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Dynamic thermal regime of permafrost beneath embankment of Qinghai-Tibet Highway under the scenarios of changing structure and climate warming

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ABSTRACT

Stability of the embankment is largely concerned with the height and pavement type in permafrost area. Climate is another key factor. The heat transfer model with phase change and finite element method are used to simulate the thermal regime of permafrost beneath embankment of Qinghai-Tibet Highway, considering the changing of pavement type, height of embankment and climate warming since the building of the road was started in 1954. In-situ observation of ground temperature was performed. Simulated results indicate that increasing embankment height can decrease the depth of permafrost table temporarily, and then the permafrost table goes deeper soon. Heat absorbing of black pavement is a key factor that causes permafrost degradation beneath the embankment. Both the simulated and the measured results indicate a continuous trend of permafrost degradation beneath both the embankment and the natural ground under the scenario of climate warming, which implies that only increase the embankment height is not enough to keep it stable.

1. Introduction

The thermal status of permafrost is sensitive to the changes of ground surface temperature. Global warming and human infrastructures can change the ground surface temperature, which will lead to extensive degradation of permafrost. Many studies have focused on this issue (Shiklomanov and Nelson, 2013; Fortier et al., 2011; Goering and Kumar, 1996; Zarling et al., 1983; Yang et al., 2010; Simonsen and Isacsson, 1999). Degradation of permafrost can cause surface settlement, and structures are then subject to thaw-induced damages such as thawing settlement and longitudinal cracks of embankment. These kinds of damage have occurred on the Qinghai-Tibet Highway (QTH).

The construction of QTH was started in 1950. From Golmud to Lhasa, it is about 1100 km long, and about 965 km of it is located at an altitude above 4000 m. The highest elevation along the route is about 5231 m at the Tanggula Pass. 550 km of the highway overlies continuous permafrost and 82 km is built on island permafrost.

The designers and constructors have no idea what permafrost is during that period. They did not consider the permafrost problem at first and there was no measure adopted to prevent permafrost from thawing. Therefore, severe thaw settlement problems have been occurring on the roadway. Hundreds of research works have done and tried to solve this problem (Tong and Wu, 1996; Yu et al., 2013; Wang et al., 2010; Tian et al., 2010; Huo et al., 2010; Dai et al., 2006). So far, it had experienced four reconstructions, increasing the height of embankment and changing the pavement from gravel to asphalt. Even so, the thaw settlement problems of permafrost are still severe. It needs many human and material resources to guarantee the traffic every year.

So far, there is no report on the dynamic process of permafrost beneath the embankment of QTH, considering the construction history and climate warming. The construction history means the four reconstructions, including the changes of height of embankment and pavement type. This paper will focus on this issue and try to present a clear understanding of dynamic process of permafrost beneath the embankment of QTH and supply information for improving of design idea in permafrost area.

2. Methodology

In order to investigate the dynamic thermal status beneath the embankment, in-situ observation and numerical simulations are performed.

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2.1. In-situ observation

The in-situ observation site is situated in the Wuli Basin of Qinghai-Tibet Highway (Fig. 1). The red triangle indicates the observation site (N34°28′36″, E92°43′45″). The elevation is about 4579 m. Vegetation cover is sparse. Salinization of ground surface is severe. The average precipitation is 399 mm in this area. The current pavement type is asphalt, which is about 7.2 m wide. The shoulder is 1.5 m wide and the embankment is about 3.0 m high. The borehole used for ground temperature measurement is located in the centerline of the embankment, which is 20.0 m deep. The first measured position is 0.5 m under the pavement surface. The interval between each two measured positions at the first 10.0 m is 0.5 m. And it is 1.0 m during the next 10.0 m. The other borehole used for ground temperature measurement is located at the natural ground, which is about 253.0 m away from the embankment. The surface is covered by sparse and short grass. The depth of this borehole is 16.0 m. The first measured position is near the ground surface. The interval between each two measured positions is 0.5 m during the completely investigated depth. Thermistors are used to monitor the ground temperature. The measurement precision is 2%. The thermistor string was installed in a sealed seamless steel tube that was inserted into the borehole after the drilling was finished. The gap between the soil wall and the tube was filled with sand. The data acquisition frequency is once per 15 days. The data span is between Oct. 2003 and Oct. 2012.

Because the in-situ observation was performed after the embankment reached its current height, the observation data shows the final results affected by climate warming, the historical construction and maintenance of Qinghai-Tibet Highway. They did not show the effects of the pavement type change and the height change of embankment.

2.2. Numerical simulation

Numerical simulation can present the effect of height, pavement type and climate warming on the thermal regime beneath the embankment since the QTH was built.

Table 1
Construction history of Qinghai-Tibetan Highway (QTH).

Span of time	Embankment height	Calculation time	Pavement type
1954–1979	0.2 m	26 years	Gravel
1980–1993	0.5 m	14 years	Asphalt
1994–1998	1.2 m	5 years	Asphalt
1999–2012	3.0 m	14 years	Asphalt

2.2.1. Theory model

In cold regions, the problem of the influence of embankment on permafrost is an unsteady heat transfer process. Phase change between ice and water occurs during the process. Therefore, a two-dimensional heat transfer model with phase change is adopted. The differential equation, the continuous condition, the conservation of energy, boundary conditions and the method for dealing with the phase change are presented by the references (Lai et al., 2004; Zhang et al., 2002; Bonacina and Comini, 1973; Liu et al., 2015). Based on the theoretical models, the software ANSYS was adopted to simulate the thermal regime of the permafrost affected embankment, considering the changes of embankment height, the change of pavement type and climate warming.

2.2.2. Geometric model, boundary conditions, and parameters

Details of the four construction stages of QTH are shown in Table 1. The height of the embankment is not for the full road. It is higher in lower places. The simulated geometric models are based on the information shown in Table 1.

According to Table 1, there are four models simulated in total (Fig. 2). The problem focused in the paper can be looked as symmetric. Therefore, only half of the model is drafted. The shoulder of the embankment is indicated with dash line. The height of the embankment is 0.2 m, 0.5 m, 1.2 m, and 3.0 m, respectively for the four stages. Each stage corresponds to a model.

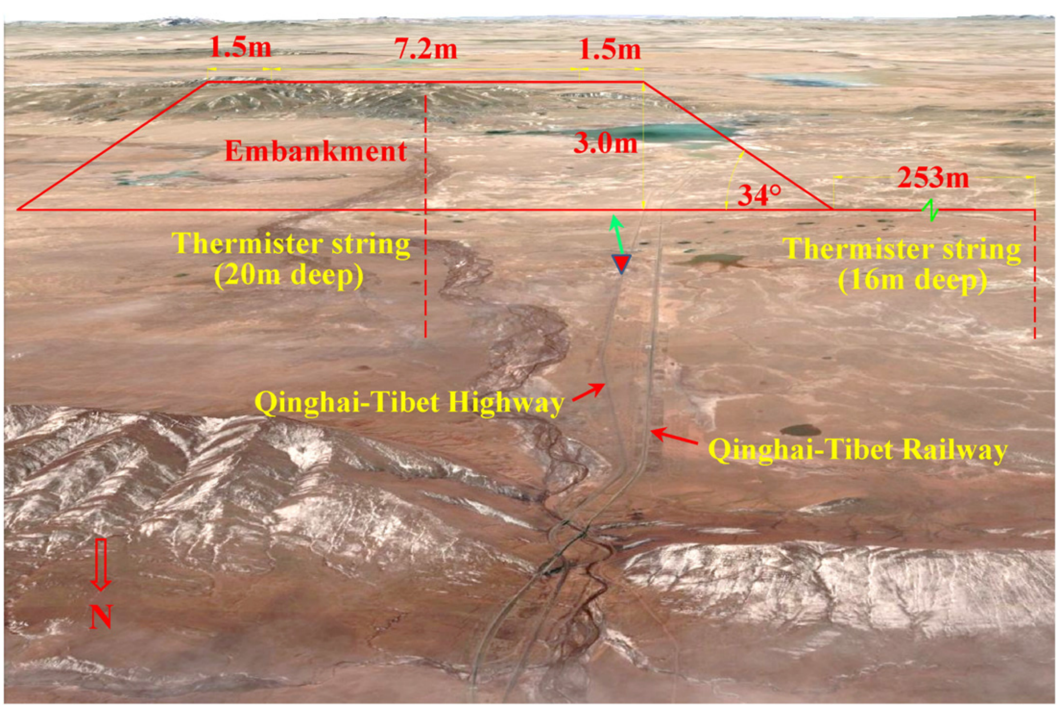

Fig. 1. Location of the in-situ observation and the cross section of the embankment.