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Analysis on stability of slope in a typical cold region based on thermo-mechanical coupling

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Factors which affect slope stability in cold regions are more complex than in normal temperature region. Physical and mechanical properties of rock and soil vary greatly in the process of freezing and thawing cycle. And the slope stability also changed with this. In this paper, the numerical simulation method was used to analysis temperature distribution of rock and soil in cold area and the displacement of slope affected by temperature based on phase transition of rock and soil in cold regions. The paper also analysis the change of slope stability in the different freeze-thaw cycles, freeze-thaw depth and water content of slope by establish a stability analysis model.

Keywords: stability analysis; stability of slope; thermo-mechanical coupling; cold regions

INTRODUCTION

As a typical representative of the cold regions, the slope stability of Tibet is influenced drastically by temperature. The physic-mechanical properties and initial properties of geotechnical material after freezing and thawing cycle changes to some extent. And the stability of the slope depends largely on the physic-mechanical properties of rock-soil mass [1]. So the damage and frost heaving of rock-soil mass in cold regions engineering affected by temperature amplitude, alternating frequency, moisture content and its mechanical properties, etc [2,3].

The stability of slope in cold regions is closely related to the temperature distribution. External temperature effects the temperature field distribution inside the slope. At the same time, we also need to consider the effect of heating and phase change process on the slope [4]. Besides, freezing and melting process have a great influence on the stability of slope as well. So the stability conditions have great difference with normal temperature region [5, 6]. In this case, it is significant to study the slope stability in cold regions.

THE FORM OF SLOPE FAILURE IN ALPINE REGION

Thaw slump. Thaw slump is the unique form of instability in permafrost region [7]. It is generally occurred in the excavation disturbance. The thermal equilibrium state of shallow slope is rapidly destroyed in a human disturbance conditions. Shear strength and cohesion of melting soil dramatic decrease for its saturated state in the condition that the quickly enrichment of water after melting. So the melting soil will slide along the frozen layer under itself weight in this condition. This type of landslide often happens in the summer melt season. Its specific form is as shown in figure 1.

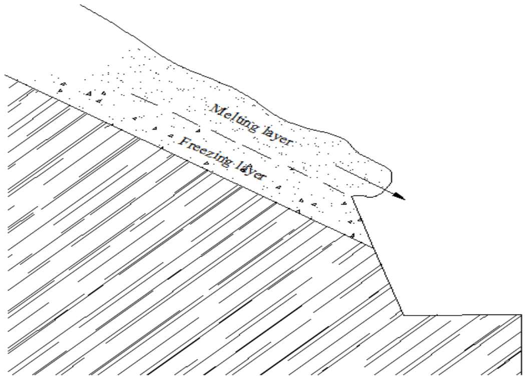

Fig. 1. Sketch map of thaw slump.

The collapse of rock slope. Freeze-thaw collapse usually occurred in rock slope [8]. That is because the crack of rock slope growth for its volume expansion after the rain penetrated into the primary pores and freeze, then the slope will collapse in the freeze-thaw cycle. The instability process is as shown in figure 2.

Slope stability is closely related to the temperature field distribution. Soil slope failures are usually happed at the melting period and their stability are closely related to the melting depth. But the major form of rock slope failures is shallow collapse which is related to the depth of the freeze-thaw cycle effect. So if we want to analyze slope stability, the first thing we need to determine is the influence of temperature on geotechnical engineering.

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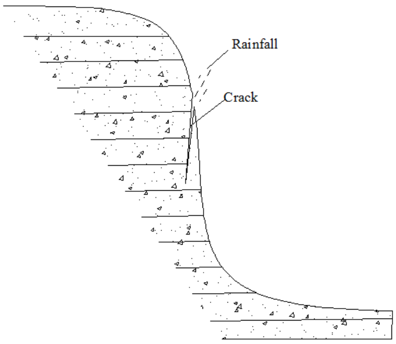
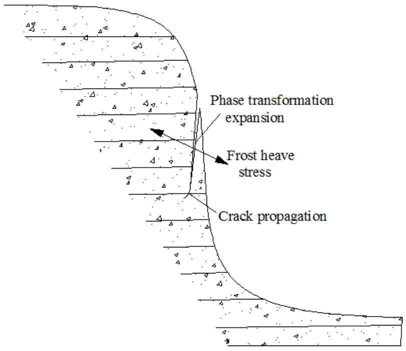
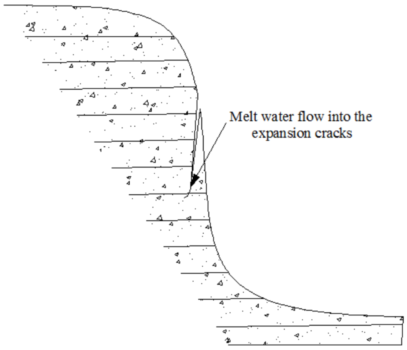


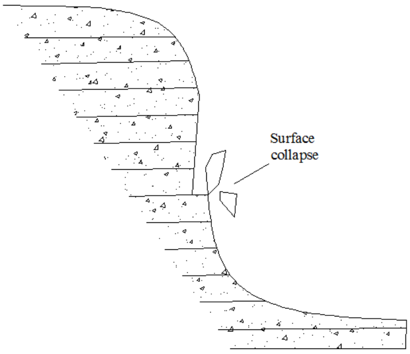
(a) Hydrating process



(b) Phase change and crack extension



(c) Melt water flow into the extension fractures



(d) Surface collapse

Fig.2. Sketch map of freeze-thaw collapse.

THE THERMO-MECHANICAL COUPLING ANALYSIS OF SLOPE

A slope of hydropower in Tibet was chosen as an example to research. The rock of slope mainly contains the unweathered diorite porphyries and strongly weathered diorite porphyries, and its surface is soil-rock-mixture covering layer which thickness is 3-6m. The slope model is set up based on these dates. The thickness of covering layer of model is select 5m. Slope profile is as shown in figure 3 and the finite element mesh is as shown in figure 4.

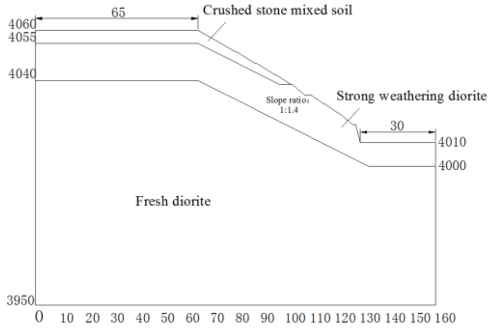


Fig.3. Sketch map of slope profile.

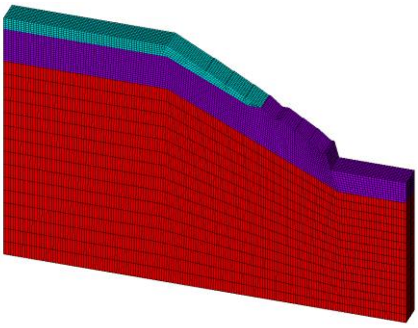


Fig.4. The finite element mesh.

The setting of temperature boundary conditions is important to analyze the temperature. It is the drive to make heat transfer occurrence and development. There are three kinds of thermal boundary conditions.

(1) The value of temperature on boundary surface is given and the value is a function of time and space.

(2) Define the heat flux density on boundary surface as a known function.

(3) Define the state of heat convection on boundary surface.

The surface of slope is mainly influenced by air temperature. The periodic change of external environment temperature cause the change of slope surface temperature, and this main performance is the convection heat transfer between slope surface and air. According to the above classification boundary conditions and the establishment of the geometric model, the surface and plain stage of slope choosing the first boundary condition which the temperature changed with time was given based on the local climatic conditions. Both sides of the model chose the adiabatic boundary conditions for the slope temperature changes have little effect on the temperature outside the slope angle. And bottom boundary is input constant temperature.

Climate of Lhasa is semi-arid plateau temperate monsoon climate zone and its annual sunshine has 3000 hours. So the temperature changes can be simplified into the following trigonometric formula according to its features.

$$T(t) = T_0 + A_0 \sin(\frac{2\pi}{365}t + B)$$

T_0 is the average temperature of slope surface and its value is 1°C based on the climate data. A_0 is the temperature amplitude and its value is 16°C based on the climate data. B is the initial phase for calculation.

The first step to solve the temperature field is to determine the initial temperature field. And the initial formation temperature field determines the accuracy of the unsteady temperature field analysis. Thermal analysis parameters are in Table 1. The initial temperature distribution is as shown in Figure 5.

The temperature field distribution inside slope changes with ambient temperature. That means the heat will be passed out from the high temperature to low temperature due to the temperature gradient. Surface temperature began to decline when it is higher than the ambient temperature and the shallow section begins freezes in this time. Figures 6 to 11 are the temperature contours of the freezing (Nov., Dec. and Jan.) and thawing (Mar., Apr. and May.) period.

As it can be seen from figures 6 to 8, depth of freezing increased over time in freeze period. The changes of slope surface temperature are more obvious than the changes of deep rock mass which reason is that freeze is only in a certain degree of shallow part. And figures 9 to 11 show that when the surface temperature of the frozen section rises, the shallow part firstly began to melt and there are still frozen in the center of the freezing layer.

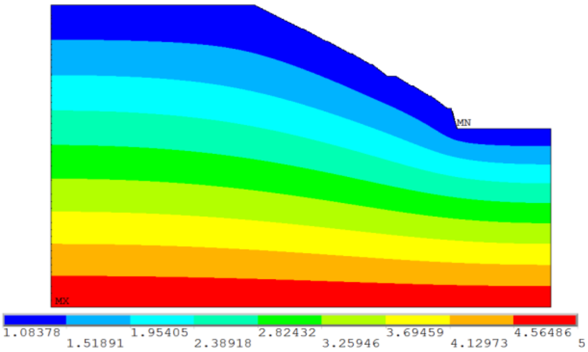


Fig. 5. The initial temperature field contours.

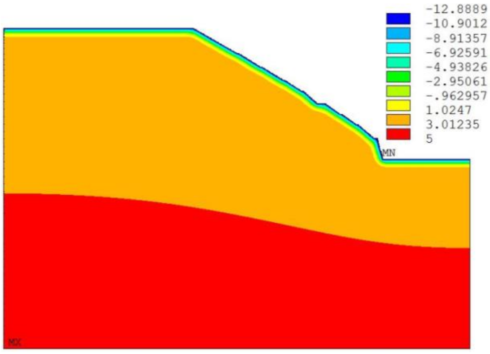


Fig.6. Temperature field contours of Nov.

Table. 1. Thermal analysis parameters

sample	status	specific heat capacity J/(Kg·k)	thermal conductivity W/(M·k)	enthalpy $10^7 J/m^3$
gravel	freeze	1833	1.95	2.762
mixed soil	melt	2043	1.72	3.329
strongly weathered diorite	freeze	1109	1.99	2.901
	melt	1235	1.83	3.521
unweathered diorite	freeze	1077	1.98	2.698
	melt	1140	1.90	3.281

Take a temperature of characteristic point every 1 meter along the normal direction inside slope from the top of the hill covering layer and strongly weathered layer until 5 meter. Then the changes trends of freezing and melting temperature with depth are plotted in Figures 12 and 13.

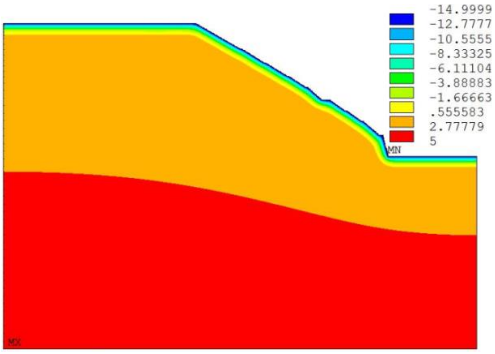


Fig. 7. Temperature field contours of Dec.

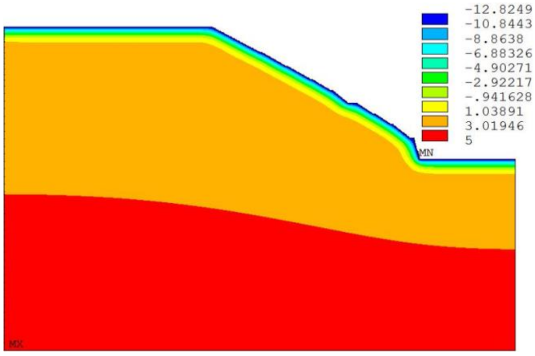


Fig. 8. Temperature field contours of Jan.

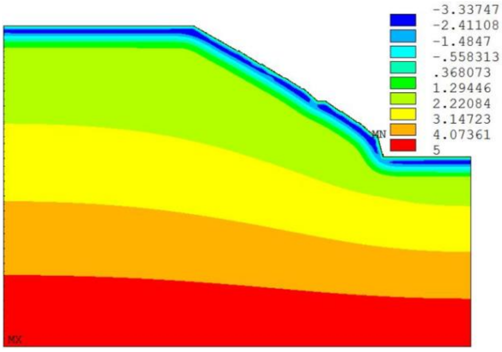


Fig. 9. Temperature field contours of Mar.

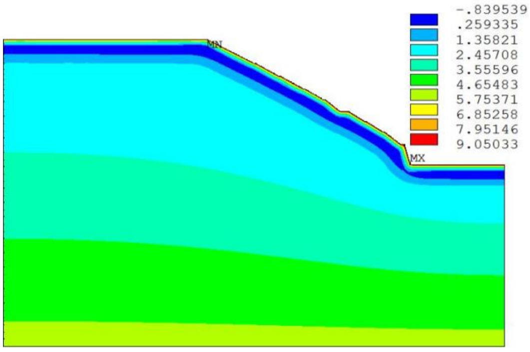


Fig. 10. Temperature field contours of Apr

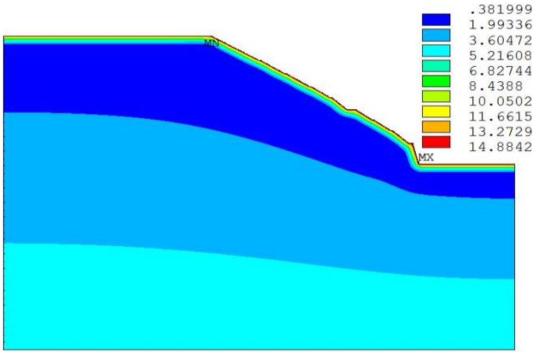


Fig. 11. Temperature field contours of May.

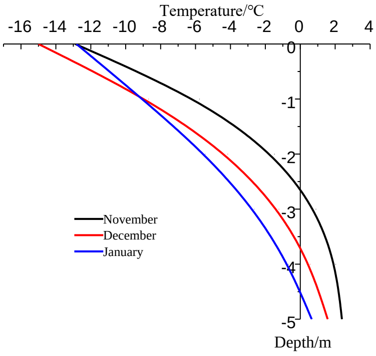


Fig. 12. Changes of temperature in freezing period

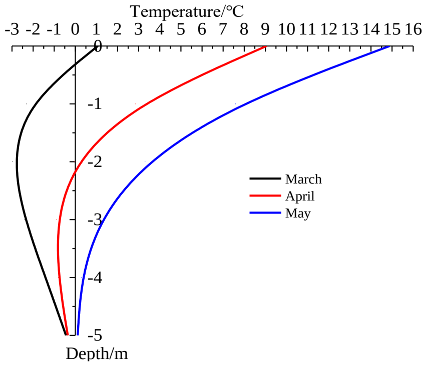


Fig. 13. Changes of temperature in melting period.

From the figures 12 and 13 we can find that the change of the depth is more hysteresis than the shallow's. That means effect of temperature on the deep rock mass is much smaller. Apparent from the figure the temperature of melt in the vertical direction have two times to cross over the phase-change interval. So in the slope, the freezing and thawing times of rock and soil vary from different depths.

In view of the rock and soil in cold regions affected severe by temperature, the figure 14 and 15 are the change of rock displacement simply caused by thermal effects. And the figure 16 is a tendency of rock displacement caused by frost heave and thawing-settlement.

In figure 14 and 15 the trends of vertical displacement of the slope versus time consistent with the change of ambient temperature. Because the magnitude of displacement is closely related to temperature loads. When the temperature changed in the same, the displacement generated by the thermal expansion is less than the displacement of gravel mixed soil.

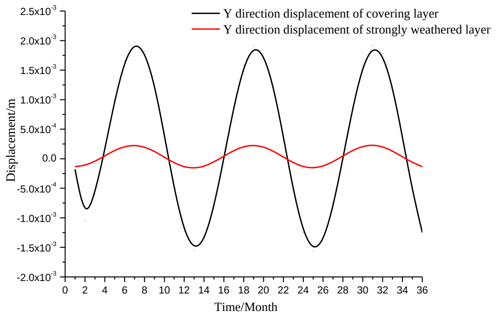


Fig. 14. Vertical displacement versus time curve of surface in different properties of rock and soil slope.

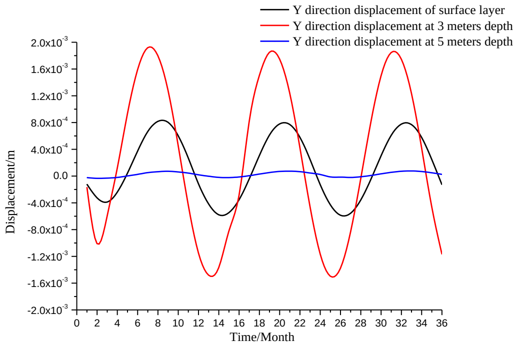


Fig. 15. Vertical displacement versus time curve under different overburden depth.

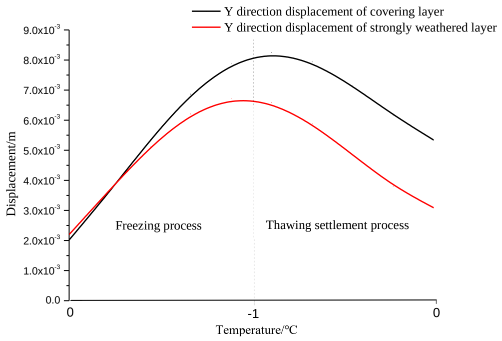


Fig. 16. Vertical displacement versus time curve of surface in different properties of rock and soil slope considered frost heave and thawing-settlement.

That is because the thermal expansion coefficient of diorite is less than the coefficient of thermal expansion of cement mixed soil. As it can be seen from Fig. 16, the displacement of rock and soil caused by phase transition in slope has the opposite trend with the change of temperature. When the temperature drops, unfrozen water phase becomes ice and its volume expansion. When the temperature rises, the ice melted and its volume decreases. Since the coefficient of linear expansion of the freezing and thawing process is so great that the shift change during the phase transition is more intense then it simply caused by the heat.

THE SLOPE STABILITY ANALYSIS

The slope stability analysis is to the rock slope and the soil slope, and the materials partitions of these slopes shows in the figure 17 and 18. The calculation parameters are as show in the table 2 and 3.

Table 2. Physical and mechanical parameters of the rock slope.

sample	density(kN/m^3)		shear(breaking) Strength				elastic modulus	Poisson's ratio
	dry	saturation	air-dry		saturation			
			C(KPa)	ψ(°)	C(KPa)	ψ(°)	E(GPa)	μ
strongly weathered diorite	24.9	25.6	100	37	40	35	3	0.34
unweathered diorite	26	26.3	130	49	50	47	40	0.26

Table 3. Physical and mechanical parameters of the soil slope.

soil type	water content	severe（KN/m^3）	elastic modulus（MPa）	Poisson's ratio	cohesion（KPa）	angle of internal friction（°）
thawed soil	11.80%	18.00	5	0.38	15.20	28.70
	13.06%	18.20	5	0.38	12.93	28.49
	14.17%	18.38	5	0.38	11.02	28.40
	15.40%	18.58	5	0.38	9.52	28.21
	16.80%	18.80	5	0.38	7.74	28.10
normal temperature soil	-	17.00	6	0.35	28.00	30.00
frozen soil	-	18.00	30	0.32	40.00	28.00

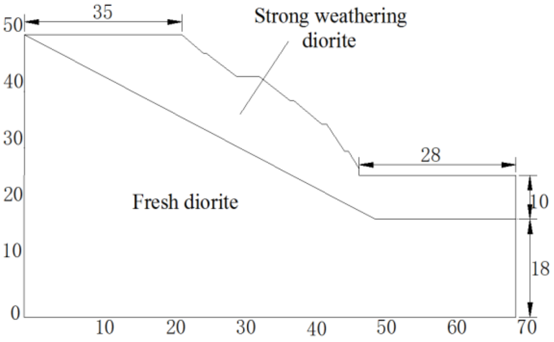


Fig. 17. Model of the rock slope.

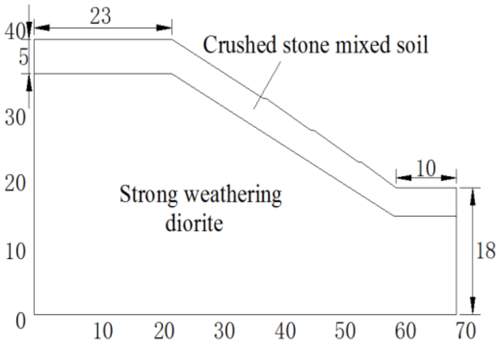


Fig. 18. Model of the soil slope.

For the rock slope, the temperature field of the shallow slope is mainly affected by the temperature change in the cold regions. The rock intensity of the shallow slope moves down in a certain degree as the thawing depth and the Freezing-thawing cycles increase. To explore the impact of freezing-thawing on the slope stability, the freezing-thawing deterioration is set as 10% and using the strength reduction method analyses the stability in the different freezing-thawing thickness(0m, 1m, 2m, 3m and 4 m). The safety factor and the shear strain increment cloud of 2m freezing-thawing thickness show in the figure 19. Figure 20 shows the variation of the safety factor.

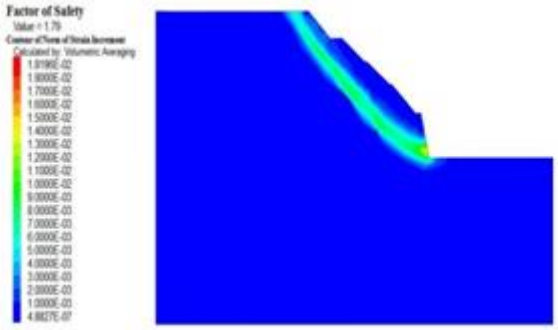


Fig. 19. Safety factor and shear strain increment cloud.

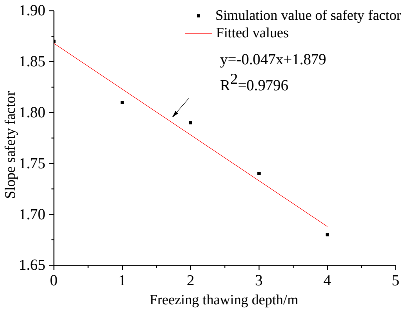


Fig. 20. Relations of the freezing-thawing thickness and safety factor.

Figure 20 shows that the safety factor of the slope is 1.87 in normal state (the freezing-thawing thickness is 0m). The safety factor linearly moves down as the freezing-thawing depth increases. The safety factor is only 1.68 when the freezing-thawing thickness is 4m, and the safety factor decreased by 10%. Therefore, with the expansion of the temperature, the stability of the rock slope decreases.

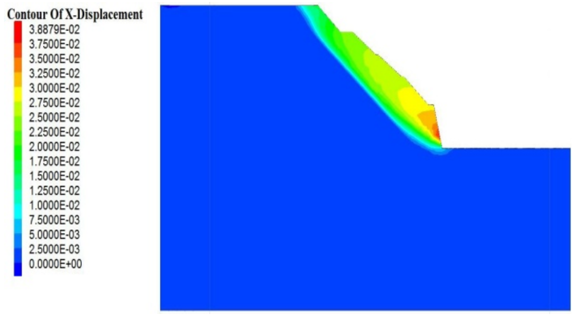


Fig. 21. Displacement vector in x direction of thaw layer which thickness is 2m.

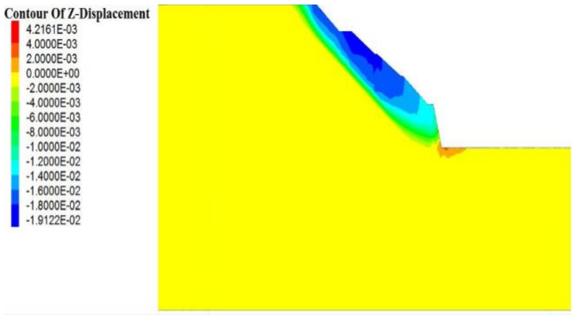


Fig. 22. Displacement vector in z direction of thaw layer which thickness is 2m.

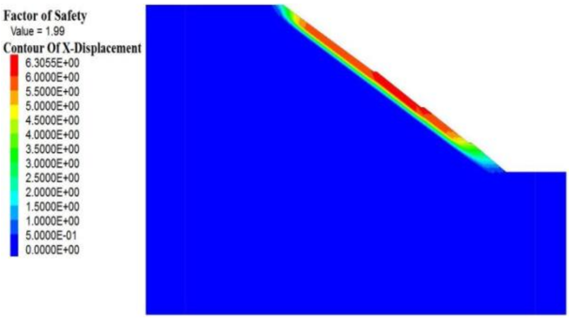


Fig. 23. Displacement contour under the critical state of slope(the water content: 11.80%, the thawing depth: 2m)

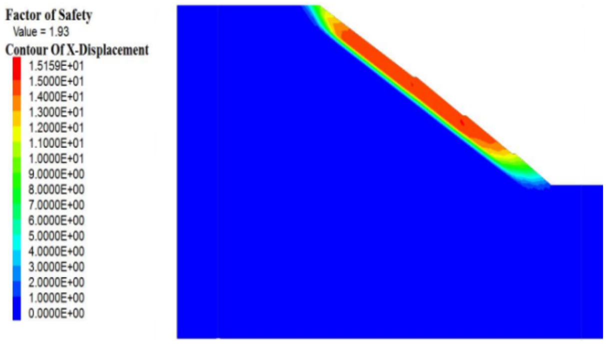


Fig.24 Displacement contour under the critical state of slope(the water content: 11.80%, the thawing depth: 3m).

As can be seen from figure 21, X direction of displacement gradually increase along the slope downward and obvious stratification at 2m freeze-thaw unstable situation at the critical layer thickness. The maximum displacement in the x direction is located at the foot of the slope, which is located at the node level of destruction toe. As can be seen from figure 22, the vertical displacement of rock slope mainly concentrated in the top of the hill and gradually reduced along the top of the hill down gradually. Due to the slope of the upper rock mass has a negative displacement, when slope toe will be squeezed, positive displacement in the slope toe.

For soil slope, the melting depth and water content is closely related to the stability of the slope. In order to study moisture content and melting depth effect on the stability of soil slope, the slope stability safety coefficient Fs is obtained by using the strength reduction in moisture content is 11.80%、13.06%、14.17%、15.40%、16.80% and the melting layer thickness in 1-4 m.

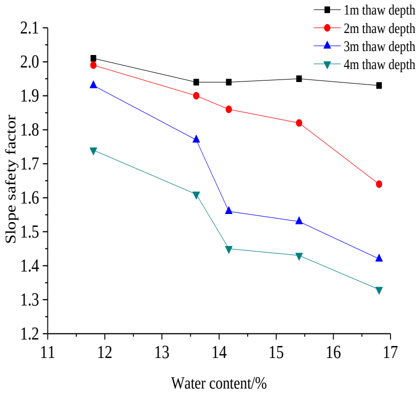


Fig. 25. Relations of the water content and the slope safety factor.

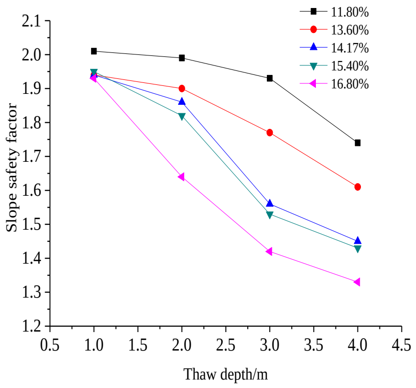


Fig. 26. Relations of the thawing depth and the slop safety factor.

Figure 23 and 24 show that the failure of the soil slope usually occurs in the shallow parts of soil and the slip surface located in the thawing interface. The slip surface gradually moves down as the thawing depth increases. The slipping body in a critical state is a ribbon and some parts of the soil at the foot of the slope has upward trend when the slope is in a thawing state. The reason is that the bottom of the slipping body is arcuate and the soil under the arc gradually moves up due to the pressure of the soil above the arc. This is consistent with the actual situation of the slipping slope in the hot-thawing state.

Figure 25 shows that the safety factor decreased as the water content increases. However, the variation of the safety factor is not obvious when the thawing depth is 1m. The safety factor is 1.93 and 2.01 when the water content of the slope is 16.80% and 11.80%, and the safety factor decreased by only 4%. Therefore, the slope stability and the water content are less relevant. The impact of the water content to the slope stability becomes obviously as the thawing depth increases. The safety factor is 1.74 and 1.33 when the water content is 11.80% and 16.80%, and the safety factor changed 24%.

Figure 26 shows that the safety factor changed 13.4% when the water content is 11.80% and the thawing depth goes from 1m to 4m. The safety factor changed 31.1% when the water content is 16.80%. The impact of the thawing depth on the slope stability becomes significant as the water content increases. The angle of internal friction and cohesion is mainly determined by the thawing depth and the water content. And the cohesion changed 49% when the water content goes from 11.80% to 16.80% and the angle of internal friction is close. Therefore, the decrease of the cohesion is the essential reason for the slope collapse.

CONCLUSION

This paper makes some research on the slope stability condition under the effect of temperature in cold regions, drawing the following conclusions:

The main influence of external temperature on the temperature field of the slope is shallow part, the shallow part of the temperature cycle changes significantly and the deep part of the temperature field is consistent of the initial temperature field.

In the non phase transition region, the displacement of the slope is similar to that of the change of the environment temperature; Compared to the strong weathered layer, the change of the displacement of the cover layer is more significant. In the phase transition region, the change of slope displacement is opposite to the change of environment temperature. And under the same temperature change, the deformation of the non phase transformation zone is smaller than that of the phase change region. In the cold regions, the phase transition caused by freezing and thawing cycle is the primary factor causing the deterioration of rock mass.

The stability condition in rock slope and the effect range of freeze-thaw cycle are closely related to the number of freeze-thaw cycles. With the deepening of the freeze-thaw depth, the slope stability safety factor decreased significantly, the influence range of freezing and thawing is closely related to the temperature peak value and the number of freeze-thaw cycles is related to the temperature change cycle. So the lower of the temperature and more frequent changes in the temperature, the worse the slope stability. The stability of soil slope is closely related to water content, and when the water content is lower and the melting depth is lower, the slope stability is not changed much with the normal temperature slope and as the increase of the water content and the depth of melting, the stability of the slope decreases rapidly.

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