Cold Regions Science and Technology 106–107 (2014) 216–231

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Study on thermal regime of roadbed–culvert transition section along a high speed railway in seasonally frozen regions

Liu Hua [a,b], Niu Fujun [b,*], Niu Yonghong [b], Yang Xifeng [c]

[a] Xi'an University of Architecture and Technology, School of Civil Engineering, Xi'an 710055, China
[b] State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China
[c] China First Railway Survey and Design Institute, Co., Ltd., Xi'an 710043, China

ARTICLE INFO

Article history:
Received 17 February 2014
Accepted 23 July 2014
Available online 1 August 2014

Keywords:
High-speed railway
Roadbed–culvert transition section (RCTS)
Seasonally frozen regions
In-situ monitoring
Numerical modeling

ABSTRACT

Harbin to Dalian passenger dedicated line (HDPDL) was the first high-speed railway in the moderately deep seasonally frozen regions in the Northeast China. The roadbed–culvert transition section (RCTS) was paid special attention, as it was prone to uneven deformation. In this paper, the temperature field and its changing process of a typical RCTS at Siping site along HDPDL were discussed based on monitoring data. The results showed that during the freezing period (from November, 2010 to March, 2011), the thinner of the fill layer on the culvert, the higher temperature amplitude appeared in the RCTS. Due to the solar radiation difference on the sunny and shady slopes, the temperature in the sunny-slope was 1–3 °C higher than that in the shady-slope, and the difference increased as roadbed height increases. However, the culvert serves as a large ventilation duct, exchanging the amount of thermal rotation and weakening the temperature difference between the two sides. Numerical simulation of the temperature fields was carried out for discussing roadbed fill materials and culvert structures. The results indicated that, under the current design conditions, a pipe-style culvert shows a more stable thermal regime in the freezing period, while a box-styled culvert showed a more stable thermal regime in the thawing period. The anti-frost and insulation engineering measures were also discussed, and several critical design parameters were proposed and optimized. At last, it was found that the most suitable configuration was a box culvert with one section transiting to embankments, and this configuration was recommended for construction of high-speed railway in the seasonal frozen regions.

1. Introduction

From a safety viewpoint, the engineering properties of roadbed–culvert transition section (RCTS) in cold regions, e.g. the bearing capacity, deformation characteristics, etc. are affected by its temperature status. In order to reduce the risk of structure failure in a cold environment, thermal stability of the roadbed has become a considerably important subject (Harris et al., 2009). Harbin to Dalian passenger dedicated line (HDPDL) goes through the piedmont plain in the Northeast China, where it belongs to seasonally frozen regions. The seasonally frozen regions account for approximately 30% (Williams et al., 1989) and 53.5% (Xu et al., 2001) land area of northern hemisphere and China, respectively. HDPDL is more than 900 km in length, and about 231 km of it is built on embankment. In these sections, there is at least a culvert in each kilometer of embankment on average, due to regional changes and complex conditions of engineering geology and hydrogeology along the railway. Frost heave, thaw settlement and other cryogenic phenomena have been occurring frequently. The train speed is limited to under 200 km/h in winter season, a significant decrease from the operating speed of 300 km/h in summer season; the original design speed is 350 km/h (Sheng, et al., 2013).

Many studies on culvert and roadbed–culvert transition section have been done since the last century. In permafrost regions, styles of culvert, bury depth of culvert foundation, temperature distribution and changing process of the roadbed and foundation, thermal-stress actions among culvert, roadbed and foundation, and anti-thaw engineering measures were all analyzed (FSDI, CAREERI, 2003), which provide useful methods and experience for solving engineering problems. Kunitake (1993) analyzed the temperature of the concrete box culvert by 3D Finite Element Modeling (FEM). Zhang (2003) studied the effect of the hydration heat of a culvert foundation along the Qinghai–Tibet Railway, and proposed a suitable construction season. Wu (2002) proposed an improved culvert style and foundation burial depth along the Qinghai–Tibet Railway. Cao (2003) found that the assembled box culverts have the best thermal state in permafrost regions. Ma (2003) compared the different construction methods, including cast-in-situ concrete method and the prefabricated method in culvert construction. Zhang (2007) studied the proper construction techniques in a unique environment on the Qinghai–Tibet Plateau, and discussed the effect of culverts on the ground temperature and variation of the permafrost table. Sun

* Corresponding author.

http://dx.doi.org/10.1016/j.coldregions.2014.07.008
0165-232X/

(2008) studied the thermal state of a thermosyphon roadbed and a normal roadbed with culvert through numerical modeling. All the works mentioned above concerned the engineering problems of culverts in permafrost regions.

A culvert can be considered as a ventilating duct in an embankment. In permafrost regions, duct-ventilated embankment was effective in lowering the temperature of frozen soil subgrade, along with a number of cooling techniques adjusting heat transfer patterns (e.g. solar radiation, heat convection, heat conduction) in the roadbed (Cheng, 2005). Furthermore, duct-ventilation method was also effective in adjusting the temperature distribution in the roadbed.

Other than the settlement problem in permafrost regions, the frost heave was a major engineering problem in seasonally frozen regions. For design purpose, the frost susceptibility of soils was systematically classified (Dai et al., 1992), so as to prevent the occurrence of the frost heave (Ye et al., 2004; 2007). Reed et al. (1979) examined the relationship between the frost heave and the pore-size distribution of compacted silty soils, and proposed that frost susceptibility criteria based on the porosity distribution was more logical and versatile than those based on soil type and grain size. Tester and Gaskin (1996) found that the amount of frost heave increased linearly as the fines content increased. The fines content was limited within 8%, according to the CRREL frost susceptibility criterion. Konard (1999) analyzed several different soils in their frost heave susceptibility test, and found that the frost heave was well related to the average size of the fines fraction, the specific surface area of the fines fraction and the ratio of the material's water content to its liquid limit. Côté and Konrad (2003) discussed the influence of the properties of fines particles on the hydraulic characteristics of granular base-courses. Konard (2005) found that the frost susceptibility of the fines was varied with different mixtures of granitic fines and commercially available kaolinite clay. And furthermore, Konard (2008) found that the frost susceptibility of coarse grained soils cannot be solely evaluated with respect to frost heave but need to consider the amount of water drawn to the freezing front during the freezing process and the consequences of this water during thaw.

An asymmetric problem of a roadbed in cold regions caused by slope faces needs to be considered in its thermal stability evaluation (Cheng et al., 2003). Based on field experiments at Beiluhe on the Qinghai–Tibet Plateau, Hu et al. (2002) studied the relationship between solar radiation and temperatures of the two side-slopes with different embankment orientations. Sheng et al. (2005) observed temperatures of two side-slopes of an experimental embankment at Beiluhe for one year, and concluded that the higher temperature of the south-facing slope in winter time contributed to the thermal difference between the south- and north-facing slopes. But in the seasonally frozen regions, there are less research considering the effect of slope facing.

Above all, past experience and engineering examples (Cheng, 2008) demonstrated that the key to the success of railways in permafrost regions lies in the roadbed, the key to the stability of the roadbed lies in the frozen soil, and the key to the stability of the frozen soil lies in its thermal stability. However, there were still limited studies on construction measures and thermal regime of high-speed railways in seasonally frozen regions. Particularly, the thermal regime of the roadbed–culvert transition section (RCTS) in high-speed railway was seldom studied. HDPDL was the first designed and constructed high-speed-railway in the moderately-deep seasonally frozen regions in China. Due to the complicated geographical and geological conditions in the Northeast Plain, many different kinds of engineering structures, such as embankment, bridge, culverts were used in the railway construction. In this paper, the temperature distribution and variable characteristics of roadbed surrounding the culvert were analyzed by site monitoring and numerical simulation.

2. Study area

2.1. Meteorology and engineering geological conditions

The experimental section is located at Siping site (DK673 + 820 ~ DK673 + 840 in mileage) along HDPDL (Fig. 1). The study site is in semi-humid monsoon climate region of the Northeast Plain,

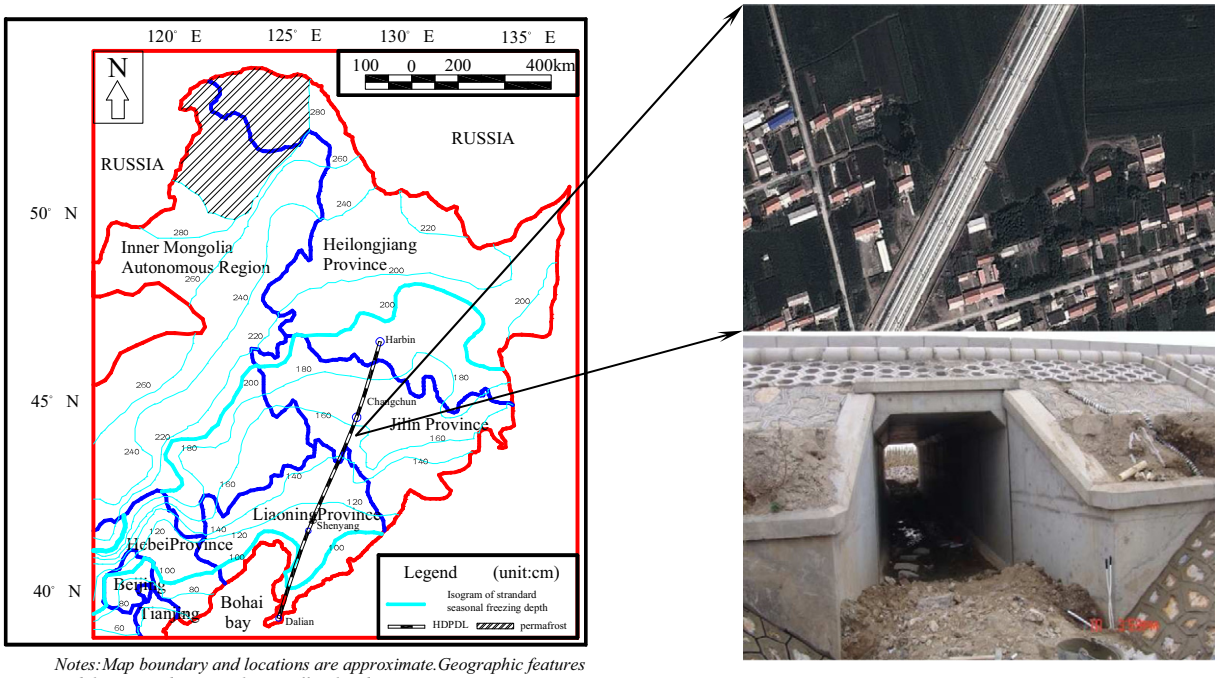

Fig. 1. The location of the studied roadbed–culvert transition section (RCTS) and typical culvert along the HDPDL in the Northeast China. (a) The location of the RCTS; (b) a typical culvert in HDPDL.