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Comparison of permafrost degradation under natural ground surfaces and embankments of the Qinghai–Tibet Highway

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ABSTRACT

Permafrost under road embankments often degrades more seriously than that under natural ground surfaces due to the influences of both climate warming and road embankment. In a companion paper, we analyzed the states of permafrost degradation under road embankments in the five typical regions along the Qinghai–Tibet Highway (Yu et al., 2013a). In this paper, the states of permafrost degradation under natural ground surfaces, near the road embankments, are analyzed based on up to 15 years of in-situ geothermal data, while that under road embankments are also further analyzed. On this basis, the states of permafrost degradation and related processes are compared between the natural ground surfaces and road embankments. Possible influences of climate warming and road embankment on permafrost degradation are discussed. The results show different characteristics of permafrost degradation under natural ground surfaces and road embankments. The contributions of climate warming and road embankment on the thermal regime of permafrost may vary during the process of permafrost degradation.

1. Introduction

Qinghai–Tibet Highway (QTH), with a total length of 1937 km, is the only highway connecting Qinghai and Tibet. It passes through 632 km of permafrost terrain, including 528.5 km of continuous permafrost and 103.5 km of discontinuous permafrost (Sheng et al., 2002). From the 1970s to 1990s, mean annual ground temperatures (MAGTs) within continuous permafrost have increased by 0.1–0.3 °C, while those within discontinuous permafrost have increased by 0.3–0.5 °C (Wang et al., 2000). Permafrost thawing rates (incremental rate of active layer) were 0.8–8.4 cm/year (Wu and Liu, 2004). The increase in mean annual air temperature (MAAT) was sufficient to account for the permafrost degradation including both increasing ground temperature and permafrost thaw (Wu and Zhang, 2008), as an increase of MAAT of about 0.5–2.5 °C along the QTH has been observed since the 1960s (Tong and Wu, 1996; Wu et al., 2005). In addition to air temperature, other factors such as terrain, hydrology, vegetation, geology and disturbances may also play important roles in permafrost degradation (Osterkamp, 2007).

With regard to the permafrost degradation under road embankments along the QTH, strong heat absorption and reduced evaporation caused by the asphalt pavement are important (Wu et al., 2003). Under the influences of both climate warming and asphalt pavement, taliks have emerged in 60% of road sections of the QTH within permafrost regions, and their length within permafrost area has shortened by 18 km since the 1970s (Wang and Mi, 1993). Permafrost thaw rates of about 2–25 cm/a and increasing rates of ground temperatures of 0.2–0.6 °C/10a at a depth of 10 m were observed under road embankments along the QTH since 1990s (Wu et al., 2007, 2010a). Wu et al. (2007) have also discussed the responses of permafrost along the QTH to climate warming and engineering construction, which is probably the sole paper so far in attempt to separate these two major influencing factors. However, it is still difficult to differentiate the influences of climate warming and asphalt pavement on permafrost under road embankments.

In addition, QTH has been experiencing serious deformations, and statistical results showed that 85% of roadbed destruction was caused by thaw settlement and 15% by frost heaving (Wu et al., 2002). Thaw consolidation was therefore considered to be the main cause of embankment settlement for many years (Wu and Liu, 2005). Recent studies indicated that creep of warm permafrost layer can be another cause (Qi et al., 2007; Yu et al., 2013b; Zheng et al., 2010). Different road sections show different settlement characteristics, which are controlled by two crucial factors, namely the current permafrost condition and the characteristic of permafrost degradation (Yu et al., 2013b). For one road section, the characteristic of embankment settlement would vary in the process of permafrost degradation, as the permafrost thawing and warming rates change every year (Yu et al., 2013a). Therefore, the analysis of permafrost degradation becomes increasingly important to the stability of the QTH.

Given the need to improve our understanding of permafrost degradation and embankment deformation of the QTH, five typical regions, i.e. mountainous region, hilly region, high plain, basin and

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permafrost boundary were first summarized, then degrading states of permafrost under road embankments in the five typical regions were analyzed from one representative road section (Yu et al., 2013a). This paper is an extension of the previous one. The states of permafrost degradation under natural ground surfaces in the five regions, near road embankments, are examined and then compared to road embankments. Possible influences of climate warming and road embankments on permafrost degradation are discussed.

2. Study sites, methods and instrumentation

In the companion paper, five road sections, Fenghuo Mt. (mountainous region), Kekexili Mt. (hilly region), Chumaer River (high plain), Zhangjiazangbuhe River (basin) and near Anduo (permafrost boundary), were selected for analyzing the states of permafrost degradation under road embankments based on in-situ long-term ground temperature data (Yu et al., 2013a). The geographical locations and geological conditions can be seen in the earlier paper. The five sites are abbreviated as FM, KM, CR, ZR and NA respectively. The elevations and mean annual ground temperatures (MAGTs) along the QTH are shown in Fig. 1 (Zhao et al., 2010), with red circles denoting the five study sites.

The instrumented sites are within about 30 m from the road section. An illustration of two boreholes and instrumentation setups is shown in Fig. 2(a), with an example in Fig. 2(b). Temperature data were collected on a daily basis by CR3000 data loggers, which were protected by metal containers. The distances between road embankments and boreholes under natural ground surface were considered sufficient for the temperatures beneath the natural surfaces to be unaffected by the thermal influence of the road embankments, and for ground stratigraphy and original permafrost conditions to be similar.

3. Results

For ease of discussion, some definitions and explanations are stated as follows. 0 °C is defined as the thawing temperature, as it varies with soil type, load, water and salt contents, etc. (Xu et al., 2010). MAGT is defined as the ground temperature at the depth of 6 m for natural ground surfaces and 15 m for road embankments due to the limitation of monitoring depths. MAGT is different from the average annual permafrost temperature (AAPT) at any depth. Warm permafrost region is defined as the MAGT warmer than −1.5 °C, whereas cold permafrost is colder than −1.5 °C (Cheng, 2003). The artificial permafrost table is the upper boundary surface of permafrost under road embankments, whereas the permafrost table is for permafrost under natural ground surfaces. In addition, the layout of this section is similar to the companion paper for comparison.

3.1. The basic characteristics of the thermal regimes

The isothermal distributions beneath natural ground surfaces at the five sites are shown in Fig. 3. The average thicknesses of the active layer, i.e. the depths of permafrost tables were approximately 1.5 m at FM, 2 m at KM, 4 m at CR, 3 m at ZR and 5 m at NA. It can be seen from the 0 °C isotherms that the permafrost tables have deepened in all permafrost regions. The areas enclosed by the X-axis and 0 °C isothermal lines stand for the seasonally thawed layers every year. It can be seen that the enclosed areas were generally smaller in cold regions (FM and KM) than warm regions (CR, ZR and NA), indicating that permafrost in cold permafrost regions was more stable than that in warm permafrost regions. Every enclosed area is unconnected with the neighboring areas, indicating that no talik has emerged during the recording periods.

3.2. Permafrost thawing and warming rates

Fig. 4 shows the variations of permafrost tables of the five monitoring sites. The slopes of the fitted lines are the thawing rates, indicating that permafrost thawing rates at FM, KM, CR, ZR, and NA were about 5, 4, 7, 2 and 16 cm/a respectively. The values of coefficient of determination (R^2) reflect the fluctuation of the thawing rates, the larger the number is, the more stable the thawing rate is. The thawing rates of FM and KM were stable because the permafrost layers were relatively cold. For the permafrost on Qinghai–Tibet Plateau, the cold permafrost not only stands for a thick and stable permafrost layer itself but also implies a cold air temperature there (Liu et al., 2002; Wu and Zhang, 2008). The 5-meter thick active layer at NA, acting as a “buffering layer”, may retard the heat from the road embankment transferring into the permafrost layer, resulting in a relatively stable thawing rate. In contrast, the irregular thawing rates at CR and ZR were mainly caused by the warm permafrost layer or the thin active layer.

Fig. 5(a) illustrates the mean permafrost warming rates at selected depths during the recording periods. The warming rates differed from site to site, and varied with depth at each site. Generally, warming rates were higher in cold permafrost regions than warm permafrost

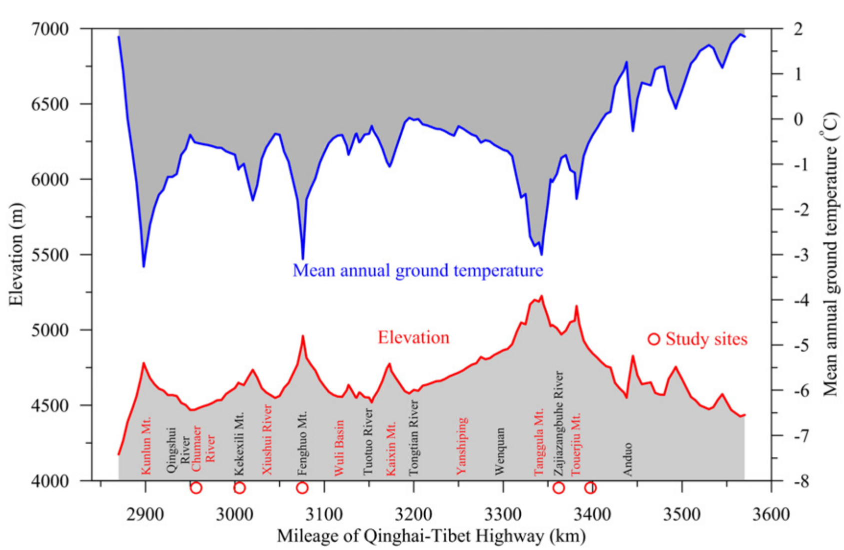

Fig. 1. Elevations and MAGTs along the Qinghai–Tibet Highway (after Zhao et al., 2010).