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The thermal budget evaluation of the two-phase closed thermosyphon embankment of the Qinghai–Tibet Highway in permafrost regions

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ABSTRACT

The two-phase closed thermosyphon (TPCT) is a passive high-performance thermal transfer device that can efficiently decrease the ground temperature. However, only a few studies focus on the quantization of working efficiency of thermosyphons. Thus, in this study, based on data obtained from an experimental TPCT embankment on the Qinghai–Tibet Highway from 2004 to 2012, the ground temperature fields of the TPCT embankment were obtained, and the horizontal and vertical ground temperature characteristics were analysed. The results showed that the TPCT embankment exhibited better thermal stability than that of a traditional embankment. The artificial permafrost table was elevated to or maintained at the original natural level due to the cooling effect of the TPCT. To quantitatively analyse the cooling effect of the TPCT embankment, a thermal budget evaluation method is proposed. The calculated results revealed the dynamic working state of the thermosyphon during its service period. The annual average energy of the TPCT transferred in a year was generally determined to be between 1500 MJ and 2000 MJ. The results of this study could provide a method to evaluate the TPCT embankments and provide technological support in designing the TPCT embankments in permafrost regions.

1. Introduction

Frozen soil is a special type of soil that is highly sensitive to temperature change and consists of solidus mineral particles, ice inclusions, liquid water (unfrozen water and tightly bound water) and gaseous inclusions (water vapour and air) (Tsytovich, 1985). The physical and mechanical features of frozen soil are intrinsically unstable and depend on temperature (Zhou et al., 2000). As a result, construction work in permafrost regions must overcome challenges with the frozen ground soil (Cheng et al., 2008; Ma et al., 2009). Many permafrost-related engineering problems have been studied in infrastructure construction projects in permafrost regions over the past century (Ma et al., 2009). The Qinghai–Tibet Corridor is over 1000 km in length, 600 km of which resides in permafrost regions. In 1990, the permafrost-related damage rate of the Qinghai–Tibet Highway (QTH) in China was approximately 31.7% (Cheng and He, 2001; Ma et al., 2009; Wu et al., 2002). The thawing of permafrost ground is primarily attributed to the effects from modern society, particularly the combined effect of global warming and engineering disturbances. According to recent predictions, the mean annual air temperature on the plateau will increase by 2.2 °C to 2.6 °C by the year 2050 (Qin, 2002). From the QTH survey data, approximately 85% of the damage is caused by thaw settlement (Cheng et al., 2008). The stability of the embankment in permafrost regions is primarily affected by changes in the frozen ground soil. Many researchers have studied the thermal and mechanical stabilities of embankments in permafrost regions (Jin et al., 2012; Li et al., 2009, 2012; Ma et al., 2011; Qin and Li, 2011; Qin and Tang, 2011; Zhang et al., 2005) and concluded that measures to strengthen embankments should be performed to ensure long-term stability of traditional embankments, particularly in warm permafrost regions (Cheng, 2005a, 2005b).

One of the strengthening measures is to use a two-phase closed thermosyphon (TPCP), which is a passive high-performance thermal transfer device (Farsi et al., 2003; Noie, 2005). Characterised by continuous liquid–gas cycles of the working medium in a TPCT, the device can efficiently transfer heat from its evaporator section to its condenser section. Studies have shown that the effective thermal conductivity of the TPCT exceeded that of copper by 200–500 times (Noie, 2005). Due to its highly efficient cooling process, TPCTs have widely been applied in civil engineering projects in permafrost regions, such as railways, highways, airport and oil pipelines. In China, the TPCT test embankments on the Qinghai–Tibet Railway (QTR) were successfully established in 2001 (Yang et al., 2005). In this test project, TPCTs were installed on the shoulders of the embankments. The monitored data showed that the TPCTs effectively lowered the ground temperature. The working period of the TPCT was approximately 7 months, where the cooling radius was greater than 2.5 m. The monitored data of the thermosyphon embankments in the Chaidaer–Muli Railway project located in the Qinghai province of China indicated that the maximum radius of TPCTs could reach 2.3 m (Chen et al., 2011; Zhou et al., 2009). The TPCT effectively

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cooled the underlying permafrost and raised the permafrost table in this wetland (Zhang et al., 2011a). In addition, TPCTs were also built to remedy the serious thaw settlements of the QTH (Song et al., 2013; Wang et al., 2008). Compared with traditional embankments, a TPCT embankment can create a relatively long freezing period in a given year. The monitored data showed that the permafrost ground of the test embankments had maintained a relatively stable low-temperature condition (Song et al., 2013). Xu and Georing (2008) reported an application of a new combined structure with a TPCT and an air convection embankment near Fairbanks, Alaska, which could effectively reduce the embankment and foundation soil temperature.

In recent years, many researchers have focused on determining the working characteristics of the TPCT embankments by numerical simulations and laboratory tests. Shabgard et al. (2014) developed a two-dimensional numerical model to predict the optimal filling ratio of a TPCT. B. Zhang et al. (2011) and M.Y. Zhang et al. (2011) presented a three-dimensional model that coupled the air–thermosyphon–soil for a TPCT embankment, which for the first time, considered the convective heat transfer between the wind and the TPCT. This study has an important theoretical significance in the computational theory of the TPCT. Wen et al. (2005) suggested a combination of thermal-insulation and a TPCT to protect warm permafrost ground using numerical computation. Zhang et al. (2013) performed a laboratory experiment to study the heat transfer characteristics and working state of a TPCT placed in soil. Lai et al. (2009) presented an L-shaped TPCT with a crushed-rock revetment and insulation. The laboratory test indicated that this joint structure could better cool permafrost ground. Furthermore, Dong et al. (2010) studied the long-term thermal stability of high-grade highway with a length of 26.0 m with this special structure installed. Wang et al. (2005) hypothesised that the working process of a TPCT was not continuous and instead, fluctuated during a single working cycle. In addition, many other researchers have performed similar studies.

Many studies have investigated the influence of structure parameters on the working process of TPCTs, such as length, declining angles and filling ratio (Haynes et al., 1992; Hichem et al., 2003; Payakaruk et al., 2000; Yang et al., 2005, 2006; Zarling and Braley, 1988). However, there are few studies that have quantified the working efficiency of TPCTs. There are only a few researchers that are focused on this field. Wu et al. (2010a, 2010b) estimated the entire heat income/expenses of the TPCT embankment on the QTR at the Beilu River site and determined an average “generation of cold quantity” of a single TPCT, which was approximately 1259 MJ per year. Xu and Xiong (2006) computed the cooling capacity of the TPCT embankment on the QTR at the Qingshuihe test section. In this study, monitored data of TPCT embankments at the QTH were collected from 2004 to 2012. The thermal budget evaluation of the TPCT was based on the monitored data. The research results of this study could provide a quantitative evaluation of TPCT embankments for engineering projects and provide technological support in designing the TPCT embankments in permafrost regions.

2. Experimental engineering project on the TPCT embankment along the QTH

From 2002 to 2004, a reinforcement/rebuilding project for the QTH from Golmud to Lhasa was performed to remedy the serious thaw deformation problem that was caused by the effect from the thermal accumulation of the asphalt pavement in the permafrost regions. In this project, a nearly 2.0-km long experimental engineering project on the TPCT embankment was built from K 2937 + 100 to K 2939 + 160 along the QTH in the Chu Kumar River Plain to control the clearly observed shady–sunny effect.

The experimental engineering project was located in the Chu Kumar River Plain, which is characterised by a flat topography. There is sparse vegetation in these regions, except for the developed thermokarst lakes, and it has an average elevation of over 4400 m. The directions of the QTH were 70° south by west in these regions. The experimental embankment experienced a significant shady–sunny effect. Due to the offset thaw bulb resulting from the shady–sunny effect, the embankment problems, which include longitudinal cracks, sliding collapses and thaw settlement, are extremely common in these regions. Therefore, a one-sided TPCT embankment was designed at the sunny slope of the embankment (Fig. 1). It should be noted that the left side of the embankment was on the sunny side, and the right side was on the shady side. Up to 1558 TPCTs were used in the experimental embankment in the Chu Kumar River Plain on the QTH. The longitudinal space of the TPCT was 4.0 m; the distance from the TPCT to the central line of the embankment was 5.1 m. The length of the TPCT was 12.0 m. The evaporator and condenser sections were 6.0 m and 4.0 m, respectively, with a diameter of 83 mm. The working temperature limitation of the TPCT was from −60 °C to +60 °C with a maximum power of 6.0 kW.

The heights of the experimental embankment in the regions varied from 2.0 m to 3.8 m. Two insulating berms were designed at both sides of the embankment with heights between 1.0 m and 1.5 m and widths between 2.0 m and 5.0 m. The natural and artificial permafrost tables varied from 2.7 m to 3.0 m and from 5.7 m to 7.7 m, respectively. The frozen soil types in these regions are typically ice-rich permafrost with a mean annual ground temperature between −0.8 °C and −1.0 °C. According to the geological transverse section (Fig. 2, Song et al., 2013), the stratigraphical structure can be divided into three parts. Part I consists of silty clay; part II consists of pebbly clay; part III consists of strongly decayed mudstone.

The experimental embankment construction began in 2002 and was completed in October 2003. To investigate the long-term stability of the TPCT embankment, a monitoring system for the field-test embankment was installed at K2939 + 120 along the QTH. At this monitoring section, ground temperatures were monitored by thermal probes, and the data were collected twice a month. Furthermore, another monitoring section at K2939 + 185 that did not have any cooling measures was installed to contrast the cooling effect of the TPCT. At each monitoring section, 5 temperature boreholes were embedded, including a central bore, left-shoulder bore, right-shoulder bore, left-toe bore and right-toe bore. In addition, another two temperature boreholes around the TPCT were installed at K2939 + 120 to monitor the horizontal working state of the TPCT.

3. Working state of the TPCT embankment

3.1. Analysis of the ground temperature fields of the TPCT embankment

Figs. 3 and 4 show the ground temperature fields of a traditional embankment and the TPCT embankment on Oct. 20 in 2005 and 2008. During this season, the permafrost table under the embankment

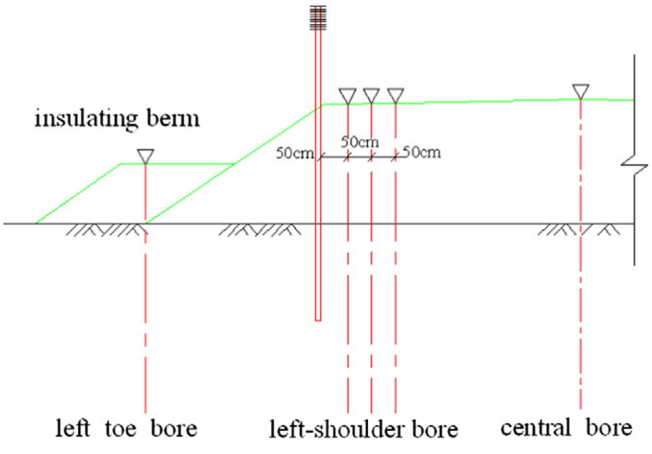

Fig. 1. Distribution of ground temperature boreholes in cross section.