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Study of water migration and frost heave of an articulated concrete slope under freezing and thawing

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Abstract. To study the frost heave and water migration behaviors of an articulated concrete block slope undergoing freezing and thawing, based on a similar experimental theory for permafrost, the time and geometric dimensions of the model were analyzed, using articulated concrete for slope protection. An experimental study on the frozen soil slope was conducted, and we reached the following conclusions. With increasing soil depth, the soil temperature was gradually weakened by the ambient temperature, which is consistent with the results of the numerical simulation of the temperature field. The maximum freezing depth of the experimental section of the hinged concrete slope was 7.2 cm, and the maximum freezing depth was 2.3 cm in the soil slope section. AC (Articulated hinge concrete) slope protection had a strong inhibitory effect on the development of the frost depth. The maximum frost heave of the channel slope occurred at 1/3 of the slope height. After the freezing and thawing test, the channel slope had residual frost heave deformation, with maximum residual deformation at 1/7 of the slope height. After freezing and thawing, the moisture content of each layer was redistributed; the water migration in the channel after freezing and thawing was greater than that at the maximum freezing depth, and the migration of the soil slope was notably greater than that of the AC slope protection.

Key words. Frost heave, water migration, frost depth, freezing and thawing.

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1. Introduction

Approximately 98.9% of area is covered by permafrost in china; the area of seasonal frozen soil affected by channel construction is 137,000 km^2 [1]. For groundwater-level shallow channels, protection from and treatment of frost heave damage to slopes in seasonally frozen soil are technical problems that need to be solved [2−5]. Hinged concrete block slope protection is a new type of slope protection that can meet ecological requirements, such as revegetation and soil and water conservation. It is an ideal slope protection material[6−8].Researchers worldwide have increasingly studied the mechanical damage resulting from frozen soil undergoing seasonal freezing and thawing[9−13], but the physical properties of frost heave and water field changes have been studied less [14−16]. This study, combined with the " North Conveyance " area of Heilongjiang Province, evaluated the mainline canal climate, groundwater level, and other engineering conditions. According to the contrast between indoor articulated concrete slope protection and a soil slope model test, the changes in the temperature field, frost heave, and water migration of the channel slope were studied.

2. Test materials and methods

2.1. Test equipment and material parameters

The test equipment consisted of a low-temperature laboratory, PT100 temperature sensor, displacement sensor, DT515 data acquisition system, oven, and other equipment, as shown in Fig. 1.

Test soil was taken from the "North Conveyance" project test section. Using the standard soil test method (GB/T50123-2007) [17], the soil particle gradation was measured, and the soil particle gradation curve was drawn. The test used hinged concrete measuring 0.45 m *0.44 m * 0.15 m, meeting the requirements of strength grade C30 and frozen level F300. The articulated concrete is an ecological revetment structure that has a permeable, porous, plant-able surface, and other engineering features.

Table 1. Basic physical parameters of soil samples λ for a trapezoidal plate for different values of taper constant β_1 and constant aspect ratios $a/b = 1.0$, $c/b = 0.5$

Fig. 1. Basic testing equipment

parameter name	Unit	Value
Moisture content (ω_0)	%	13.2
Dry density (ρd)	g/cm3	1.67
The proportion of soil (GS)	-	2.73
Porosity ratio (e)	-	0.803
Saturation (S)	%	96
Liquid limit (WL)	%	35.6
Plastic limit (WP)	%	19.8
SL-237-2007 classification		the slay of low liquid limit (CL)

2.2. Test method

2.2.1. Model test design and performance Similar to how the analysis of a thermal model is conducted by using the integral analogy method [19−21], model time scale is the square of the geometric scale, The soil samples were selected such that C_a=C_q=C_m =1 and simulated the measured temperature at the scene, C_t=1, so this is C_t=C_l^2,Based on the size of the model chamber and practice of the " North Conveyance " trunk slope, the geometric similarity theory was used to simplify the test slope model, so the geometric scale of the model is C_L = 1: 4, as shown in Fig. 2. Before the experiment, the model was saturated with water and the soil saturation after the water needed to reach the top foot of the channel to ensure that the bottom of the channel was without water, as shown in Fig. 3.

2.2.2. Temperature control scheme The field temperature of Wu Nan, chmetcn-vUnitNamekmSourceValue54HasSpaceTrueNegativeFalseNumberType1TCSC054 km

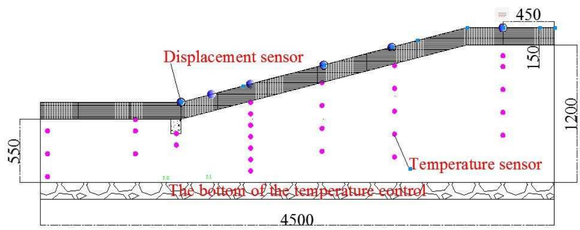

Fig. 2. Channel model cross section

Fig. 3. Process of constructing the channel slope model

distant from the "north-sited" channel, was the basis for temperature control, as shown in Fig.4. Since the geometric scale was C_L = 1:4, the time scale was $C_t = C_l{}^2$ = 1:16. The experiment used a cooling scheme to control the development process of the frozen depth, simulating the slope from the beginning of freezing through the complete melting process. The experimental temperature control was simplified into four stages: the cooling stage (AB), low-temperature constant-temperature stage (BC), heating stage (CD), and high-temperature constant-temperature stage (DE). The time of the freeze-thaw cycle temperature control was 144 h, as shown in Fig. 5. To simulate the warmth of the underlying natural soil layer, based on field conditions and test experience, the floor temperature was controlled at 3.0 ˜ 4.0 .

3. Test results and analysis

3.1. Soil temperature changes with time and frozen depth

The experiment simulated a one-way freezing process and a two-way melting process. Comparisons between the temperature of the AC slope and temperature of the soil slope were made, as shown in Fig. 6. At chmetcnvUnitNamecmSourceValue9.5HasSpaceTrueNegativeFalseNumberType1TCSC09.5 cm from the top of the

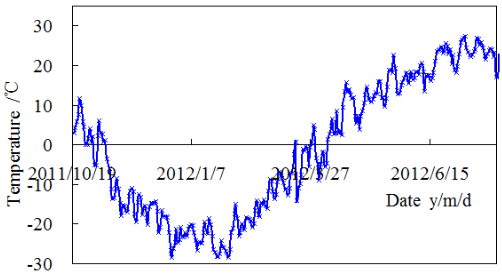

Fig. 4. External ambient temperature (2011-2012)

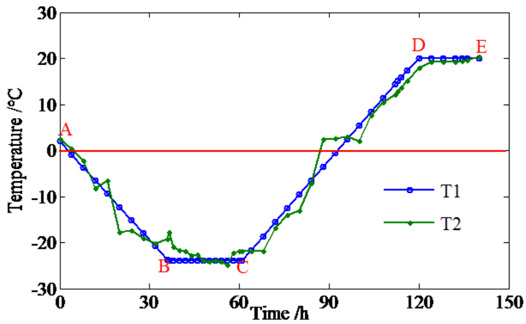

Fig. 5. Freeze - thaw cycle temperature control process

channel slope, the AC slope and soil slope temperature trends and test environment temperature were consistent, but the minimum temperature at 9.5 cm in the soil layer of AC slope was 0-5.7 , while the minimum temperature at 9.5 cm in the soil layer of soil slope was 0-7.7 . At a depth of 29.5 cm in the soil layer of the AC slope, the lowest temperature was 0.8 at the end of the experiment. During the 102h test run, the soil slope reached its minimum recorded temperature of 0-2.1 . In addition, the remaining soil layer's temperature continued to decline until the end of the test. Therefore, on the one hand, the results show that AC slope protection can attenuate the influence of the ambient temperature on the soil temperature. On the other hand, with increasing soil depth, the effect of this temperature attenuation was lessened. Fig. 7 shows the development, at the top of the channel, of the freezing depth over time. The maximum depth of freezing of the AC slope was 27.2 cm, and the maximum freezing depth of the soil slope was 42.3 cm. Obviously, development of the frozen depth was inhibited by the AC.

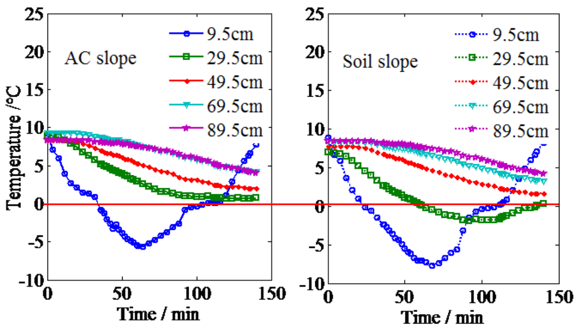

Fig. 6. The temperature at the top of the channel slope

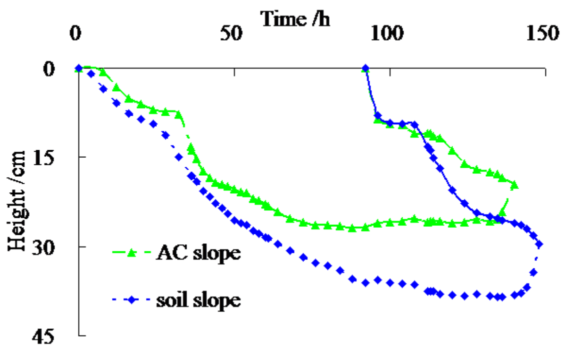

Fig. 7. Development of the freezing depth

3.2. Analysis of water migration

Fig. 8 shows the change in water migration at the top of the channel. The distribution of the soil moisture were studied. Based on the distribution of the overall moisture content, the migration of the soil moisture was affected by the temperature potential, leading to migration of soil moisture to the upper part; thus, the soil moisture in the upper part increased, and the upper part of the soil contained the peak soil moisture. From the comparison of the positions of the water migration in the AC slope and soil slope, the maximum water content of the AC slope and soil slope were at a at depths of 25cm and 35cm, respectively; the position of the maximum water content of the soil slope was deeper. Endorse: A1/A2-The initial water content, B1/B2-Water content at the maximum frozen depth of the soil slope, C1/C2-Water content of the soil slope after freezing and thawing

3.3. Analysis of frost heave

To study the amount of frost heave in channels with different slope configurations (1/7 H, 1/3 H, 1/2 H, and 3/4 H), the frost heave amounts at the maximum freezing

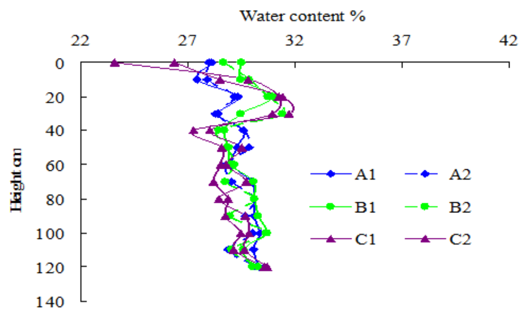

Fig. 8. Changes of water migration in different slope soils

depth and at the end of the freeze-thaw cycle were calculated, as shown in Fig. 9. As seen from Figure (a), when the channel slope was frozen to the maximum frost depth, the maximum frost heave amount in the histogram was at 1/3 of the slope height, maximum frost heave amount of the soil slope was 31.02 mm, and maximum frost heave amount of the AC slope was 25.06 mm. As seen from Figure (b), the maximum amount of residual deformation was at 1/7 of the slope height at the end of the freeze-thaw cycle of the channel slope, maximum residual deformation of the soil slope was 8.72 mm, and maximum residual deformation of the AC slope was 6.24 mm. From the comparison between the frost heave of the AC slope and soil slope, the trend of the frost heave amount at the maximum freezing depth and freezing and thawing cycle was the same, and the frost heave of the AC slope was less than that of the soil slope, demonstrating that the AC slope protection had a strong inhibitory effect on the frost heave, which was beneficial to the stability of the channel slope.

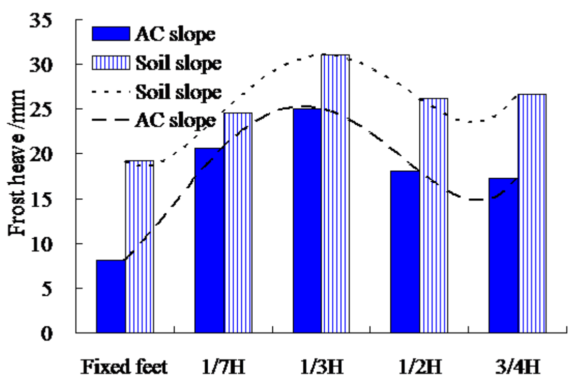

Fig. 9. Maximum frost depth at different slope height

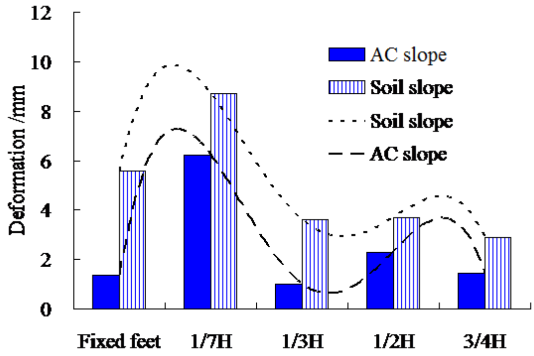

Fig. 10

4. Numerical simulation of temperature field

4.1. Basic assumptions

The soil of the channel model was homogeneous, continuous, and isotropic. Water evaporation and the roles of salt and other chemical potential fields were ignored. The external load of the hinged concrete lining was ignored, and the heat conduction was assumed to be uniform and seamless.

4.2. Basic equations and thermodynamic parameters

Based on the law of conservation of energy, ignoring the convective heat transfer term, the equation for the temperature field of the freezing process is: The physical parameters of the soil layers needed for the calculation are summarized in Table 2.

Boundary conditions: Initial conditions:

Table 2. Thermal parameters of soil permafrost

Sequences	From	Frames	Resolution
Ballroom	MERL	250	640×480
Vassar	MERL	250	640×480
Exit	MERL	250	640×480
Race1	KDDI	300	640×480
Ballet	Microsoft	100	1024×768
Breakdancers	Microsoft	100	1024×768
Doorflowers	HHI	150	1024×768
Jungle	HHI	250	1024×768

4.3. Analysis and numerical simulation results of the temperature field

Taking the simulated temperature and actual temperature at the end of the freeze-thaw experiment in the channel with the AC slope protection as an example, as seen from Fig.10, the simulated temperature better reflected the actual temperature of the end of the freeze-thaw experiment in the channel.

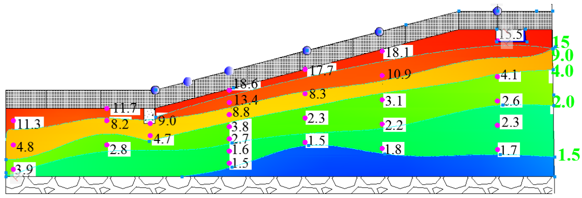

Fig. 11

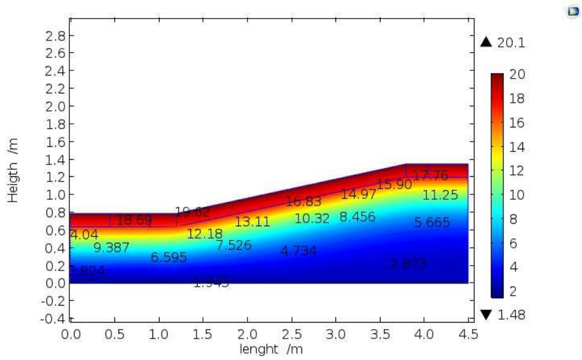

Fig. 12. Fig.10 the simulated temperature and actual temperature of AC slope

5. In conclusion

1. With increasing soil depth, the temperature of the soil layer was less influenced by the ambient temperature, and the protection of the AC slope was able to lessen the influence of the ambient temperature on the soil temperature. The protection of the AC slope certainly had an inhibitory effect on the development of the frozen depth.

2. Affected by the temperature potential, the channel's soil moisture moved to its upper part. Water migration after freezing and thawing was greater than the change in water migration at the maximum freezing depth. The protection of the AC slope inhibited the water migration.

3. The protection of the AC slope was consistent with the development process of the frost heave of the soil slope, but the protection of the AC slope can restrain the frost heave deformation caused by the change of ambient temperature.

4. The numerical model of the temperature field established in this study can accurately predict the variation of the permafrost temperature field, and can be

used as a basis for further estimates of frost heaving and melting deformation of the channel.

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