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Dynamic process of the thermal regime of a permafrost tunnel on Tibetan Plateau

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ABSTRACT

The thermal status of the rock surrounding tunnel will change during construction and operation periods in cold regions, thereby affecting the stability of tunnel. Field observations of thermal regime of a permafrost tunnel were conducted on Tibetan Plateau. The results show that during the past 12 years, the surrounding rock experienced a warming that subsequently returned to the natural thermal regime, and that was followed by a cooling process. The thermal disturbance distance of the surrounding rock was approximately 30.5 m after the construction. Compared with the air temperature outside the tunnel, heat source of the construction has a great influence on the temperature of the permafrost surrounding the tunnel. The temperature of the permafrost is sinusoidally varying, which achieves a steady state after twelve freeze–thaw cycles. The mean annual ground temperature of the permafrost, and the maximum and minimum temperature amplitudes decreased with time. The heat convection between the air in the tunnel and the surrounding rock during the operation of trains needs to be considered for the design of the permafrost tunnel that could gradually reduce the temperature of the permafrost. The permafrost tunnel could occur to freeze–thaw damage for the sections that lack laid insulation material.

1. Introduction

The excavation of tunnels in permafrost regions could inevitably break the original thermal steady state. Then, a new boundary of convection ventilation forms. This change leads to the seasonal freezing-thawing in the surrounding rock. The long-term effect of the freezing-thawing cycles on the lining structure has a detrimental impact on the stability of the tunnel and its operation (Lai et al., 2009). The understanding of thermal regime of the surrounding rock of tunnels is the key to solve the frost-heave and thaw settlement problems of tunnel in cold regions. Thus far, many studies have been conducted on the thermal regime of the surrounding rock of tunnels by numerical methods. These studies predicted the temperature fields of the surrounding rock by considering heat conduction or convection or seepages or the coupled analyses of these factors (Lai et al., 1999, 2002; He et al., 1999; Zhang et al., 2002, 2004; Lai et al., 2005; Zhang et al., 2006; Tan et al., 2013; Zhou et al., 2016; Wang et al., 2016; Zeng et al., 2017). The stress and strain of surrounding rock are another key issue concerned by engineers. Frost-heave behind the lining because of water gather in winter is the main destructive pressure in cold regions (Lai et al., 1998, 2000; Lai et al., 2000; Gao et al., 2012; Feng et al., 2014). The popular way to mitigate the frost heave or thaw settlement of permafrost is to install insulation material behind the lining of tunnels, which has been applied in real engineering and was studied by numerical method (Zhang et al., 2002; Tan et al., 2014; Feng et al., 2016; Li et al., 2017). Insulation gate, electric heat tracing and thermosyphon are also studied to mitigate the frost problems of tunnels in cold regions (Lai and Wu, 2003; Lai et al., 2016; Zhang et al., 2017).

By now, there is no field data report to show the real response of the thermal regimes of surrounding rocks to the construction and operation of tunnels in permafrost regions. This paper presents some novel information interpreted from long-term field data obtained from a permafrost tunnel on Tibet Plateau. These findings are informative for tunnel designs in cold regions.

2. Site description and methodology

The Fenghuo tunnel is located in the mileage from DK1159 + 000 to DK1160 + 338 of Qinghai-Tibet railway in China, whose total length is approximately 1338 m, and whose highest altitude is approximately 4996 m. The excavation of the tunnel began in October 2001, the cut-through of the tunnel was implemented in October 19, 2002, and the

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construction of the outer lining structure was completed in August 2003. Moreover, the installation of the railway track was finished in November 2003, and the official opening and operation of trains occurred in July 2006. The Fenghuo Mountain tunnel, whose maximum buried depth is 100 m, and whose design slope in the longitudinal section is 1.2%, consists of a single track and a composite lining structure.

2.1. Geological conditions, climate and permafrost

The main strata of the Fenghuo Mountain tunnel are the proluvial and colluvial silty clay of the Quaternary Holocene, basal to the tertiary mudstone and sandstone. The proluvial silty clay, whose thickness ranges from 2.1 to 4.0 m, was distributed in the piedmont gentle slope zone of the tunnel inlet and outlet, has a brownish red color, has vegetation coverage, and is partly filled with a silt thin layer. The colluvial silty clay, whose thickness ranges from 1.0 to 2.1 m, was mainly distributed in the hillside and intermountain gentle slope, has a brownish red color, has sparse vegetation, and is filled with a silt thin layer. The primary terrane surrounding the tunnel is sandstone with a mudstone layer, which is well developed for joint fissures. The characteristics of sandstone and mudstone layers are similar in their bedded structure, have a worse diagenesis, and full light weathering. The sandstone layer consists of amaranth, has a fine structure and calcium cementation, while the mudstone layer has a politic texture, an argillaceous cementation, and a brownish red. The depth of the weathered layer at the inlet and outlet sides of the tunnel is generally more than 20 m, while it is 10–15 m in massif. Based on laboratory test, the active layer is a completely weathering layer with $\sigma_0 = 200$ kPa. σ_0 is the uniaxial compressive strength. Correspondingly, the permafrost layer is a weathered layer with $\sigma_0 = 400$ kPa, and the bedrock is a slightly weathered layer with $\sigma_0 = 800$ kPa.

The Fenghuo Mountain region resembles the climate type of the Tibetan Plateau with snow and ice, which is dry, changeable, with brief spring and autumn seasons, and with low air temperature and air pressure. Based on the meteorological observation data, its annual average air temperature is approximately −6.11 °C. The maximum and minimum average air temperatures in extreme cases are 23.2 °C and −37.7 °C, respectively. The mean annual rainfall and evaporation are 290.9 mm and 1316.9 mm, respectively. The relative air humidity and the maximum wind velocity are 57% and 31 m/s, respectively.

The Fenghuo Mountain tunnel, whose entire span is in permafrost, is the plateau permafrost tunnel (Fig. 1). There is no poor permafrost layer surrounding the tunnel except from the ice-rich permafrost, the ice-saturated permafrost, and the ice layer with soil, in its inlet and exit. The permafrost table ranges between 1.2 and 1.5 m in depth in the inlet side. The thicknesses of the ice-rich and the ice-saturated permafrost range from 2.1 to 4.0 m, which has rich content in the silty clay layer and at the interface between the soil and rock. The thickness of the ice-saturated permafrost ranges between 1.0 and 2.5 m in the weathered bedrock layer. The permafrost table ranges from 1.45 to 1.8 m in depth in the outlet side. The thickness of the ice-rich and ice saturated permafrost ranges between 1.75 and 4.0 m, which has rich content in the weathered bedrock layer. The bedrock of the tunnel trunk has low ice content and high ice content permafrost, and its permafrost table is approximately 1.5 m in depth. The ice-rich and ice-saturated permafrost is well developed among the weathered bedrock layer locally, and its thickness ranges between 1.0 and 2.5 m (Zhang et al., 2002, 2006).

2.2. Methodology

Combined with the Fenghuo Mountain tunnel of the Qinghai-Tibet railway, the observation site is located in the mountaintop at an altitude of approximately 4996 m in order to deeply investigate the long-term thermal regime response of the rock surrounding the permafrost tunnel (Fig. 2). The depth and drilling diameter of the thermometer hole are 100.4 m and 105 mm, respectively. The distance between the thermometer hole and the inlet of the tunnel is 799.9 m in the horizontal direction, while the distance in the vertical direction between the bottom of the thermometer hole and the innermost concrete lining structure is 0.5 m (Fig. 1). The ground and air temperature are respectively monitored by a thermometer cable and a thermometer with a 0.05 °C precision. The layout of the temperature sensors are listed in Table 1.

The observation data utilizes an automatic collection system considering the adversely environmental conditions, which is regularly loaded and analyzed. The frequency of observation is once a day. This study adopts monitoring data of the ground temperature collected from December 21, 2002 to March 19, 2014.

3. Results and analyses

3.1. The geotemperature of the surrounding rock

Based on the observed in-situ data of the ground temperature (Fig. 3), the variation of the ground temperature exhibits the typical characteristics of the permafrost. According to the maximum seasonal thaw depth recorded from 2002 to 2012, the permafrost table varied from 2.4 m to 2.9 m. However, the range changed from 2.9 m to 3.4 m in 2013. This change could have resulted from an increase of the mean annual air temperature. The surrounding rock was in a state of complete freezing under a depth of 3.4 m. The mean annual ground temperature was −2.58 °C, which is usually derived from the ground temperature at the depth of 34.4 m, with annual amplitude of ground temperature of 0.1 °C. The temperature distributions of different periods intersect at the depth of 65.4 m, and disperse from 65.4 m to 100.4 m. The change of the ground temperature amplitude for the observation points is equal to, or greater than 0.1 °C, and it ranges between 75.4 m and 100.4 m in depth. The ground temperature is gradually reduced as time progresses and the fluctuation range of the ground temperature increases upon the decrease of the distance between the observation points and the lining structure within the period from 2002 to 2013. This indicates that the tunnel construction and operation can produce a thermal disturbance to the surrounding rock.

Based on the field data, the temperature gradient of different time is calculated to illustrate the dynamics process of the thermal regimes of the tunnel's surrounding rock. It can be divided into three processes

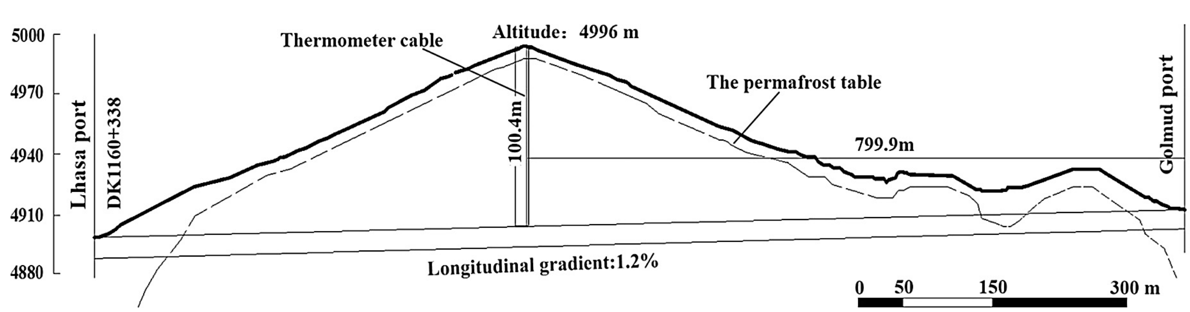

Fig. 1. The longitudinal profile of the Fenghuo tunnel.

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