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Comparative analysis of temperature variation characteristics of permafrost roadbeds with different widths

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ABSTRACT

According to Expressway Network Plan of China, an expressway is to be constructed in the permafrost regions on the Qinghai–Tibet Plateau. The understanding of the heat transfer characteristics of the subgrade in expressways with wide pavements is crucial for damage prevention and control, and the long-term stability of the roadbed. Based on the monitored data from the Qingshuihe section of the Qinghai–Tibet Highway (QQTH) and Qinghai–Tibet Test Expressway (QTTE) in the permafrost regions on the Qinghai–Tibet Plateau, the heat-transfer process and the ground temperature response of highways and expressways with different embankment widths were analyzed. The results from QQTH showed that during the past 17 years, the variation of the ground temperature of QQTH embankment was mainly affected by the solar radiations and heat absorption process of pavement surface. The intensity of heat absorption of the soil at the base of the roadbed was much more than that in natural conditions, and it resulted in a more rapid and continuous increase of the temperature under the embankment, which could reach up to 0.8 °C/a. Comparing with QQTH in the initial period after its reconstruction, the variation characteristics of the ground temperature in embankment of the QTTE was generally the same, but the intensity of heat absorption in embankment increased by nearly 30% in the QTTE, and permafrost degeneration was further accelerated. The increase in ground temperatures at different depths and the maximum thawing speed of permafrost were nearly doubled as that on the QQTH. On the QTTE, the effect of sunny–shady slope in the embankment was identified. During the observation period of 4 years, the sunny–shady effect caused the ground temperature to be offset by about 2 m from the axis of symmetry to the sunny slope direction, and longitudinal cracks of roadbed have been resulted. Stricter technical standards for future expressways, will mean that the permafrost issues will become more important and serious, and corresponding research is more urgent and significant.

1. Introduction

The Qinghai–Tibet Highway was built on the Qinghai–Tibet Plateau and it traversed more than 630 km in the permafrost regions, 134 km of which were built over the warm and ice-rich permafrost (Cheng et al., 2008). The changes of the permafrost conditions impacted the land surface hydrology, ecosystems, carbon cycle, landscape and geomorphologic processes significantly, and also resulted in the degradation of permafrost (Jin et al., 2008; Wu et al., 2010a). The influence caused by the anthropogenic engineering was more severe. The construction of highways in permafrost regions caused changes in the thermal regime under embankments because of the heat absorption (and reduced evaporation capability) of the asphalt pavement, which resulted in the permafrost temperature increases and embankment instability (Cheng and He, 2001; Wu et al., 2002a,b, 2010b). As a result, various engineering damages, such as uneven frost heave and thaw settlement of the roadbed, and the longitudinal cracks of the embankment have been resulted (Dou et al., 2007; Liu et al., 2002; Yu et al., 2002). Since the 1990s, sections of Qinghai–Tibet Highway with severe damages have been repaired and reconstructed on a large scale at intervals of 4–6 years. However, the thaw settlement of the embankment has not yet been resolved (Wu and Niu, 2013; Yu et al., 2013).

According to Expressway Network Plan of China (Department of Transport, National Development and Reform Commission, 2005), the Qinghai–Tibet Expressway (QTE) will be built along the existing Qinghai–Tibet Highway corridor and pass through the permafrost regions on the Qinghai–Tibet Plateau. The numerical simulation results showed that, compared with the highway, the intensity of heat absorption in QTE will be double because of the width of the asphalt pavement being increased. Also, the heat at the center of the embankment can hardly diffuse to the surrounding permafrost, and more obvious a "heat gathering effect" will occur, leading to the permafrost degenerating rapidly (Yu et al., 2007). Since the present research was mainly focused on the low-grade Qinghai–Tibet Highway, the research into the problems of the expressway in permafrost regions is not enough.

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Facing the higher technical standards on the high-grade expressway, the permafrost engineering problems will bring more challenges and difficulties for the expressway construction (Yu et al., 2010, 2014). Therefore, research on the expressway in permafrost regions is important for the practice in these regions.

This paper focus on the thermal regime of roadbed with different widths in permafrost regions, based on the field data collecting at Qingshui River and Beiluhe, Qinghai–Tibetan Plateau. For the first time, the data collected from engineering entities were compared in this paper.

2. Introduction to the compared observation fields

To investigate the heat transfer characteristics in embankments and the response of permafrost under highways and expressways with different widths of pavement, data was collected from Qingshui River section of the Qinghai–Tibet Highway (QQTH) and Qinghai–Tibet Testing Expressway (QTTE), which shared similar permafrost and engineering conditions.

2.1. QQTH observation field

The QQTH observation area is a section of the highway in operation (Fig. 1a), located in the hinterland of Chumar high plains, nearly at the center of the permafrost regions on the Qinghai–Tibet Plateau, which has a flat terrain and a mean annual air temperature (MAAT) was −4.5 to −5.0 °C (Wu et al., 2005). Initial permafrost table of the site was about 2.5 m depth. The height of the highway embankment is 2.5 m above natural ground surface, and the top width of the embankment is 10.0 m (of which, a: the asphalt pavement is 7.0 m wide, including the traffic lanes 3.5 m × 2 wide; b: the soil shoulders on both sides are 1.5 m wide). The construction of asphalt pavement in this section was completed in 1985, the height of the embankment was less than 1.0 m at that time. The embankment height was raised to 2.5 m from 1990 and it was completed and put into operation in 1993. The ground temperature in the embankment of an observed profile was measured from 1996, and 17 years of data were monitored. The depth of thermometer borehole in the center of the embankment is 15.0 m, 10.0 m at the right-side shoulder and 10.0 m in the natural field. This section is in a typical permafrost region with warm and high volumetric ice content, causing frequent and serious engineering damage. The geological survey data showed that soil type in this section was mainly brown tinted red intensive weathered mudstone. The permafrost characteristics in this section are given in Table 1.

Table 1
Permafrost conditions of QQTH on Chumaer River high plain.

Permafrost conditions	Time	
	1996	2011
Permafrost table in natural field	3.0 m	4.3 m
Ground temperature at 10 m depth of the natural borehole	−0.85 °C	−0.55 °C

2.2. QTTE test field

Based on the needs of the Expressway Construction Plan of China, a high-grade expressway experimental section of the Qinghai–Tibet Test Expressway (Fig. 1b) was built by the State Key Laboratory of Frozen Soil Engineering of Chinese Academy of Sciences (Yu et al., 2009). The QTTE was located in about 1.0 km southeast of the Beiluhe Observation Station of Frozen Soil Environment and Engineering (34°49′N, 92°55′E, 4640 m in elevation), the strike of the embankment was about 198° from the north. The QTTE was built according to the "Technical Standards of Highway Engineering GB-T2003" of China. The field of QTTE was located in front of Fenghuo Mts. regions and near the Beilu River, where the MAAT was −5.0 to −7.0 °C (Wu et al., 2005). Due to field limitations and funding restrictions, the test section was built as a one-way road, with half the width of a conventional expressway. Various engineering measures were used in the construction of the experimental road. The height of embankment was 3 m above natural ground surface. The width was 13 m, the width of the asphalt pavement was 11.5 m, including the 2 × 3.75 m of traffic lanes with 3.0 m of hardened shoulder at the right side and 1.0 m at the left side. Both sides of the soil shoulders were 0.75 m, the gradient of the slope surface was about 34°, and the total length of QTTE was 315 m. In the middle of it, a section without any engineering measures was chosen for comparison and also for analysis in this paper. The ground temperature of natural field near the experimental engineering showed that the maximum depth of permafrost table was at about 2 m, and the mean annual ground temperature (MAGT) was −0.9 °C. The soil type was mainly brown tinted red intensive weathered mudstone, the type of permafrost was mainly warm and ice-rich.

2.3. The comparison between QQTH and QTTE

With the limitation of the actual conditions, it is unrealistic to find both testing fields with completely similar conditions in every aspect. It is true that there are some differences between QQTH and QTTE, but these are not enough affecting the analysis and reasonable results getting in this paper. For the first, the mean air temperature of these two observations filed was slightly different indeed. However, among the monitoring sections in Qinghai–Tibet Highway, the permafrost and geological conditions were similar between Qingshuihe section and Beilu River testing section in large degree. For example, warm and ice-rich permafrost were identified under the two monitoring sections, the mean annual ground temperature (MAGT) in Qingshuihe and Beilu River was −0.9 °C and −0.55 °C, respectively. Secondly, the QQTH was rebuilt in the early 1990s, so the ground temperature monitoring data which were used in this was in the initial operational period. Similarly, the observation data of QTTE was also the first in several years after the construction. So the monitoring data results should be compared; For the third, because of lower MAGT and higher embankment in QTTE, the engineering conditions of the QTTE should better than

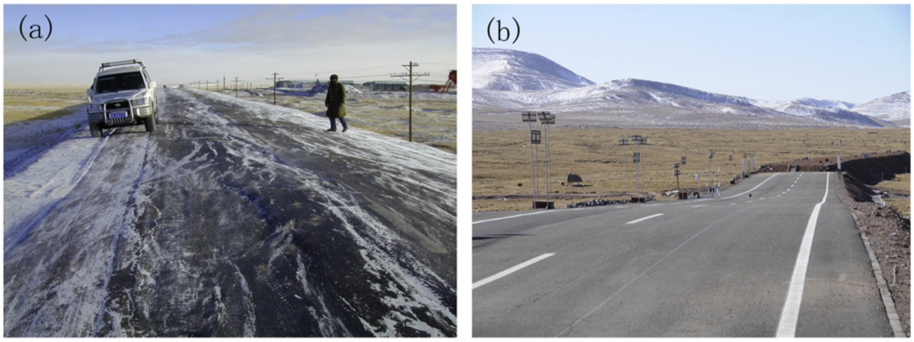

Fig. 1. Photos of the QQTH (a) and QTTE (b).