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Experimental and numerical investigation on temperature characteristics of high-speed railway's embankment in seasonal frozen regions

Liu Hua, Niu Fujun *, Niu Yonghong, Lin Zhanju, Lu Jiahao, Luo Jing

State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou, Gansu, 730000, China

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ABSTRACT

By analyzing temperature characteristics of tested embankments at the Changchun site of Harbin to Dalian Passenger Dedicated Line (HDPDL), we found that the temperature changing process is different in parts of the roadbed and foundation under seasonal freeze–thaw cycles. In cold seasons, the temperature under the reinforced concrete component was higher than that under the shoulders. This difference decreases with the depth of roadbed. In warm seasons, these phenomena appear as a reverse trend, and also the temperature difference decreases with the depth of roadbed as usual. In different parts of the roadbed, the maximum seasonal frozen depths were all higher than that in the natural ground, because of the roadbed materials, that changed the heat exchange process between the air and the ground surface. It should be multiplied by an appropriate correction factor for the standard depth of seasonal freezing to allow the setting design of the anti-frost layer thickness of the roadbed. By changing the roadbed filling materials, a series of computer simulations were carried out. The thermal states of roadbeds were simulated 50 years under the climate warming. It was indicated that the modified common A/B group fills do not improve the thermal state, though the filled layers were designed to increase the roadbed bearing capacity. The maximum frozen depth was 1.5–1.6 m under the track plates, and 1.7–1.8 m under the shoulders. The reinforced concrete component made the isothermals appear as a saddle shape, and change to be flatter with the depth of roadbed.

1. Introduction

Seasonal frozen regions and permafrost possess 53.5% and 25% of China's land area. The seasonal frozen ground is broadly distributed in northern China (Xu et al., 2001). In the past, there has been no rigorous or accurate national standard code for anti-frost and anti-thawing designs, which caused frost and thawing settlement damages to subgrade, tunnels and transition sections between bridges and embankment. The damages display as different types, such as longitudinal and transverse cracks on the roadbed surface, thaw slumping deformation, frost boiling, landslide, gelifluction (Wu et al., 2005), etc. In order to solve the problems mentioned above, a great deal of research has been carried out since the last century. In the permafrost regions where the Qinghai–Tibet Railway (QTR) crosses, a series of engineering measures and a cooling principle have been researched and proposed (Cheng et al., 2001). Field-tested and numerical simulation results showed that the duct-ventilated embankment, the crushed rock sloped embankment, and the crushed rock basement embankment, have all displayed certain effects on cooling the roadbeds. Thus they are advantageous to protecting the underlying permafrost (Ma et al., 2006; Niu et al., 2003, 2006). In some sections of the QTR, especially the transition section between cutting and filling, extruded polystyrene (EPS) and polyurethane (PU) were used as insulation layers in the embankment construction. And it was also used in infrastructure construction in cold regions in America, Japan and Canada, etc. Field and laboratory experimental results indicated that extruded polystyrene has a combination of properties that made it more acceptable than other types of insulation (Gandahl, 1978; Johnson, 1983; Olson, 1984).

Most of the engineering practices which mentioned above were for highway or common railway construction in permafrost regions. In seasonal frozen regions, the soils' susceptibility to frost heave was a major engineering problem. The susceptibility was systematically classified (Dai et al., 1992), so that the roadbed was designed with anti-freezing layers (Ye, 2004; Ye et al., 2007). The frost heave distribution varies with depth depending on different groundwater and soil conditions (Zhu et al., 1988). Various coarse and fine-grained roadbed soils were tested at selected temperatures, from normal positive temperature down to −10 °C and back to the positive temperature. The results indicate that all the soils exhibited a substantially-reduced subsidence modulus after the freeze–thaw cycle (Simonsen et al., 2002). But there was little research on materials and construction measures related to high-speed railways in seasonal frozen regions.

Harbin to Dalian Passenger Dedicated Line (HDPDL) is the first designed and constructed high-speed-railway in middle-deep seasonal frozen regions in China. Because of the complicated geographical and geological conditions in the Northeast Plateau, many different

* Corresponding author. Tel.: +86 931 4967263; fax: +86 931 8271054.
E-mail address: niufujun@lzb.ac.cn (F. Niu).

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kinds of engineering structures, e.g. embankment, cutting, tunnel, bridge, were used alternately in the railway construction. The depth of seasonal freezing along the line is 0.88–1.90 m, from the south to the north. The temperature influences on the embankment are the most important factors in designing anti-freezing measures. In this paper, the temperature distribution and its variation characteristics were analyzed by in situ measurements, and then by using an enthalpy model and the finite element program ANSYS. The thermal regime of the roadbed was studied under the local conditions, and the two-dimensional simulation of nonlinear phase change heat transfer was conducted for different filled materials and construction times. The recent climate warming was taken into consideration during the computation. The roadbed thermal regime evolution was reported and analyzed, so that to give some recommendations to new high-speed railways constructions in seasonal frozen regions.

2. In situ investigation

2.1. Site conditions and the design of roadbed

The experimental sections located in Changchun (D3K692 + 840–D3K692 + 860 in mileage) along HDPDL are shown in Fig. 1. The study site is in semi-humid monsoon climate region of Northeast Piedmont, where the freezing period is from November to March of the next year. The mean annual air temperature is about 9.2 °C with extremes of about −38 to −36.5 °C. Weather records show that the mean annual precipitation and mean annual evaporation are about 821 mm and 1,628 mm, respectively. The mean annual relative humidity is 84% and the mean annual wind speed is 3.9 m/s. Engineering geological investigations at the site indicate that the maximum frozen depth is 1.3–1.4 m.

Shown in the right part of Fig. 2, the width of the roadbed surface is 13.6 m and the height is 3.5 m. The roadbed's upper layer is well-graded gravel mixed with cement to 0.7 m in thickness. The filling materials of the middle layer is A/B group fills (high quality and good filling materials in China railway construction code)with a thickness of 2.3 m, and the filling materials of lower part of the roadbed is composed of 3 layers of well-graded crushed-stone interlayered by 2 layers of sand. Each of the interlayer is 10 cm thick and the total thickness of the lower part is 0.5 m. The surface of the embankment is covered by CRTS-I (China Railway Track Slab-I) track plate. The foundation soil is yellow clay, reinforced by 20 m long CFG-piles (Cement Fly-ash Gravel-piles).

2.2. Methods and data acquisition

The geometry of the selected observation section and the positions of temperature sensors are shown in the left part of Fig. 2. In the boreholes of the foundation and nature surface, the spacing of the temperature sensor is 0.5 m in vertical and the top one is set up at the natural ground surface. The spacing is 1.0 m in horizontal in the roadbed at different depths. The accuracy of the temperature sensors is ±0.05 °C and it is assembled and calibrated in the State Key Laboratory of Frozen Soil Engineering (SKLFSE). Soil temperatures were collected once per week by a set of datataker system (Compell3000). The observation starts on October 30, 2010 and ends on May 28, 2011.

2.3. Analyses of observed results

During the period from October 30, 2010 to May 28, 2011, the temperature distributions in different boreholes at the observed section were shown in Fig. 3. In this study we particularly concerned the temperature regime in the foundation at 2.0 m under the natural ground surface. The temperatures at this layer reached to the lowest value on April 30 when the subgrade thawing has been complete. From Fig. 3 we can deduce that temperature amplitude gradually decreased with the depth of the roadbed in the freezing period and the temperature amplitude was about 8.4 °C at 3.0 m above the natural ground surface, 4.5 °C at the natural ground surface, and 3.2 °C at 2.0 m below the natural ground surface, respectively. The data of the temperature change with depth in different boreholes are listed in Table 1. There was a slight difference in temperature between the shoulder and the left center. It can be seen that the temperature changes in different boreholes have obviously difference. In the cold season, the temperature on the shoulder was lower than that in the left center at the same depth. However, in the warm season, their temperature difference decreased gradually at the same depth. It can be also surmised that the temperature on the shoulder was higher than that in the left center at same depth in the warm season. In the upper layer of roadbed, the thermal resistances near the two boreholes were apparently inconsistent so that the difference of temperature can reached 5 °C. And in the lower layer of roadbed, the thermal resistances near the two boreholes were similar so that the difference of temperature declines. In the foundation, the changing process of temperature difference between the shoulder borehole

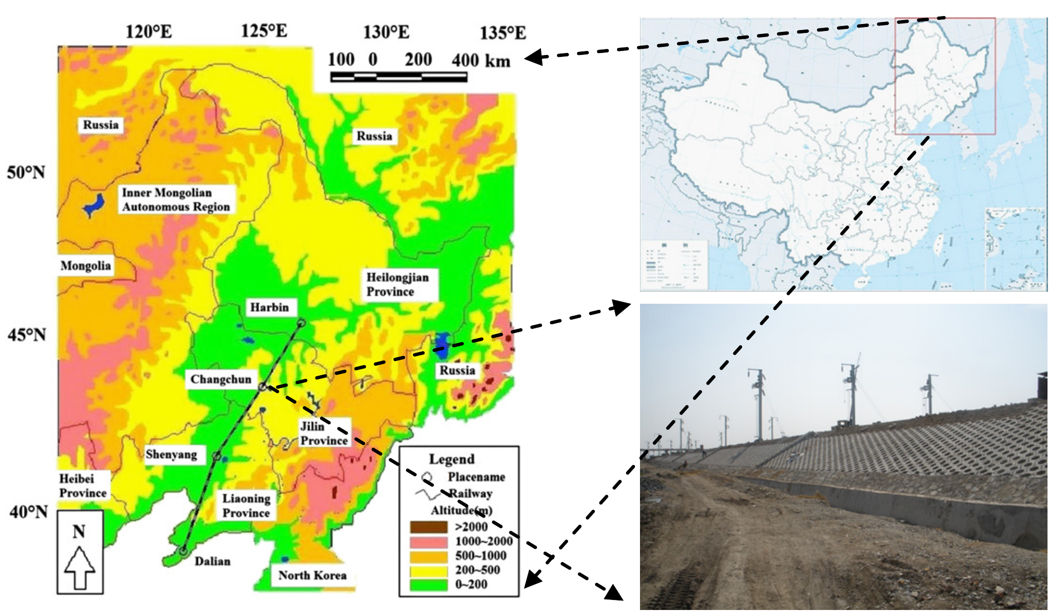

Fig. 1. Experimental section in Changchun.