

# Influencing Factors and Significant Analysis of Mechanical Properties of Silty Clay Subgrade in Seasonal Frozen Area



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**Abstract** To explore the influence of different factors on the mechanical properties of highway subgrade soil, taking the soil specimen of the highway roadbed in Zhangjiakou as a research object, the factors of freezing and thawing times, water content, compaction degree, and freezing negative temperature are investigated. Using an orthogonal test design, freeze–thaw, temperature monitoring, and static triaxial tests are conducted. Significance analysis of the orthogonal test results is applied to determine the effect of the interaction between the factors, both individually and in combination, on the static strength, internal friction angle, and cohesion of the soil. Test results show that (1) after freeze–thaw cycles, the factors that significant influence the soil strength, cohesion, and internal friction angle are water content, compaction degree, freeze–thaw cycles, and freezing negative temperature; (2) these factors affect the freezing and thawing rate of soil samples, which affects the change of soil mechanical properties; (3) for increasing freezing and thawing times, the soil strength decreases continuously, and the intensity decay trend is slow after the fifth freeze–thaw cycle.

**Keywords** Freeze–thaw cycles · Freeze–thaw rate · Interaction · Orthogonal test · Significance analysis

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## 1 Introduction

In China, permafrost and seasonally frozen areas distribute widely; the frozen areas distribute mainly in the northern region of China [1]. With the demands of economic construction, national defense construction, resource development, and improvement of the living standards of rural residents, the frequency of production and living activities in these areas has been increasing. From previous engineering accidents, it has been found that only an in-depth understanding of the nature of the frozen area can reduce the economic losses caused by accidents.

After many years of exploration, experts and scholars at home and abroad have conducted a lot of research on the changes of soil static and dynamic strength, elastic modulus, soil quality, and compressive modulus after freezing and thawing cycles. Simonsen finds that the elastic modulus of soil is reduced after freeze–thaw cycles [2]. Based on freeze–thaw experiments on Jinzhou silty clay, Zhang Wenjiao concludes that the volume of Jinzhou silty clay increases after the freeze–thaw cycle, the cohesion decreases, and the internal friction angle first increases and then decreases [3]. Through a triaxial test of Qinghai–Tibet clay, Wang Dayan finds that the elastic modulus of Qinghai–Tibet clay first decreases and then increases after freeze–thaw cycles [4]. The strength of the sample decreases at first but increases after the tenth cycle, and the cohesion decreases gradually, while the angle of internal friction fluctuates between  $15^\circ$  and  $30^\circ$ . Through a triaxial test of saturating clay, Yu Linlin finds that the cohesion decreases after freezing and thawing and that the internal friction angle increases; the cohesion and internal friction angle gradually stabilize after 5–7 freeze–thaw cycles [5]. The lower the freezing temperature, the smaller the effect on both cohesion and internal friction angle. Wang Weina et al. use a load-bearing plate method to measure the rebound modulus of a roadbed and conclude that the rebound modulus of the subgrade soil decreases with an increase in freezing and thawing times and is basically stable after six freeze–thaw cycles [6]. Through a freeze–thaw cycle test on sandy clay and light sub-clay open systems, Yang Chengsong et al. find that during repeat freeze–thaw cycles, the soil dryness tends to a certain value [7]. Tan Yunzhi et al. study the effect of the freeze–thaw cycle on the strength of modified silt and conclude that the strength of modified silt decreases with increase in the number of freeze–thaw cycles; they observe stabilization after six freeze–thaw cycles [8]. Through the uniaxial compression tests conducted for silty clay freeze–thaw cycle of the Qinghai–Tibet Railway, Zhang Ying et al. find that the soil achieves dynamic stability after 30 freeze–thaw cycles [9]. Through a freeze–thaw cycle test for silty clay and loess, Qi Ji Lin et al. find that soil dry weight affects soil cohesion and early consolidation pressure, and that soil cohesion and early consolidation pressure of soil samples decreases after freeze–thaw cycles [10, 11]. Based on silty clay in the area of Tianjin and loess in the Lanzhou area, freeze–thaw cycles are simulated after remodeling and over consolidation, and it is concluded that the cohesion is decreased and the internal friction angle is increased. After freeze–thaw cycles, Ono et al. conducted a non-drainage shear test on normal consolidated remolded clay,

loose silty soil, low-density clay, and remolded clay and finds that shear strength increases [12–14]. Wang Xiaobin et al. conduct consolidated drainage shear tests on undisturbed soil and remolded clay, respectively, after a freeze–thaw cycle and demonstrated that the cohesive force decreases and the internal friction angle increases after freezing and thawing, and that freezing and thawing temperatures have little effect on soil strength [15]. Li Shunqun et al. study the influencing factors of the mechanical properties of frozen soils, with the main aim of investigating the interaction between factors and the significance of the various factors [16]. Their results show that temperature has the greatest influence on the mechanical properties of frozen soil, and that water content, salt content, and strain rate have different degrees of influence; moreover, an interaction effect between different influencing factors is found. Chang Dan et al. conducted a conventional triaxial shear test on the siltation of Qinghai–Tibet silt to study the effects of the freeze–thaw cycle on stress–strain curve, static strength, elastic modulus, and static strength [17]; finally, the significance of the effects of freeze–thaw cycles, freezing negative temperature, confining pressure, and factors on the mechanical effects of silt soil is determined.

In previous studies, the main focus is usually on damage strength, static strength parameters, elastic modulus, water migration, and stress–strain curves. In recent years, Li Shunqun and Chang Dan conducted a significance analysis of existing research results. In previous studies, the influencing factors investigated include confining pressure, freezing negative temperature, freezing and thawing times, water content, strain rate, and salt content; most of these studies used three factors in their significant analyses. In this study, the effects of freezing and thawing cycles on the static properties of silty clay are investigated. In the case of interaction, the influence of different factors is determined using an orthogonal test, and the factors influencing soil strength as well as the significant interaction factors are determined.

## 2 Test Content and Method

Following the *Test Methods for Soils Highway Engineering*, the basic soil parameters are determined experimentally; the maximum dry density is  $1.98 \text{ g/cm}^3$ , and the optimum water content is 11.3%. According to the method specifications, a number of soil samples are prepared, with a height of 80 mm and a diameter of 39.1 mm. After each sample is prepared, it is frozen in a low-temperature box, at a temperature of between  $-10$  and  $-5$  °C, before melting at a melting temperature of 20 °C, with freezing and melting times of 12 h. To investigate the effects of freezing negative temperature, freeze–thaw cycles, water content, compaction degree, and confining pressure on the mechanical properties of soil, the specific test scheme shown in Table 1 is followed.

To investigate the effect of freezing negative temperature, freeze–thaw cycles, water content, compaction degree, and confining pressure on the mechanical properties of soil during freezing and thawing, an orthogonal experiment is carried

**Table 1** Table of the freezing–thawing test

Test number	Compaction degree (%)	Water content (%)	Freezing negative temperature (°C)	Thawing temperature (°C)	Freeze–thaw cycles (n)
1	94	11	−5	20	0, 1, 5, 11
2	97				
3	94	13			
4	97				
5	94	11	−10	20	
6	97				
7	94	13			
8	97				

out to explore the interaction between the factors. Considering the interaction, using an L16 ( $4 \times 2^{12}$ ) orthogonal table, a table is designed as shown in Table 2. Table 3 is an orthogonal experimental design scheme of L16 ( $4 \times 2^{12}$ ). *A* denotes the number of freeze–thaw cycles, which is 0, 1, 5, or 11. *B* represents the degree of compaction, which is 97 or 94%. *C* represents the water content, which is 11 or 13%. *D* represents the freezing negative temperature, which is −10 or −5 °C.

### 3 Significance Analysis Principle

Factors affecting the mechanical properties of silty clay usually include water content, compaction degree, freezing negative temperature, and freeze–thaw cycles. In this study, these four aspects are subjected to significance analysis. Significance analysis is actually an analysis of variance; a single-factor test analyzes the changes in only one factor, while a multi-factor test analyzes the changes in a number of factors. The multi-factor analysis can be divided into repeated tests and multi-factor no-repeat tests. There are four factors in this analysis; multiple factors without repeated tests and the interaction between factors are considered.

Considering the interaction between the factors, the theoretical analysis of the four factors is as follows. First, the factors are numbered *A*, *B*, *C*, and *D*, where factor 1 has *a* levels, as  $A_1, A_2, \dots, A_a$ , factor 2 has *b* levels, as  $B_1, B_2, \dots, B_b$ , factor 3 has *c* levels, as  $C_1, C_2, \dots, C_c$ , and factor 4 has *d* levels for  $D_1, D_2, \dots, D_d$ . A test is conducted at each combination level ( $A_i, B_j, C_k, D_l$ ); test results are labeled  $X_{ijkl}$ .

The calculation process is as follows:

The total sum of squares is:

$$S_T = \sum_{i=1}^a \sum_{j=1}^b \sum_{k=1}^c \sum_{l=1}^d X_{ijkl}^2 - \frac{T_{ijkl}^2}{abcd}$$



**Table 3** Orthogonal experiment design scheme A of L16 ( $4 \times 2^{12}$ )

Test number	A	B	(A × B)1	(A × B)2	(A × B)3	C	(A × C)1	(A × C)2	(A × C)3	B × C	D	空	空
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1(0)	1(94)	1	1	1	1(11)	1	1	1	1	1(-10)	1	1
2	1	1	1	1	1	2(13)	2	2	2	2	2(-5)	2	2
3	1	2(97)	2	2	2	1	1	1	1	2	2	2	2
4	1	2	2	2	2	2	2	2	2	1	1	1	1
5	2(1)	1	1	2	2	1	1	2	2	1	1	2	2
6	2	1	1	2	2	2	2	1	1	2	2	1	1
7	2	2	2	1	1	1	1	2	2	2	2	1	1
8	2	2	2	1	1	2	2	1	1	1	1	2	2
9	3(5)	1	2	1	2	1	2	1	2	1	2	1	2
10	3	1	2	1	2	2	1	2	1	2	1	2	1
11	3	2	1	2	1	1	2	1	2	2	1	2	1
12	3	2	1	2	1	2	1	2	1	1	2	1	2
13	4(11)	1	2	2	1	1	2	2	1	1	2	2	1
14	4	1	2	2	1	2	1	1	2	2	1	1	2
15	4	2	1	1	2	1	2	2	1	2	1	1	2
16	4	2	1	1	2	2	1	1	2	1	2	2	1

The variance squared sum of factor *A* is

$$S_A = \frac{1}{bcd} \sum_{i=1}^a T_1^2 - \frac{T_{ijkl}^2}{abcd}$$

The variance squared sum of factor *B* is

$$S_B = \frac{1}{acd} \sum_{j=1}^b T_2^2 - \frac{T_{ijkl}^2}{abcd}$$

The variance squared sum of factor *C* is

$$S_C = \frac{1}{abd} \sum_{k=1}^c T_3^2 - \frac{T_{ijkl}^2}{abcd}$$

The variance squared sum of factor *D* is

$$S_D = \frac{1}{abc} \sum_{l=1}^d T_4^2 - \frac{T_{ijkl}^2}{abcd}$$

where

$$T_{ijkl} = \sum_{i=1}^a \sum_{j=1}^b \sum_{k=1}^c \sum_{l=1}^d X_{ijkl}$$

$$T_1 = \sum_{j=1}^b \sum_{k=1}^c \sum_{l=1}^d X_{ijkl}$$

$$T_2 = \sum_{j=1}^a \sum_{k=1}^c \sum_{l=1}^d X_{ijkl}$$

$$T_3 = \sum_{i=1}^a \sum_{j=1}^b \sum_{l=1}^d X_{ijkl}$$

$$T_4 = \sum_{i=1}^a \sum_{j=1}^b \sum_{k=1}^c X_{ijkl}$$

Considering the interaction of the four factors, according to the different permutations and combinations, the interaction can be divided into six cases for  $A \times B$ ,  $A \times C$ ,  $A \times D$ ,  $B \times C$ ,  $B \times D$ , and  $C \times D$ , and the calculation process is as follows (each case follows the example given).

**Table 4** Critical values  $F_\alpha(f_1, f_2)$  for  $F$  test

Significance level $\alpha$	$F_\alpha(f_1, f_2)$		
	$f_1 = 1$ $f_2 = 2$	$f_1 = 1,$ $f_2 = 5$	$f_1 = 1,$ $f_2 = 8$
	$f_1 = 3,$ $f_2 = 2$	$f_1 = 3,$ $f_2 = 5$	$f_1 = 3,$ $f_2 = 8$
0.100	8.53/9.16	4.06/3.62	3.46/2.92
0.050	18.51/19.16	6.61/5.41	5.32/4.07
0.010	98.5/99.17	16.26/12.06	11.26/7.59
0.005	198.5/199.2	22.78/16.53	14.69/9.60
0.001	998.5/999.2	47.18/33.20	25.42/18.49

Considering the interaction, the sum of the squares of factors  $A$  and  $B$  is

$$S_{A \times B} = \frac{1}{cd} \sum_{i=1}^a \sum_{j=1}^b \left( \sum_{k=1}^c \sum_{l=1}^d X_{ijkl} \right)^2 - S_A - S_B + \frac{T_{ijkl}^2}{abcd}$$

The variance estimates for the various combinations of factors, and the different combinations of factors are calculated as (using the sum of the squares of factors  $A$  and  $B$  as an example):

$$F_A = (S_A/f_A)/(S_E/f_E)$$

$$F_{A \times B} = (S_{A \times B}/f_{A \times B})/(S_E/f_E)$$

where  $f_A, f_{A \times B}$ , and  $f_E$  are, respectively, the degrees of freedom of factor  $A$ , factor  $A \times B$ , and the error.

At different levels of significance,  $\alpha$ , when  $F_A \geq F_\alpha(f_1, f_2)$  (using the  $F$  distribution table shown in Table 4), indicating that the impact of factor  $A$  on the test is significant, and vice versa; the other factor is not significant; the same reasoning can be applied to other factors to determine the significance of the different characteristics. According to the test, the hypothesis value can be divided into six significance levels:  $\alpha < 0.001$ , defined as level 1;  $0.001 \leq \alpha < 0.005$ , defined as level 2;  $0.005 \leq \alpha < 0.01$ , defined as level 3;  $0.01 \leq \alpha < 0.05$ , defined as level 4;  $0.05 \leq \alpha < 0.1$ , defined as level 5; and  $\alpha \geq 0.1$ , defined as level 6.

### 4 Analysis of Test Results

The silty clay samples, with the different values of water content, compaction degree, freezing negative temperature, and freezing and thawing times, are shown in Table 1, as well as a control sample, and are subjected to freeze–thaw tests. After the end of the test, according to the methods described in *Highway Geotechnical*



*Test Procedures*, a static triaxial test is conducted. The test strain rate is set to 0.8 mm/min, and the peak strain is 15%, which is the specimen failure strain. The test results are shown in Table 5.

### 4.1 Analysis of Static Intensity of Soil

After the orthogonal analysis, the values of soil strength, internal friction angle, and soil cohesion under different working conditions are collated in an orthogonal table. The static soil strength is analyzed statistically for variations in freezing and thawing times, moisture content, compaction degree, and freezing negative temperature. The results are shown in Tables 6 and 7.

Through the analysis of Tables 6 and 7, it can be found that the effect of each factor on the static strength of the soil is  $B > C > B \times C > A > A \times D > A \times C > B \times D > D > A \times B > C \times D$ , for a confining pressure of 20 kPa, considering the interaction between the factors, that is, compaction degree > water content > interaction of water content and compaction degree > freezing and thawing times > freezing negative temperature > interactions between water content and freezing negative temperature > interaction between freezing and thawing times and water content > interaction between compaction degree and freezing negative temperature effect.

**Table 5** Orthogonal experimental results of the triaxial test

Test number	Static strength ( $\sigma_3 = 20$ kPa)	Static strength ( $\sigma_3 = 100$ kPa)	Static strength ( $\sigma_3 = 180$ kPa)	Cohesion (kPa)	Internal friction angle (°)
1	436.4	604.7	774.8	111.55	30.93
2	472.0	619.6	746.7	134.97	27.49
3	703.4	872.4	1027.2	192.04	30.19
4	385.4	535.6	668.6	106.95	27.99
5	391.0	569.9	741.7	97.83	31.52
6	393.1	548.2	691.1	106.4	28.82
7	625.2	806.3	952.2	167.01	30.36
8	331.8	482.4	621.3	89.38	28.35
9	512.6	718.0	929.4	120.75	33.76
10	305.1	469.8	616.5	79.35	29.54
11	333.8	530.1	690.5	84.05	31.76
12	359.1	517.3	672.8	93.22	29.67
13	501.0	698.0	901.0	120.01	33.85
14	300.8	462.1	611.8	77.49	29.52
15	324.4	522.6	683.7	81.26	31.88
16	350.4	515.9	666.4	91.56	29.80

**Table 6** Significance test *A* of soil strength considering interactions

Source of variation	SS	Df	MS	<i>F</i>	Significance level
<i>A</i>	40836.29	3	13612.1	398.24	2
<i>B</i>	63491.4	1	63491.4	1857.53	1
<i>AB</i>	837.16	3	279.05	8.16	6
<i>C</i>	77715.5	1	77715.5	2273.67	1
<i>AC</i>	2898.62	3	966.21	28.27	4
<i>BC</i>	21017.75	1	21017.75	614.90	2
<i>D</i>	565.25	1	565.250	16.54	4
<i>e</i>	68.36	2	34.18	–	–
Total variation	207498.7	13	–	–	–

**Table 7** Significance test *B* of soil strength considering interactions

Source of variation	SS	Df	MS	<i>F</i>	Significance level
<i>A</i>	40836.29	3	13612.1	60.94	1
<i>B</i>	63491.4	1	63491.4	284.23	1
<i>CD</i>	70.98	3	23.66	0.11	6
<i>C</i>	77715.5	1	77715.5	347.91	1
<i>BD</i>	2618.88	3	872.96	3.91	5
<i>AD</i>	21086.11	3	7028.70	31.47	2
<i>D</i>	565.25	1	565.25	2.53	6
<i>e</i>	1045.92	2	522.96	–	–
Total variation	208547.2	17	–	–	–

When the confining pressure is 20 kPa, the factors influencing soil strength are the interaction of water content, compaction degree, freezing and thawing times, moisture content and compaction degree, and the interaction between freezing temperature and freezing and thawing times. The effect of the combination of water content, the degree of compaction, freezing temperature, and the number of freeze–thaw cycles on the soil strength is calculated, as shown in Tables 8 and 9.

According to Tables 8 and 9, for  $B_1C_1$ ,  $A_1D_1$ , the static strength of the soil has a maximum; here, the combination is no freeze–thaw times, a water content of 10%, a compaction degree of 97%, and freezing temperature of  $-10$  °C. For  $B_2C_2$  and  $A_4D_1$ , the static strength of the soil has a minimum value. Here, the combination is 11 freeze–thaw cycles, a water content of 12%, a compaction degree of 94%, and a

**Table 8** Tie-in effect calculation of  $B \times C$ 

$B \times C$	$B_1$	$B_2$
$C_1$	588.8	390.325
$C_2$	376.925	323.425

**Table 9** Tie-in effect calculation of  $A \times D$

$A \times D$	$A_1$	$A_2$	$A_3$	$A_4$
$D_1$	544.4	466.95	410.4	402.7
$D_2$	454.2	388.4	350.3	341.6

freezing negative temperature of  $-5\text{ }^\circ\text{C}$ . The maximum value represents the static strength of the soil without freeze–thaw cycles, and the minimum represents the largest combination of all the factors.

Similarly, according to the data given in Table 5, it can be calculated that when the confining pressure is 100 kPa, the influence of the static strength on the soil is:  $B > C > B \times C > A > A \times D > A \times C > D > A \times B > B \times D > C \times D$ . When the confining pressure is 180 kPa, the influence of the static strength on the soil is:  $B > C > B \times C > A > A \times D > A \times B > A \times C > B \times D > D > C \times D$ .

As can be seen from Table 4, when the critical value is less than F0.010, the value for F0.005 is significantly smaller than that for F0.010, so it can be assumed that the critical value is less than F0.01 when the impact is not significant. After analyzing the influence of the static strength values on the three kinds of confining pressure, the factors influencing the strength value are determined to be the interaction between water content and compaction degree and numbers of freeze–thaw cycles.

### 4.2 Effect of Freezing and Thawing Rate on Soil Strength

Considering such factors as water content, compaction degree, environmental temperature, and freezing and thawing times, the silty clay samples are subjected to freeze–thaw experiments. The internal temperature of the specimen is measured under different working conditions: freezing time, freezing temperature, cold duration, and time to reach the ambient temperature, that is, the negative temperature stability. The results are shown in Table 10.

After the orthogonal test is completed, the data for the different working conditions is combined into the orthogonal table. The freezing and melting rates of the soil samples are analyzed for variations in freezing and thawing times, moisture content, compaction degree, and freezing temperature. The results are as follows:

- (1) During the freezing process, the degree of influence on the freezing rate is in the order of environmental temperature > compaction degree > water content > interaction between compaction degree and water content.
- (2) During the freezing process, the degree of influence on the degree of freezing temperature is (from large to small) in the order of environmental temperature > compaction degree > water content > interaction between the degree of compaction and water content.

**Table 10** Orthogonal experimental results of temperature test

Test number	Freeze 0 °C (min)	Supercooled start (min)	Supercooled temperature (°C)	Duration (min)	Negative temperature stability (min)
1	63	126	-3.7	24	314
2	40	60	-3.7	7	286
3	58	74	-3.7	16	412
4	78	152	-3.7	38	490
5	69	126	-3.7	37	404
6	43	58	-3.7	9	289
7	67	78	-3.7	20	372
8	71	151	-3.7	44	521
9	46	78	-3.7	6	305
10	72	133	-3.7	29	421
11	82	153	-3.7	28	505
12	56	71	-3.7	17	430
13	44	62	-3.7	8	261
14	68	122	-3.7	35	383
15	81	157	-3.7	33	470
16	47	73	-3.7	23	391

- (3) The freezing temperature is unchanged under different working conditions, indicating that the freeze–thaw cycles only changes the mechanical properties of the soil without changing the physical properties of the soil [18, 19].

In the analysis of the influence of freeze–thaw cycle on soil strength, the results obtained for the combination of freezing rate and soil strength show that the factors influencing the strength of the soil are compaction degree, water content, compaction degree, and water content interaction. Therefore, it is considered that different factors affect the freezing and thawing rate of soil, which affect the strength of soil.

## 5 Conclusion

Experiments show that soil strength, cohesion, and internal friction angle decrease with increasing numbers of freeze–thaw cycles. After a slow decline, the soil properties stabilize after the fifth freeze–thaw cycle. The orthogonal test and significance analysis demonstrate that the factors that influence the strength of the soil are compaction degree, water content, interaction between compaction degree and water content, and the number of freeze–thaw cycles.

During the experiments, the internal temperature of the specimen is monitored periodically. The results show that such factors as compaction degree, water content,

and freezing temperature change the freezing rate of the specimen, and the freezing and thawing rate affect soil strength. The effect of freezing and thawing factors on soil strength is explained by the change of freezing rate.

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