw process of soils at different initial dry weights and the coefficient $\boldsymbol{K_0}$ to verify the applicability of the above empirical formula to collapsible loess soils experiencing freeze-thaw action.

Table 3: Lateral Pressure Coefficient at Rest of Soil Samples before and after Freeze-thaw Process

Initial dry weight γ_d/ kN·m^{-3}	Before freeze-thaw			After freeze-thaw		
	Friction angle φ/°	K_0		Friction angle φ/°	K_0	
		Test result	Calculation result		Test result	Calculation result
16.8	25.4341	0.437500	0.570527	28.8922	0.261364	0.516837
17.3	26.7814	0.404545	0.549412	29.5210	0.384091	0.507257
16.3	31.9910	0.372727	0.470214	30.2395	0.404545	0.496384
15.8	32.0359	0.371591	0.469549	31.5868	0.376136	0.476210

As can be seen from Table 3, for the Lanzhou loess specimens that did without freeze-thaw, when the φ gradually increased from 25.4341 to 32.0359, the test results of the coefficient K_0 gradually decreased from 0.437500 to 0.371591, and the calculated results also gradually decreased from 0.570527 to 0.469549. For the specimens after experiencing freeze-thaw, when the φ gradually increased from 28.8922 to 31.5868, the calculated K_0 also decreased from 0.516837 to 0.476210, while the test results gradually increased from 0.261364 to 0.384091. Therefore, K_0 of Lanzhou loess after freeze-thaw increases with the increase of φ. This conclusion is opposite to the change law of K_0 of the without freeze-thaw Lanzhou loess specimen. It can be seen that the empirical formula of φ and K_0 is not fully applicable to the Lanzhou loess that experienced freeze-thaw.

5. Conclusion

Based on the freeze-thaw cycle testing, compression, direct shear tests and lateral pressure coefficient at rest tests were conducted on Lanzhou soil samples before and after freeze-thaw process, mainly to study the changes in soil mechanical parameters of Lanzhou loess specimens with different dry weights before and after freeze-thaw process, and the results are summarized below:

(1) The effect of freeze-thaw cycle on the coefficient K_0 of soil has a double effect. When the initial dry weight of soil is less than 16.3kN·m-3, freeze-thaw will increase K_0; when the initial dry weight of soil is more than 16.8 kN·m-3, freeze-thaw will decrease K_0.

(2) Due to the randomness and uncertainty in both sample preparation and freeze-thaw testing, the critical dry weight obtained from this experiment using different mechanical indices is not a certain value, but appears in the range of 16.3~16.8kN·m-3.

(3) By combining φ of the soil before and after freeze-thaw process obtained from the direct shear test, the applicability of the empirical formula ($K_0 = 1 - sin\varphi$) has been verified. The results show that the empirical equation of φ and K_0 of unfrozen soils is not

fully applicable to the Lanzhou loess after freeze and thaw cycles.

Acknowledgments

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