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Degradation process of permafrost underneath embankments along Qinghai-Tibet Highway: An engineering view

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ABSTRACT

Embankment settlement is closely related to the process of degrading of underling permafrost. Previous studies have focused on the process of permafrost degradation under natural ground surfaces, and the degradation process under roadway embankments has yet to be investigated. With the influence of climate warming, this study becomes more and more important in the analysis of embankment settlement. In this paper, based on the in-situ geothermal data of up to 15 years of 5 typical sections along the Qinghai-Tibet Highway (QTH), the characteristics of permafrost degradation are extensively investigated. According to the characteristics, the trends of thawing and temperature rise in the process of permafrost degradation are analyzed. Corresponding to the tendencies, four stages are defined according to the mean annual ground temperature (MAGT). Combining the features of permafrost degradation in each stage with the in-situ data of embankment settlements along QTH, the sources of the embankment settlement are identified. The main results are as follows. The permafrost degrades extensively in the five typical sections with different characteristics. With the increase in MAGT, the thawing rate firstly increases and then fluctuates as temperature rise rate increases and then decreases at MAGT of about −0.5 °C. The four stages are divided: initial degradation stage, for MAGT ≤ −2.5 °C; the intensive degradation stage, for −2.5 °C < MAGT ≤ −0.5 °C; the vertical talik stage, for −0.5 °C < MAGT ≤ 0 °C; and the quasi-disappearance stage, for MAGT > 0 °C. When MAGT is less than about −1.2 °C, the main contribution of total settlement is probably thawing settlement, with the negligible creep of permafrost; when MAGT higher than −1.2 °C, creep of permafrost starts to have an increasing share in the total settlement.

1. Introduction

Long-term in-situ data of deformation along QTH indicated that settlement are the main source of embankment deformation in permafrost regions (Liu et al., 2002; Wen et al., 2009; Yu et al., 2002). The settlement is mainly due to thawing of permafrost (Wu et al., 2002), creep of warm permafrost also leads to notable settlement caused by a rise in ground temperature (Ma et al., 2007, 2008; Qi et al., 2007). Embankment settlement is closely related to permafrost degradation that includes thawing of permafrost and increase in ground temperature. The process of permafrost degradation is important in the analysis of the variation of embankment settlements during its operation period.

Numerous model studies are found to assess the permafrost response to climate warming (e.g. Lunardini, 1996; Oelke and Zhang, 2004; Zhang et al., 2003; Zhou et al., 2008). However, these models cannot be applied satisfactorily in analyzing the case on the Qinghai-Tibet Plateau (QTP), because of some special features such as thinner permafrost layers, higher ground temperatures (Cheng, 2003; Cheng and Wu, 2007; Wu et al., 2002), higher rate of increase in air temperature compared to other permafrost regions (Pan and Li, 1996), as well as strong regional distribution of permafrost and weather conditions (Wu et al., 1988; Zhou et al., 2000). Taking these features into consideration, some models for permafrost on QTP have been established (Lai et al., 1999, 2004; Li et al., 1998; Liu and Tian, 2002; Wen et al., 2007). However, there is still a large error between simulation and observed data due to the lack of accurate input parameters such as snowpack, soil moisture and wind. So far, the in-situ data of ground temperature might be the only way to reflect the genuine process of permafrost degradation.

Based on the in-situ data on QTP, Sheng et al. (2002) explained the difference of permafrost degradation between relative high and low temperature permafrost regions by analyzing the heat balance. Other researchers reported thawing and temperature rise of permafrost underneath embankments (Wang and Mi, 1993; Wang et al., 2004; Wu et al., 2007, 2010b; Zhang et al., 2000) and original ground surfaces (Jin et al., 2006; Wu and Liu, 2004; Wu and Zhang, 2008). It was noticed that the thawing and temperature rise differ from section to section and the changes with time for the same section, indicating that different characteristics are shown in the process of permafrost degradation. This similar phenomenon was also found for the embankment deformation (Liu et al., 2002; Wu et al., 2010b), which is closely related to

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degradation of permafrost underlying the embankments. Some scholars have discussed the process. Based on a large amount of observed data of ground temperature, Jin et al. (2006) found that permafrost had extensively degraded downward, upward and laterally, and for downward degradation, four stages were classified, i.e., initial degradation stage, intensive degradation stage, vertical talik stage and seasonally frozen ground stage. Similarly, Wu et al. (2010a) divided it into five stages, these are starting stage, temperature rising stage, zero geothermal gradient stage, talik layers stage, and disappearing stage. They both described the general characteristics well for each stage, but they are only for permafrost under the original ground surface. Permafrost underneath embankments will suffer from not only global warming but also thermal disturbance due to the embankments (Wu and Tong, 1995; Wu et al., 2010b). Therefore, for permafrost underneath embankment, the process of degradation is different and should be further investigated, to critically analyze the variation of embankment settlement during the operation period.

In this paper, based on the characteristics of permafrost degradation in the five typical sections of the Qinghai-Tibet Highway, the trends of thawing and temperature rise in the process of permafrost degradation are analyzed. The features of permafrost degradation and the observed data of embankment settlement along QTH are combined to discuss the sources (thawing settlement and creep of permafrost) of embankment settlement. The results will provide a good reference for theoretical and numerical analysis on embankment deformation and some scientific guidelines for embankment construction and maintenance in permafrost regions.

2. Location and method

The QTH has a total length of 1937 km. The length passing through permafrost areas is 632 km of which 528.5 km is in continuous permafrost zones and 103.5 km is in patchy permafrost zones (Fig. 1). There are five typical regions along QTH: mountainous region, hilly region, high plain, basin, and permafrost boundary. Table 1 shows the detailed information for the five regions (Liu et al., 2005; Wang and Mi, 1993; Wu and Tong, 1995; Wu et al., 2010b; Zhao et al., 2010). Five monitoring sections are selected in the corresponding typical regions, respectively: Fenghuo Mt. (kilometer: K3075 + 700), Kekexili Mt. (K3017 + 300), Chumaer River (K2959 + 970); Zhajiazangbu River (K3363 + 800); and near Anduo (K3393 + 950), shown in Fig. 1 and abbreviated as FM, KM, CR, ZR and NA. The geological conditions of each are shown in Fig. 2.

Embankment height has been found to be a factor influencing degradation of the underneath permafrost by numerous previous studies (Dai, 1983; Huang, 1983; Wu and Zhu, 1998; Zhang et al., 2005, 2006). The general recognition is that an embankment should be built at a critical height so as to make use of its thermal resistance on the one side, and avoid high heat absorption from the slopes or high external load on the other side, so as to be favorable for permafrost protection and embankment stability. Ice contents in permafrost might be different from one section to another, which may influence both permafrost degradation and settlement of embankment. However, on the Qinghai-Tibet Plateau, geomorphologic unit is closely related to ice content of permafrost (Liu et al., 2005; Wang and Mi, 1993; Wu and Tong, 1995; Wu et al., 1988). For instance, ice-rich permafrost layers are extensively developed in hilly regions because of the high precipitation, fine grained soil, and relative low air temperature. In contrast, ice-poor permafrost layers are often extensively developed in basin due to the thermal influence of rivers and the relative high air temperature. In this paper, embankments with typical condition such as height of embankment, soil strata and ice content are taken in 5 different geomorphologic units so as to investigate the general characteristics of permafrost degradation.

In each section, three 15-m-deep boreholes were installed at the shoulders and the center of the embankment. Electric cables with thermistors located every 0.5 m were installed in each hole to monitor the temperature change with depth. The thermistors have a tolerance of ±0.05 °C. All the data were collected by data logger (CR3000) on a

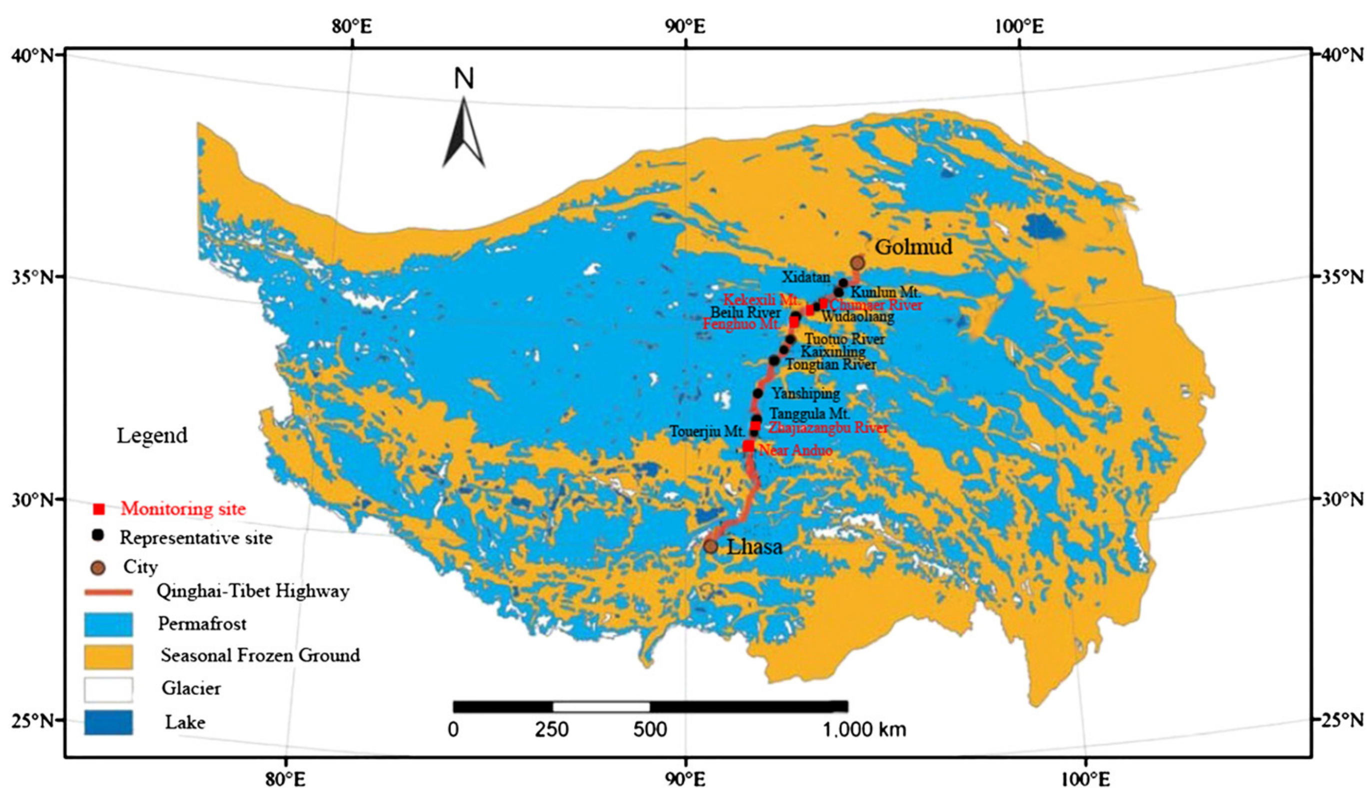

Fig. 1. Geographical locations of five ground temperature motoring sections (solid red squares) and other respective sections (solid black circles) along QTH (updated from Cheng and Wu, 2007).