Numerical Analysis of Temperature Field Distribution of Road-bridge Transition Section in Permafrost Region

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Abstract. The COMSOL Multiphysics software is utilized to establish a comprehensive two-dimensional model for analyzing heat transfer and phase change in the transition section of road and bridge located in permafrost region. The temperature distribution of the transition section and subgrade in permafrost region is analyzed considering the global warming. The temperature changes in the transition section and subgrade at different distances from the abutment, with respect to freezing depth, are analyzed. It is observed that: (1) The variation in soil properties and temperature boundary conditions significantly impact the temperature field equilibrium process of the road-bridge transition section. In general, natural foundation achieves thermal equilibrium faster than soil behind the abutment; shallow soil reaches equilibrium quicker than deep soil. Moreover, near-abutment oil exhibits better thermal equilibrium compared to distant regions. (2) The thermal properties of different materials and the temperature boundary at the bridge transition section vary, resulting in a gradual decrease in the temperature field distribution with increasing distance from the abutment. At a farther distance, this influence can be ignored, leading to a gradually uniform temperature field distribution along the longitudinal bridge transition section.

Keywords: Permafrost regions; road-bridge transition section; temperature field; numerical simulation

1 Introduction

The Qinghai-Tibet Railway from Golmud to Lhasa is 1142 km long, of which 550 km is a continuous permafrost area. With the annual temperature on the Tibetan Plateau rising year by year and human activities intensifying, the stability of the permafrost area along the route is facing a huge challenge [1]. At present, the roadbed diseases in permafrost regions are very serious due to the heating and degradation of permafrost. Especially in the transition section of road and bridge, the uneven settlement caused by the poor rigidity of roadbed and abutment and the degradation of roadbed permafrost is the main disease at present. Many scholars have carried out some exploration and research in this aspect. Through the field investigation of the transition section of the Qinghai-Tibet Railway Bridge, Niu Fujun etal [2] summarized

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the relationship between the bridge trend, subgrade height, Subsoil type and the settlement of the transition section of the Qinghai-Tibet Railway Bridge, and summarized the correlation between the settlement of the transition section and various factors. Wang Jinchang et al [3]. summarized the basic law of settlement deformation, the process of settlement deformation and the causes of the transition section of the Qinghai-Tibet Railway in the permafrost region, and put forward guiding suggestions for the treatment measures of settlement. Through the continuous monitoring of the test section of the transition section of the Qingshui River Road-Bridge, Liu Jiankun et al [4,5]. Analyzed and derived the temperature changes and subgrade settlement deformation patterns at different locations of the transition section in cold regions. Yang Ke [6] employed COMSOL software to simulate the temperature field of the subgrade. The analysis reveals that road construction exerts a detrimental impact on frozen soil stability, and the roadbed temperature gradually increases with climate warming. Wang et al [7]. utilized finite element software COMSOL to establish a coupled calculation model for water and heat in frozen soil, investigating the short-term variation pattern of frozen soil temperature field during roadbed filling and proposing a calculation method for concave distortion of freezing front in roadbed coverage. Based on this, considering global warming, a numerical model is developed for the temperature field in the transition section of roads and bridges within permafrost regions on the Qinghai-Tibet Plateau., and the variation law of the temperature of the transition section and the subgrade after the abutment with the distance from the abutment is analyzed.

2 Numerical Calculation model

2.1 Engineering overview of the test section

In this paper, the actual project of a road-bridge transition section in Beiluhe of the permafrost region of the Qinghai-Tibet Plateau is selected. With reference to the gravel subgrade structure of a transition section in Beiluhe, the formation information of a subgrade in Beiluhe [8], and the typical railway subgrade section form, size and geological drilling data of other test sections [9,10], the following finite element calculation model was established for the road-bridge transition section in the permafrost area: the geometric model of the transition section is as follows: the length of the transition section is 11.0m, the height of the embankment is 6.5m, the transition section is filled with a stepped trapezoidal embankment, the longitudinal slope of the contact section between the transition section and the embankment is 1:2, the fill material is coarse-grained soil, and the total length of the embankment is 45.0m, with a layer of crushed stone laid on the base of the embankment.

2.2 Model establishment

The grid partitioning of the numerical model for the temperature field in the road-bridge transition section within permafrost regions is depicted in Figure 1. Triangular grid division is adopted. In order to better converge between the contact surfaces, the grid division of the contact surface between the pile and the soil is encrypted, and the rest is divided according to the ordinary triangle without encryption.

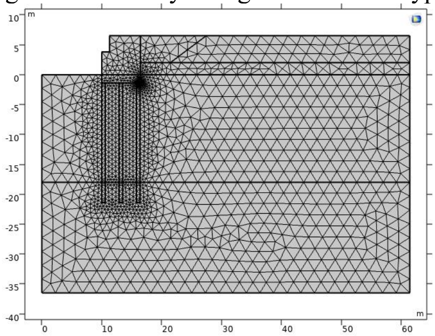

Fig.1. Numerical calculation model grid division diagram

2.3 Basic theory of temperature field

The primary issue encountered in the road-bridge transition section within the permafrost region of the Qinghai-Tibet Plateau is attributed to thaw-induced settlement. There is an ice-water phase change problem in the soil during the thaw settlement process. The latent heat of the phase change is treated as a heat source in the soil body in the unsteady heat transfer equation. In order to facilitate the calculation, the paper uses the sensible heat capacity method to solve the phase transition problem. It is considered that the unfrozen water content is only a function of temperature, and the ice-water phase transition only occurs in the phase transition temperature range [-1,0] degrees. The ice-water phase transition in the phase transition process of frozen soil is established by establishing a two-dimensional step smoothing function-Hayvieside function $H(T)$ (as shown in Figure 2). The expression:

$$H\_T(T) = flc2hs(T - T_{trans}, dT) \tag{1}$$

Where T is geothermal temperature(℃）, T_{trans} is phase transformation temperature points(℃）and dT is Half of the phase transition temperature range(℃).

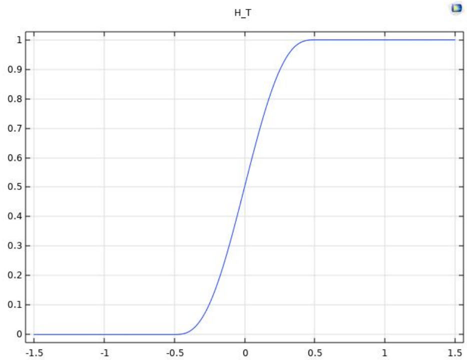

Fig. 2. Step function diagram

According to the principle of convective heat transfer in porous media, the heat transfer equation of soil under phase change is considered without considering the influence of deformation on temperature field:

$$\rho C\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\rho_i L\frac{\partial \theta_i}{\partial t} \tag{2}$$

Where T is Transient temperature of soil, ℃, t is The time of the process, s, k is Thermal conductivity of soil, $W/(m\cdot ℃)$, ρ is Density of soil, kg/m^3, C is The specific heat capacity of soil, $J/(\mathrm{kg}\cdot ℃)$, x、y is rectangular coordinate, m, L is Latent heat of phase change, for ice water phase change to take 335000J / kg, ρ_i is Density of ice, kg/m^3 ang θ_i is Ice content of soil.

2.4 Boundary conditions and physical parameters

In the established numerical model, there are three different boundaries, namely, the upper boundary, the lower boundary and the left and right boundary:

Upper boundary. Based on the principle of the boundary layer and long-term monitoring data from the Qinghai-Tibet region, we can simplify the upper boundary conditions of the calculation area into a trigonometric function form. Over a span of 50 years, there has been an observed increase in temperature by 2 °C in the Qinghai-Tibet region, the heating rate is 0.04℃/ year 。

$$T=T_0+A_0\sin(\frac{2\pi}{8760}t+\varphi)+\frac{R_0}{8760}t \tag{3}$$

Where T_0 is mean annual ground temperature （℃）, A_0 is Ground temperature amplitude （℃）, t is time （d）, φ is initial phase and R_0 is Temperature warming rate （℃/ year）, 0.04℃/ year .

The upper boundary temperature of the natural surface is：

$$T_1=-1.3+8\sin(\frac{2\pi}{8760}t-\frac{7\pi}{10})+\frac{0.04}{8760}t \tag{4}$$

The surface temperature boundary of abutment structure is：

$$T_2=-1+11\sin(\frac{2\pi}{8760}t-\frac{7\pi}{10})+\frac{0.04}{8760}t \tag{5}$$

Other boundary conditions. For the long-term on-site monitoring statistics of the Beiluhe test section of the Qinghai-Tibet Railway, the initial temperature of the numerical model is set to-1℃, and it is assumed that the annual average ground temperature in the region remains stable at the lower boundary. The lower boundary is

-1℃, for the Dirichlet boundary. The left and right boundaries are set to adiabatic boundaries. The thermal physical parameters of materials are the most important. The thermal conductivity λ , specific heat capacity C and latent heat of phase change L of various materials under different freeze-thaw conditions should be determined. The various thermal physical parameters are shown in Table 1.

Table 1. Thermal physical parameters of numerical model

Material	Depth m	ρ kg / m^3	λ_f J/(m·d·℃)	λ_u J/(m·d·℃)	C_f J/(kg·℃)	C_u J/(kg·℃)	L J / kg
coarse-grained soil	0~-4.5	2060	171072	1655792	1166	1358	11300
Gravel filler	0~-4.5	2100	129600	120960	870	1060	11333
rockfill	-4.5~-6.5	2100	33432	33432	880	880	0
silty clay	-6.5~-24.5	1920	155520	129600	1140	1270	37688
strong weathered mudstone	-24.5~-36.5	2200	216000	172800	1200	1350	19842

Note： The subscript f and u represent the freezing and melting states respectively.

3 Calculation Results and Analysis

In order to study the change law of freezing depth and abutment distance, the temperature field model is used to obtain the ground temperature distribution of different buried depths at different distances from the abutment. In this paper, it is considered that July 15 and January 15 are the highest temperature and the lowest temperature in one year respectively, and the freeze-thaw cycle commences on July 15, 2021 and serves as the baseline for predicting the distribution of temperature fields on the corresponding date of the following year.

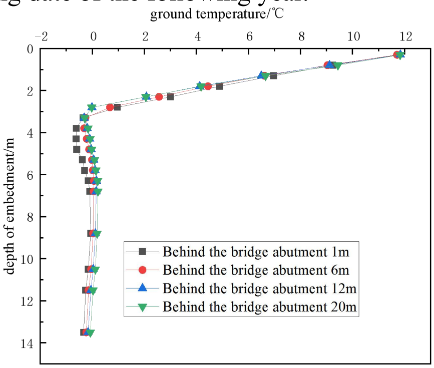

Fig. 3. On July 15,2021, the temperature distribution map of soil at different depths behind the platform

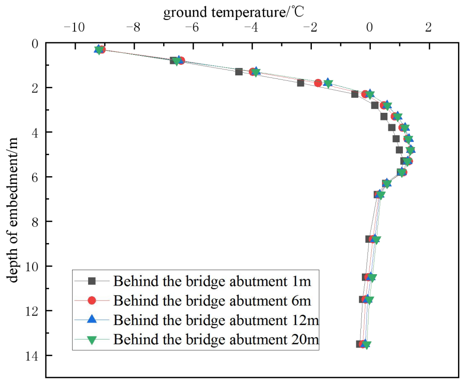

Fig.4. On January 15,2022, the temperature distribution map of soil at different depths behind the platform

From Figure 3 and 4, the ground temperature along the depth of 1m, 6m, 12m and 20m from the back of the abutment can be obtained on July 15,2021 and January 15,2022, respectively. From Figure 5, it can be seen that the upper part of the transition section behind the abutment is the same buried depth. As the distance from the abutment increases, there is a slight initial increase followed by a decrease in ground temperature at increasing distances from the back of the abutment. At the same depth within the middle region, greater irregularity in ground temperature distribution is observed with increasing distance from the abutment. In the lower part at equivalent depths, an increase in distance from the back of the abutment leads to an increase in ground temperature that gradually stabilizes. Comparison between Figure 3 and Figure 4 reveals close agreement between numerical values and trends for ground temperatures at different depths (1m, 6m, 12m, and 20m) behind the abutment with minimal differences. Although the temperature distribution at different depths at 1m behind the abutment is consistent with the change trend of 6m ~ 20m behind the abutment, there are still obvious differences in the value. This shows that the abutment structure has a significant influence on the temperature field of the road-bridge transition section in the range of about 1m behind the abutment, and this influence is closer to the abutment. The greater the distance from the abutment, the smaller the influence of the farther away from the abutment, and the smaller the influence of the 6m and farther behind the abutment.

4 Conclusion

In this paper, the numerical analysis method is used to study the temperature field distribution characteristics of the transition section of the road and bridge in permafrost regions considering global warming. By analyzing the variation of the temperature of different soil materials at varying distances from the abutment with respect to buried depth, the main conclusions are as follows:

(1)The variation in soil properties and the temperature boundary of the road-bridge transition section significantly impact the process of temperature field equilibrium. Overall, the natural foundation exhibits a faster rate of temperature field equilibrium compared to the soil behind the abutment; shallow soil achieves equilibrium more rapidly than deep soil. Additionally, near-abutment soil demonstrates greater temperature field equilibrium than distant-abutment soil.

(2)The thermal properties of different materials and the temperature boundary at the road-bridge transition section have a significant impact on the temperature field distribution. This effect is particularly pronounced within about 1m from the back of the abutment, and even more so within approximately 6m from the back of the abutment. However, as the distance from the abutment increases, this effect gradually diminishes and becomes negligible at farther distances. Therefore, there will be a gradual homogenization in the longitudinal bridge transition section's temperature field distribution.

(3)The water-heat-force coupling model can be established to analyze the mechanism of uneven settlement in the road-bridge transition section within permafrost regions. By examining the temperature, water, and deformation fields of this transition section, we can investigate the uneven settlement caused by frost heave and thaw settlement.

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