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Research Paper

Cooling performance of two-phase closed thermosyphons installed at a highway embankment in permafrost regions

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HIGHLIGHTS

- Long-term monitored data are presented for a road section of the Qinghai-Tibet Highway before and after installing the TPCTs.
- Cooling scope and period of the TPCTs are analyzed; cooling effects for the soil layers are examined.
- Cooling performance of the TPCTs is discussed from the perspectives of embankment deformation and crack formation.
- Some suggestions are proposed for a better design of the TPCTs in highway constructions in permafrost regions.

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ABSTRACT

Two-phase closed thermosyphon (TPCT) is a popular way to prevent permafrost layers from degrading, and consequently ensure the stabilities of engineering constructions in permafrost regions. Although TPCTs have been numerically and experimentally investigated for many years, long-term field monitored data concerning the cooling performance of TPCTs are limited. This paper presents the ground temperatures, embankment deformations and some related meteorological factors for a road section of the Qinghai–Tibet Highway before and after installing the TPCTs in permafrost regions. Based on the monitored data, three main aspects are analyzed: 1) cooling scope and period of the TPCTs; 2) cooling effects for the soil layers, especially for the permafrost layers; and 3) remedying effects with respect to embankment deformation and crack formation. Some corresponding suggestions are proposed for a better design of TPCTs in the construction of roadways in permafrost regions.

1. Introduction

In permafrost regions, engineering constructions have been suffering different levels of deformations caused by permafrost degradation [1,2]. Taking the Qinghai–Tibet Highway as an example, 31.7% of the road sections from Golmud to Lhasa (520 km) in the permafrost regions faced roadbed diseases in 1999 [3], among which 85% of them were caused by thaw settlement [4]. Under global warming and the thermal effect caused by road embankments, the underlying permafrost layers are degrading [5]. Thaw consolidation has been considered to be the main cause of embankment deformation for a long time [2]. In recent years, creep of warm permafrost layers has also been proved to be another main cause [6,7]. It is found that the two deformation causes are exactly the main reason why the Qinghai–Tibet Highway was reconstructed and repaired for many times [8,9]. In addition, 79% of the permafrost regions on the Qinghai–Tibet Plateau were characterized by “warm permafrost”, where the mean annual ground temperatures (MAGTs) were higher than −1.5 °C [10]. The easy-to-thaw characteristic determines that some cooling methods should be taken to protect the permafrost layers from degrading, and thus to ensure the stabilities of the engineering constructions.

Two-phase closed thermosyphon (TPCT) is one of those cooling methods, which has already been used in permafrost regions for many decades. For instances, the TPCTs were successfully used in the Trans-Alaska Pipeline System between 1974 and 1977 [11]. The TPCTs were also proved by in-situ geothermal observation between

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1990 and 1997 to be a reliable technology for rehabilitating a housing with unacceptable settlement on the Ellesmerer Island, Canada [12]. In China, the TPCTs have been frequently employed to insure the stabilities of the Qinghai–Tibet Highway [13,14], the Qinghai–Tibet Railway [15,16], and the Chaidaer–Muli Railway [17]. In addition, other cooling methods were combined with the TPCTs for better cooling effects, such as crushed rock revetment [18,19], forced-air ventilation [20] and insulating material [21]. In these engineering constructions, the evaporator sections were embedded in the soil layers, while the condenser sections were exposed in the air. The TPCTs only work when the temperature difference exceeds the threshold, i.e. the start-up temperature difference. Zhang et al. [22,23] found that it was about −0.2 °C by means of indoor physical model test and a self-designed experimental apparatus.

In order to enlarge the cooling range underneath the embankments, inclined TPCTs have been numerically and experimentally investigated [23,24]. Besides the inclining angle, there are three other influencing factors of the cooling performance of the TPCTs, including aspect ratio (the ratio between evaporator length and internal diameter), filling ratio (the ratio between the volumes of working fluid and evaporator section) and working fluid [23]. The influencing factors have been extensively investigated by previous researchers [23,25–28].

With respect to the previous numerical modeling work, for a simplified calculation, the thermal resistance of the TPCTs were usually ignored and the heat-convention coefficient between air and the radiating fins was taken as a constant when the TPCTs were working [21,29–31]. On the other hand, the heat transfer coefficients for every part of the TPCTs were introduced by Pan and Wu [32], based on which a coupled air-TPCT-soil model was put forward [33]. For ease of calculation, however, some empirical formulas were adopted for calculating the heat resistances in the coupled model, which may lead to some unavoidable errors. Under this circumstance, a fully-coupled model is urgently needed. The governing equations in the three zones have already researched respectively. The three governing equations in the air zone are continuity, momentum and energy equations [34,35]. Also, the three equations are usually used for simulating two-phase flows in TPCTs [36–38]. In the soil layers, the heat transfer equation with phase-change considered is usually adopted [39–41].

From the above analyses, it can be found that the TPCTs have been considered to be a popular and efficient way to ensure the stabilities of the engineering constructions in permafrost regions, especially in warm permafrost regions. There are many influencing factors for the cooling performance of the TPCTs, which needs further investigation. A fully-coupled air-TPCT-soil model is urgently needed for a better prediction. To date, long-term field monitored data about the cooling performance of the TPCTs are currently lacking. This would be favorable for understanding the cooling performance of the TPCTs, and for establishing the fully-coupled model for the stabilities of the engineering constructions in permafrost regions.

In this paper, more than 10-year monitored data including ground temperatures, embankment deformations and some related meteorological factors are presented for a road section installed with TPCTs in permafrost regions. The main objective is to examine the cooling performance of the TPCTs from the perspectives of thermal and mechanical (deformation) stabilities.

2. Monitoring program

The monitoring program was carried out at a road section of the Qinghai–Tibet Highway. The highway mileage is K3187 + 000, while the place is named as Kaixinling. The longitude and latitude are N33°57′29″ and E92°20′58″ respectively, and the geographic position can be seen in a previous paper [42]. An illustration of the instrumented road section is shown in Fig. 1. Ground temperatures and embankment deformations were started to monitor in 2003. Due to an unacceptable embankment deformation, TPCTs were installed around September 2009. The working fluid is anhydrous ammonia, while the container is made by carbon steel. As shown in Fig. 1, the lengths of the three parts of the TPCTs, condenser, adiabatic and evaporator, are 4, 3 and 5 m respectively. Some other parameters of the TPCTs are summarized in Table 1. A meteorological station was established in Aug. 2008. Detailed information about these three monitoring items is introduced in the following.

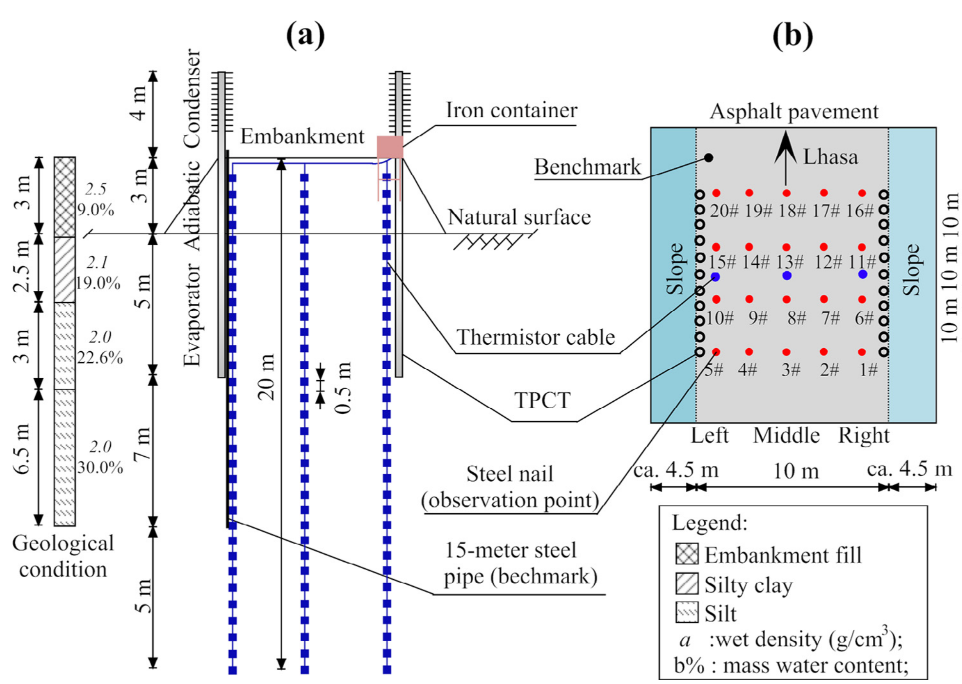

Fig. 1. Schematic cross-section (a) and plan (b) of the instrumented road section installed with TPCTs.