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Thermal performance of a combined cooling method of thermosyphons and insulation boards for tower foundation soils along the Qinghai–Tibet Power Transmission Line

Yanhu Mu [a], Guoshang Wang [b], Qihao Yu [a,*], Guoyu Li [a], Wei Ma [a], Shuping Zhao [a]

[a] *State Key Laboratory of Frozen Soils Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China*
[b] *Gansu Electric Power Design Institute, Lanzhou 730050, China*

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ABSTRACT

Preliminary field observations along the Qinghai–Tibet Power Transmission Line (QTPTL) show that foundation soils of some shallow footings (with an embedding depth of 3.7 m) with thermosyphons in permafrost regions still suffer substantial and rapid thaw settlement in warm seasons. In this paper, a series of numerical simulations on the long-term thermal performance of foundation soils of these shallow footings are carried out. The simulated results show that thermosyphons could do effectively cool foundation soils at depths 2.5 to 8.0 m under the footing. However, in warm season from mid-May to mid-October, the rapid warming of shallow foundation soils near the footing caused by heat transfer through the concrete footing could not be prevented. The maximum thaw around the footing could be as much as 1.0 m deeper than that in the natural ground. Under a warming climate, the maximum thaw around the footing would go deeper than the embedding depth of the footing with four thermosyphons in very warm (≥−0.5 °C) permafrost regions and with two thermosyphons in warm (≥−1.0 °C) permafrost regions during a 50-year operational period. To retard thaw penetration around the footing, a combined cooling method of thermosyphons and insulation boards is proposed for foundation soils. Numerically simulated results show that the additional placement of the boards on ground surface could prevent the rapid warming of shallow foundation soils and effectively reduce the maximum thaw around the footing. The method could also effectively delay permafrost warming under the footing. Thus, it is recommended to be used at shallow footings in very warm, ice-rich permafrost regions along the QTPTL.

1. Introduction

Due to increasing anthropogenic activities and climate warming, permafrost on the Qinghai–Tibet Plateau (QTP) has experienced noticeable degradation during the past 40 years (Cheng and Wu, 2007; Jin et al., 2008). The thaw settlement associated with permafrost degradation can have major impacts on the performance of engineered infrastructures. Buildings, roads, power transmission line networks and pipelines in ice-rich permafrost regions on the QTP have already been affected by thaw settlement, exponentially increasing their maintenance costs and greatly shortening their useful life-span (e.g., Jin et al., 2005; Ma et al., 2009; Wu and Niu, 2013). To protect engineered infrastructures against permafrost thawing problems, various thermal protection techniques have been developed. Two of the most widely used techniques are thermosyphons and ground thermal insulation. A thermosyphon works as an effective thermal semiconductor, which is achieved by evaporation of the working liquid in the evaporator section, condensing in the condenser section and returning of the condensate (Noie, 2005). Thermosyphons of various designs have been widely used for cooling of foundation soils of buildings, roads, railroads and pipelines in northern and permafrost regions (Esch, 1988; Hayley et al., 1983; Heuer, 1979; Leong and Hornby, 1996; Smith, et al., 1991; Terry, 1987). In recent years, thermosyphons were used as a mitigation method for roadway and railway embankments experiencing large settlement on the QTP (Ma et al., 2009; Song et al., 2013; Yu et al., 2014). Because of the advantages of structural simplicity and low cost, ground thermal insulation, using an insulation layer on ground surface over foundation soils, has also been widely used for roadways and airfields in areas of permafrost and deep seasonal-frost (Cheng et al., 2004; Esch, 1973; Johnston, 1983; Olson, 1984; Smith et al., 1973; Saarelainen, 1993; Molmann, et al., 1998; Wen et al., 2005; Zhang et al., 2008). In the northern regions of Canada, insulation sheets have also been used for power transmission line foundations (Duan and Naterer, 2010; Staudzs, 1982).

The Qinghai–Tibet Power Transmission Line (QTPTL) runs from Golmud, Qinghai Province in the north, to Lhasa in Tibet Autonomous Region in the south, crossing the central area of the QTP (Yu et al., 2013). The total length of QTPTL is about 1038 km, of which 550 km cross permafrost regions. In these permafrost regions, there are a total

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* Corresponding author. Tel.: +86 931 4967283.
E-mail address: yuqh@lzb.ac.cn (Q. Yu).

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of 1207 towers and more than 70% of them are founded on precast or cast-in-place footings. Most of these footings are buried at depths ranging from 3.7 to 6.0 m (Yu et al., 2012). To significantly improve the long-term stability of foundation soils in the actual context of climate warming, thermosyphons are extensively used at these footings for cooling foundation soils. Preliminary field observations along the QTPTL show that, when a footing is embedded at a shallow depth, such as 3.7 m, foundation soils around and under the footing cool noticeably due to the thermosyphon cooling in cold seasons. However, in warm seasons, shallow foundation soils near the footing warm more rapidly, and thaw penetration around the footing can be as much as 2.0 m greater than that in the natural ground. Heat transfer through the concrete footing is considered as the contributive factor in the rapid warming of shallow foundation soils (Duan and Naterer, 2008; Yu et al., 2013). Displacement observations along the QTPTL show that a substantial seasonal and accumulative settlement occurs at some of these shallow footings, especially in warm, ice-rich permafrost regions.

To more effectively retard thaw penetration around these shallow footings, a combined cooling method of thermosyphons and insulation boards is proposed for foundation soils. Thermosyphons in combination with insulation boards were firstly recommended as a method to increase the bearing capacity of fiction piles in permafrost regions (Long, 1973). In the maintenance and upgrading of embankment along the Qinghai–Tibet Highway, this combined cooling method was used in thermally unstable permafrost regions. Field observations show that the method can effectively cool the roadbed (Liu, 2013). Wen et al. (2008) proposed the method for embankment of the Qinghai–Tibet Railway. Numerically simulated results show that the method can provide a much better protection of permafrost foundation, especially in reducing thaw penetration in the subgrade under a warming climate. In this paper, first of all, the long-term thermal performance of foundation soils of these shallow footings with only thermosyphons is simulated using a coupled heat transfer model for the air–thermosyphon–soil system. Then, the long-term cooling effect of the combined cooling method is simulated by using the same model.

2. Numerical model and parameters

2.1. Coupled heat transfer model for the air–thermosyphon–soil system

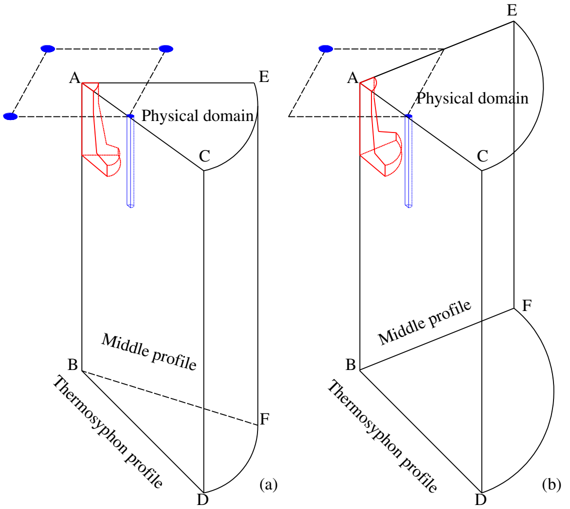

Fig. 1. Sketches of physical domains of tower foundation soils cooled by four (a) and two thermosyphons (b). In red is the tower footing and the half-cylinder in blue is the evaporator section of thermosyphon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

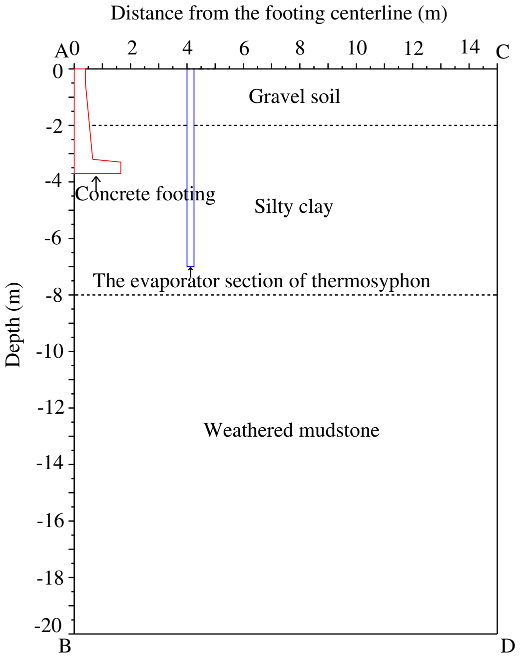

Fig. 2. Geometry and soil strata of the computational model plotted in the thermosyphon profile of a footing with two or four thermosyphons. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

The heat transfer processes in foundation soils are based on the theory of heat conduction with phase change of soil moisture. Since the ratio of thermal conduction is much larger than that of convection during the freezing and thawing process of soil (An et al., 1990), the convection and mass transfer within foundation soils were not considered. The governing equation of heat transfer processes in foundation soils can therefore be written as (Lai et al., 2009; Zhang et al., 2011):

$$C_e\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda_e\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_e\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_e\frac{\partial T}{\partial z}\right) \qquad (1)$$

where C_e and λ_e are the effective volumetric heat capacity and effective thermal conductivity of foundation soils, respectively. It is assumed that phase change of soil moisture occurs in a range of temperature $T_m \pm \Delta T$. The volumetric heat capacity and effective thermal conductivity of thawed and frozen soils are taken as constants regarding to the temperature (T). Using the method of sensible heat capacity, the definitions of C_e and λ_e can be written as (Li et al., 2009; Zhang et al., 2011):

$$C_e=\begin{cases} C_{sf} & T<T_m-\Delta T\\ \frac{L_s}{2\Delta T}+\frac{C_{sf}+C_{su}}{2} & T_m-\Delta T\le T\le T_m+\Delta T\\ C_{su} & T>T_m+\Delta T\end{cases} \qquad (2)$$

$$\lambda_e=\begin{cases} \lambda_{sf} & T<T_m-\Delta T\\ \lambda_{sf}+\frac{\lambda_{sf}-\lambda_{su}}{2\Delta T}[T-(T_m-\Delta T)] & T_m-\Delta T\le T\le T_m+\Delta T\\ \lambda_{su} & T>T_m+\Delta T\end{cases} \qquad (3)$$

where the subscripts sf and su denote the frozen and unfrozen states of foundation soils, respectively, and L_s is the volumetric latent heat of foundation soils.

Based on the thermal balance, the heat intake of the evaporator section of a thermosyphon is equal to the heat output of foundation soils. Thus, the heat transfer model for the air–thermosyphon–soil system can be coupled and written as:

$$Q=\frac{T_a-T_s}{R}=-\lambda_e\frac{\partial T}{\partial n}\pi d_o l_e \qquad (4)$$

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