Research on the critical depth deterioration of the slip surface of soil slope in seasonal frozen area

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Abstract: Soil slope is one of the main parts of the road engineering. In seasonal frozen regions, shallow landslide hazards in soil slopes usually happen, which pose a serious threat to road safety operations. During the melting process, there forms stagnant water lubrication between the melting soil and freezing soil interface, which constitutes the weak interface of landslide hazard. In order to study the shallow landslide hazard of soil slope during the spring melt period in seasonal frozen areas, considering that the freezing point of the brine is lower than pure water, a simulated test method of the internal freezing and thawing interface of soil slope was designed. The critical slip surface depths after freeze-thaw circles in different water content are compared in the test, and the failure modes of the internal freezing and thawing interface of soil slope are verified. Then the sliding face depth damage model of the soil slope is put forward according to the experimental data. The results demonstrate that with the increasing water content and freeze-thaw circle times, the value of critical slip surface depth decreases gradually after freeze-thaw circles, the damage model which is obtained from the experimental data fitting, would present more reference of the slope design in the seasonal frozen area.

Key words: soil slope landslide; freezing and thawing simulated test; soil damage coefficient

Introduction

Slope instability damage, earthquakes and volcanic are three major global geological disasters. In engineering such as embankment, excavation, channel and bank, soil slope is designed as a main part. Focused on the stability of soil slope in seasonal frozen area, the mechanical methods based on the limit equilibrium analysis methods are usually adopted nowadays. With further research, more and more scholars taking the melt flow force of already saturated soil into account at the same time considering the force of soil inside then search the slide surface of the soil slope

In seasonal frozen regions, as a result of the water moving in the soil, as well as the impact of soil weight, shallow landslide hazards in soil slopes usually happen in spring thawing period, which pose a serious threat to the safety of highway operators (Sally, 2008). The research in the impact of freeze-thaw (F-T) cycles on soil shear strength not only has a certain accelerating effect in the development of mechanics of frozen soil (Liu, 2006), but has practical significance in engineering design, construction and management in cold regions (Chen, 2003).

After F-T circles, the structure of the soil itself changes, the frost water enlarge the hole of the soil structure and reduce the shear strength of the soil structure (Xu, 2006). At the same time, the water in the F-T soil moves and results in the assembling of water on the F-T. This forms an interlayer between the soil, and the shear strength of the interlayer decrease substantially, which increase the probability of slide. It is believed that when the soil is melting, the slide surface is the freezing- thawing surface, which is parallel to the slope face (Chen, 2008). Soil slope slide depends largely on the soil shear strength indicator (Sean, 2001). When the slope angle β keeping unchanged, as the slope thawing depth increasing, the downslide force from the gravity of the thawed soil increase. The radial part of the gravity of the upper thawed soil can offer certain compressive stress, the speed of this increase is slower than the increase of downslide part of the gravity .When the shear strength of the shear surface τ_f has certain loss, the safety factor of the slope will reduce, therefore the research in the deterioration of shear strength between the freezing and thawing surface can directly present the reference for slope landslide analysis, and is the base of soil slope stability analysis with the use of mechanical model.

Because of the difficulty in modeling a freezing - thawing surface, the present literatures are limited in the research of whole sheer strength after the soil has fully melted. There is no analysis of shear strength on freezing - thawing surface and sheer strength index in limit state, as well as the analysis of shear strength deterioration in freeze-thaw cycle condition. It is necessary to design reasonable experiment method for forecasting and analyzing the ultimate shear strength of the freezing-thawing surface.

Nowadays research found that of the soil slope stability decreases with some influence, such as the critical depth, the freeze - thaw cycles and the increasing of water content in the soil, etc. For the soil slope, the affection of freeze-thaw cycles on the slope stability is about coupling effects of water heat in the damage propagation and strength degradation process. The tests about the F – T surface have been set out, and obtained the experimental results of the critical slide depth of the soil slope in seasonal frozen area. On the basis of it, considering the accrual risk and complexity of the slope engineering, the numerical simulation method combined with laboratory experiments is adopted to analyze the limit state of the slope. Then the distribution of the critical depth of sliding in seasonal soil areas is explored. The more understanding of the soil sliding state, the better reference and experience could be presented to the slope design and health monitoring in the area.

Methods of analysis of the slope stability in seasonal frozen regions

A. Basic analysis principle

For the special character of the Northeast China, soil is frozen in winter and melted in summer. It is typical seasonal frozen area. Under the continuous freeze - thaw cycles, as a result of the water migration in the soil, as well as the impact of soil self weight, the soil porosity and skeleton changed, which lead to the deterioration of the soil strength, and affect the slope stability. With the increasing period of the road engineering, the slope failure frequency gets higher gradually, shallow landslide hazards in soil slopes usually happen in spring thawing period, which poses a serious threat to the safety of highway operating.

Based on the mechanism analysis, the shear strength of freezing and thawing surface soil is lower than frozen soil or melting soil during the melting period. The strength research result of the surface has been further verified this conclusion [5].

From frozen to melted, the freezing – thawing (F-T) surface gets soften, then the mixture of ice and water become the lubrication, and weaken the shear strength. As a result, the slope failure took place on the F - T surface. So it is necessary to analysis the shear strength of the F - T surface.

In this text we define deterioration coefficient μ, whose data is the ratio of shear strength between F - T surface and normal soil surface:

$$\mu = \frac{\text{Shear strength of F - T surface } \tau_{\text{fn}}}{\text{Shear strength of normal surface } \tau_{\text{f}}} \quad (1)$$

Analysis the stability of soil slope in seasonal frozen regions, based on the shear strength deterioration of the inner slope, and considers it as the evaluation criteria.

Previous carried out experiments and obtained the fitting curve of F – T deterioration model and experimental values. Combined with the shear strength test results about the F – T surface, the shear strength deterioration state is obtained. With the increasing quantity of the freeze – thaw cycles, the deterioration is tended to mitigation, as the foundation of the research, showed in Fig. 1.

Normal soil type of the seasonal frozen area is cohesive soil, and the shear strength can be expressed as:

$$\tau_f = c + \sigma tan\varphi \quad (2)$$

Considering the deterioration of the cohesion c and friction angle φ of the F – T surface separately, shear strength can be expressed as the following formula:

$$\tau_n = c_n + \sigma' \tan \varphi_n \quad (3)$$

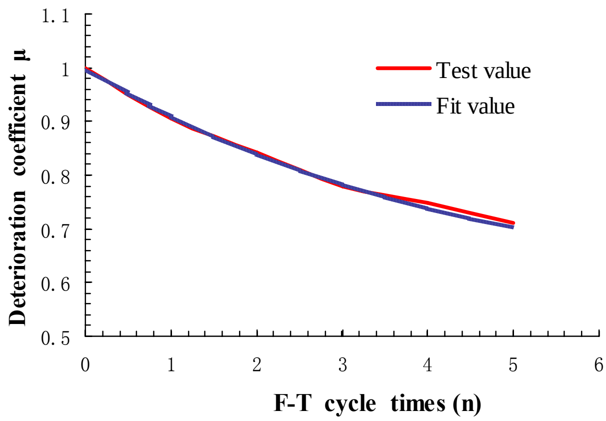


Fig. 1 Curve fitting map of F-T deterioration model and experimental values

Then get the correspondent relationship:

$$c_n = \mu_c \times c' \quad (4)$$

$$tan\varphi_n = \mu_\varphi \times tan\varphi' \tag{5}$$

Assume the soil of slide surface is saturated, and pore water of the soil will present the pore water pressure, which could reduce the soil effective stress. As a result, freeze – thawing state increased the risk of slope failure. Effective stress method is adopted to check the stability, so the shear strength could be expressed as:

$$\tau_f = c' + (\delta - \mu)\tan\varphi' \tag{6}$$

In which $\delta = \gamma_{sat} h_s cos^2\alpha$, and $u = \gamma_w h_s cos^2\alpha$.

So the shear strength on the slide surface of the slope is:

$$\tau = \gamma_{sat} h_s sin\alpha cos\alpha \tag{7}$$

From the point of Shear strength to study, consider freezing - thawing surface as the weak internal interface, and the shear strength deterioration of the surface is main inducement factor of slope instability and failure in the region.

B. Stability analysis of the soil slope

In the stability analysis of the slope, safety factor *F* is defined as the ratio of slide force and resistance force. Finishing the formulas above, can get the general safety factor *F*:

$$F = [(\gamma_{sat} - \gamma_w) h_s cos\alpha tan\varphi' + c' sec\alpha]/(r_{sat} h_s sin\alpha) \tag{8}$$

To the safety factor *F* of the aim slope, it can be expressed as:

$$F = \frac{R}{T} = \frac{\int_0^l \left(c' + \sigma' \tan\varphi'\right) dl}{\int_0^l \tau dl} \tag{9}$$

Replace the cohesion and friction angle of the F – T surface separately, and then the safety factor of F – T surface is:

$$F = \frac{R}{T} = \frac{\int_0^l \tau_{fn} dl}{\int_0^l \tau dl} = \frac{\int_0^l \mu\tau_f dl}{\int_0^l \tau dl} = \frac{\int_0^l \mu\left(c' + \sigma \tan\varphi'\right) dl}{\int_0^l \tau dl} \tag{10}$$

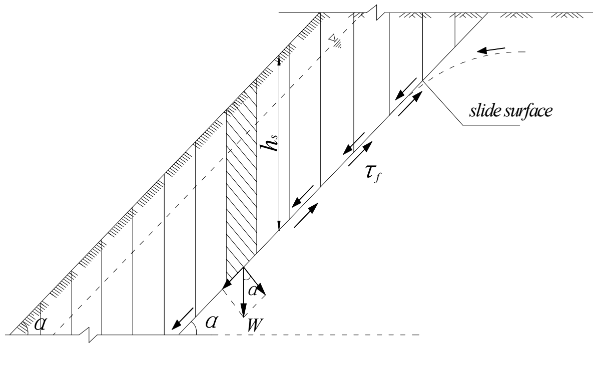


Fig. 2 Freeze – thaw failure force analysis of the soil slope

Normally, based on the generalized limit equilibrium method, considering the deterioration coefficient μ of F – T surface in seasonal frozen region, the safety factor F will decrease when the slope gets limit state.

To study the slope stability of the local area, Bishop Method is combined, as shown in Fig.2, and then the final safety factor is obtained as follow:

$$F=\frac{\sum_{n=1}^{N}[\Delta W(1-r_u)\mu_{\varphi}\tan\varphi^{'}+\mu_c c^{'}\Delta x]/[\cos\alpha(1+\mu_{\varphi}\tan\alpha\tan\varphi^{'}/F)]}{\sum_{n=1}^{N}[\Delta W\sin\alpha+\Delta QR_d]} \quad (11)$$

Tests of the stability deterioration of the freezing- thawing soil slope

In order to study the shallow landslide hazard of soil slope during the spring melt period in seasonal frozen areas, considering that the freezing point of the brine is lower than pure water, the study designs a simulated test method of the internal freezing and thawing interface of soil slope. The critical slip surface depths after freeze-thaw circles in different water content are compared in the test, and the failure modes of the internal freezing and thawing interface of soil slope are verified. Then the sliding face depth damage model of the soil slope is put forward according to the experimental data.

A. Stress simulation by external loading

The soil specimen is set on the below fixed baffle of the slope and the bottom plate in steady. When the sample is applied to the external load, specimen itself will be subjected to external weight interaction, the sliding force is on the slope direction, whose quantity is known. The stress state is shown in Fig.3. The sample size is 5cm ×5cm ×20cm. The Lower (frozen layer) depth is 2cm, and the volume is 200 cm^3. The upper (thawing layer) depth is 3cm, and the volume is 300 cm^3.

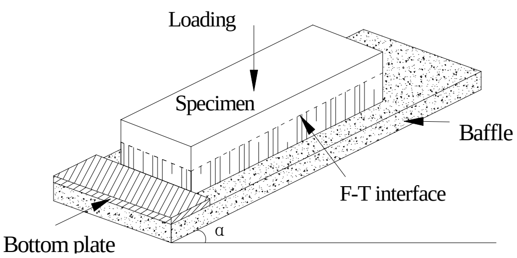
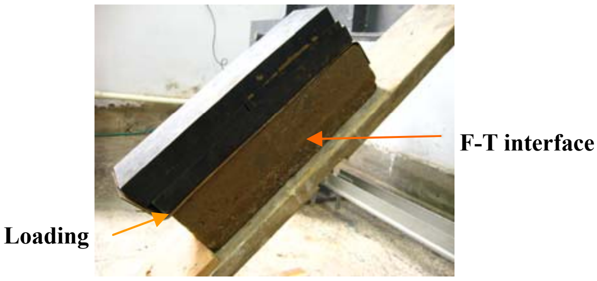


Fig. 3 Schematic diagram of experiment design

B. Freezing Thawing surface simulation

In order to ensure the production of specimen integrity, test use the same soil sample preparation. Specimens containing lower by ordinary water soil sample production, upper layer by including 1% concentration saline soil sample preparation. Considering the physical characteristics of the freezing point below the freezing point of water, so in -3 ℃ test temperature, lower soil freezing, become frozen layer. And the upper layer soil is in unfrozen state, namely the melting layer; they form a freezing and thawing interface. Considering the two kinds of soil strength differences, the freeze thawing interface for direct shear test of soil samples was researched on, in contrast to the common and freezing and thawing interface test direct shear test results presented, freezing and thawing interface coefficient of shear strength is 0.946.

In -3 ℃ test temperature, put the sample in inclined plate, simulation of road slope. On the specimen loading stage, finally specimens damaged. When the upper part will damage the specimen loading weight conversion into soil height, the destruction of freezing-thawing interface soil height, is destroyed when the freezing and thawing depth.



(a) The initial forms of test

(b) The final broken forms of specimen with freezing and thawing (F-T) interface

Fig.4 The schematic diagram of breaking process of the test

Table.1 The test results of F-T interface specimens

Water content（%）	16	18.5	21
Loading（kg）	65.5	60.3	36.8
Critical depthH（m）	2.88	2.65	1.63

C. Critical slide depth load test under free thaw cycles

By comparing the test results with the former two groups, freezing and thawing interface of the loading capacity were significantly lower than those test pieces without freezing and thawing interface. It is necessary to combine cycle of freezing and thawing on the same bearing test of the seasonal frozen soil area, and study the change rule of critical depth.

Using the same designed soil, water content is 18.5% with 1% salt content. The average water content of frozen soil layer is 16%, in the test temperature formed under freezing and thawing interface. Test piece after n (1-5) freeze thaw cycle load test, the critical depth change was observed. Under freeze-thaw cycle loading test results are listed in Table 2.

Table.2 The results of F-T interface samples after F-T cycles

Cycle times n	1	2	3	4	5
Loading（kg）	57.3	51.1	45.3	44.2	40.5
Critical depth H（m）	2.52	2.25	1.99	1.95	1.79

Test results and data analysis

The experimental data demonstrates that, due to the freeze-thaw action the moisture migrated, leading to the shear strength of freezing and thawing interface was significantly lower than thawed soil, at the same time the sliding failure surface is the freezing and thawing interface. Due to the freeze-thaw cycles on soil has great influence on its properties, the research on the impact of different freezing and thawing cycle times and different water content to the critical depth is very necessary.

Destruction test piece upper applied load weight m_S, which is the critical test loading, due to two kinds of materials with different density, so the soil weight need to be converted to a height quantity, then the critical depth calculation is achieved. The height conversion coefficient of soil is as follow:

$$\xi = \frac{m_s}{\rho_0 \times A} \qquad (12)$$

In which: m_S——Loading up of the slope;

ρ_0——Saturation density of the thawed soil

A——The area of upper slope surface $A{=}l_1 \times l_2$

With the height conversion coefficient, the thickness of thawed soil layer is 3*cm*, so the critical depth of the broken slope is $H = \xi + 0.03$.

A. Comparison of the critical depth with freezing and thawing interface or not

In Fig.5, the critical depth comparison between normal specimens and freezing - thawing interface specimens is put forward.

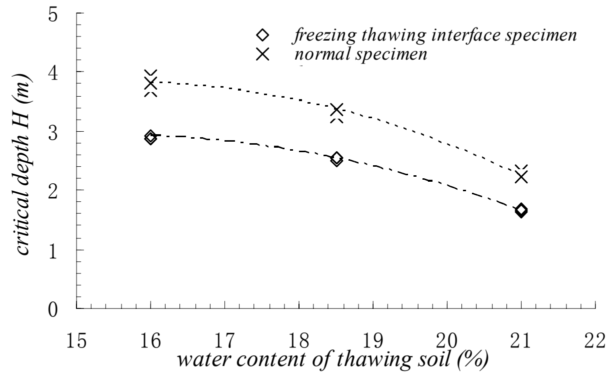


Fig.5 The critical depth comparison between normal specimens and freezing - thawing interface specimens

In Fig. 4, it can be found that in the same water content condition, the critical depth of the slope with freezing and thawing interface was significantly lower than the ordinary soil specimens, and the critical depth with freezing and thawing interface is about 70% to the ordinary specimens. So in the seasonal frozen area, when analyzing the soil slope safety, the freezing and thawing interface is needed to be researched for further.

B. The influence on critical depth of water content on the freezing and thawing interface

In view of different water content on the freezing and thawing interface critical depth, through the comparison of test results with different water content of critical depth *H*, as shown in Fig. 6.

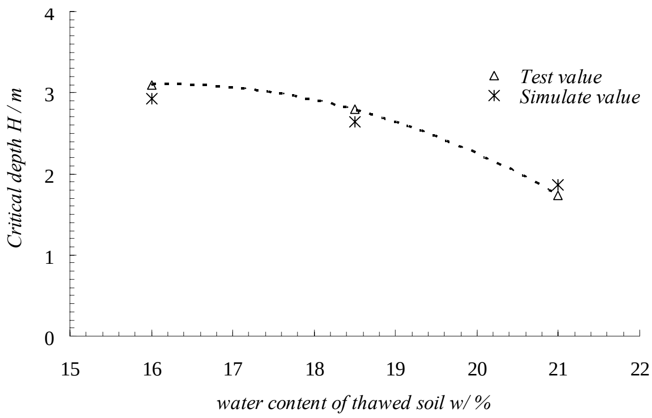


Fig.6 The critical depth comparison with different water content

It can be found that, with the water content increasing, the critical depth is decreasing. This is due to the soil cohesion value decreased as water content changing, so the corresponding critical height becomes lower. The test result coincides with the reality.

C. The critical depth comparison with different F-T times

Based on the experimental results, Fig. 7 compares the relationship of critical depth value *H* of slope sliding surface and freeze-thaw cycle times *n*, under the water content of 18.5%.

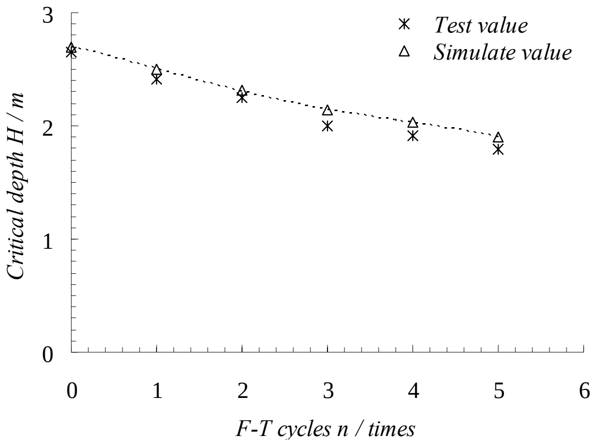


Fig.7 The critical depth comparison with different F-T times

It illustrated that by the increasing in the number of freezing and thawing times, the critical depth result is decreasing, and the tendency is mitigating. This is due to the freezing and thawing times increasing, soil void ratio increases gradually, while tending to critical void ratio, the soil gradually stabilized.

D. Critical depth damage coefficient of the freezing-thawing

In view of the water content is the direct influence factor of slope stability, the fitting analysis of critical depth under optimal water content 21% is carried out. For quantitative analysis of freeze-thaw cycle times on the landslide section critical depth, definition:

$$\eta = \frac{H_N}{H_0} \qquad (13)$$

In which: η ——Critical depth damage coefficient of the freezing-thawing;

H_N ——The critical depth of the soil slope after *N* F-T cycle times;

According to the test data, using the generalized least squares method, the test results are analyzed, the landslide damage model for critical depth analysis of soil slope in seasonal frozen area is determined:

$$\eta = 0.452 \times e^{-0.252 \times n} + 0.548 \qquad (14)$$

In which: *n*——F-T cycle times.

The damage fitting model is compared with experimental results, and is shown in Fig. 8.

It is demonstrated that with the increasing of cycle times of freezing and thawing, the interfacial shear strength of landslide damages, and the critical depth value is reducing, the limit data *H* can reach 55% of the original depth, which makes the original design reasonable slope structure, may be in the spring thawing period for the development of shallow landslide, and it should pay more attention to the slope design in season frozen areas.

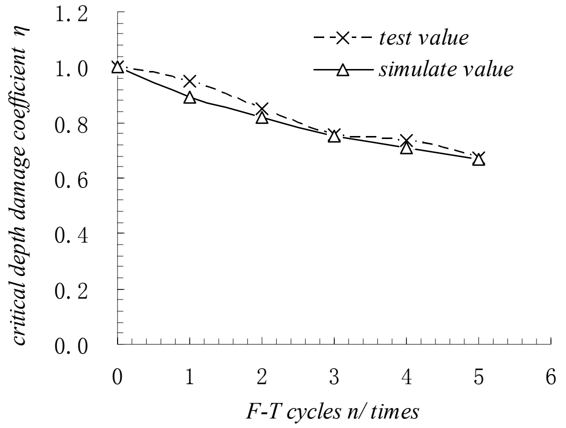


Fig.8 The comparison of the critical depth deterioration between the fit and test values

E. Safety factor according to F – T times of seasonal frozen slope

As reached the critical state, the critical safety factors are shown in Table 3.

Table 3 Safety factors under different F – T cycles

F – T cycles	0	1	2	3	4	5
Safety factors	1.09	1.15	1.19	1.24	1.27	1.30

It can be indicated that with the increasing of F – T times, the safety factors of reaching the critical state are also increasing. This illustrates that the soil strength varied with F – T times, and then the inner part of the slope formed the plastic throughout zone at higher safety factor state, and the failure occurred. The calculating results also illustrate that if the slope experienced more F – T times, it is more negative to the slope stability.

Conclusions

In seasonal frozen area, road slope shallow slip disease usually occurs. As certain the damage location and damage morphology is very important for the reasonable design and structure safety. The physical characteristics of freezing point of water freezing brine is lower than that of the common water is adopted, based on which a set of experiments were designed, and the glide slope shape and depth of the test results were obtained.

(1) To the same soil, respectively with 1% saline water and ordinary water preparation, by the volume ratio of 2:3 specimens, the temperature of -3℃, in two kinds of material interface implementation of freezing and thawing interface.

(2) Adopting corresponding device for soil slip resistance test, test results show that the soil slope sliding in seasonal frozen areas, sliding body is a rectangular body, and the slip surface is approximately for a plane.

(3) With the increasing of freezing and thawing cycle times, slope slip critical depth damage model, according to the results, was fitted out by freeze-thaw cycles with different soil conditions, and would present more reference to design and construction of soil slope in seasonal frozen areas.

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