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Stability analysis of transmission tower foundations in permafrost equipped with thermosiphons and vegetation cover on the Qinghai-Tibet Plateau

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ABSTRACT

During the construction of the ±400 kV direct current power transmission line (DCPTL), frozen blocks were backfilled into the foundation pits in permafrost regions because of the lack of backfilling materials and other problems, but this resulted in less compact backfilled soils. To ensure the stability of the tower foundations, a large number of thermosiphons were installed. This study discusses the threat to the stability of tower foundations of water infiltration along the large voids created within the backfilled soils by the use of frozen blocks, and quantifies the efficacy of a combination of thermosiphons and vegetation cover in enhancing tower stability, based on field collected data from January 2011 to April 2017. The results indicate that the cooling effects of thermosiphons caused a large amount of net heat removal from the foundation soils, even during the first operational year of the foundation, while foundation soils without thermosiphons exhibited net heat input during the same period. Ponding in the pits and downward infiltration of water obviously work to warm the foundation soils, and can result in the settlement of the tower footings, threatening the tower stability. The combination of thermosiphons and vegetation cover is shown to effectively cool the foundation soils and to reduce the settlement of the footings, thus ensuring the continued tower stability. This study also shows that the backfilling of frozen blocks should be avoided in the current climate conditions, even though effective cooling measures like thermosiphons are used because the downward infiltration of water along the large voids between the frozen backfilled blocks can't be totally prevented. If the current degradation of the frozen state of the backfilled soils continues, the infiltrated water, which has been frozen at the bottom of the backfill, will begin to thaw again, threatening the stability of the tower foundations.

1. Introduction

The project of the ±400 kV direct current power transmission line (DCPTL) from Golmud in Qinghai province to Lhasa, Tibet Autonomous Region, China is an important part of the Qinghai-Tibet Power Transmission Line and is of great significance to the economic and social development of the Tibet Autonomous Region of China [31]. The DCPTL, generally paralleling to the Qinghai-Tibet Highway (QTH), traverses ~550 km of permafrost region at an altitude higher than 4000 m; a region that exhibits a relatively warm and ice-rich environment compared to higher latitude permafrost environments, presenting challenges associated with the mechanical sensitivity of structures to temperature variation [23,32]. Under conditions of a warming permafrost on the Qinghai-Tibet Plateau (QTP) [25,7], engineering structures will be forced to confront the threat of subsidence resulting from thaw settlement and creep of underlying warm ice-rich permafrost [20,1,33]. In response to such threats, lowering the temperature of the frozen foundation soils seems, in most cases, to present an effective approach for increasing the stability of structures in permafrost regions [8].

Many different engineering measures have been proposed to cool the foundation soils that underlie engineering infrastructure, and the effectiveness of some of these measures have been verified through field application [9]. Among these measures, the two-phase closed thermosiphon (or simply "thermosiphon"), processing an effective thermal conductivity 200–500 times that of copper, is one of the most efficient. Due to its high heat conductivity, a thermosiphon can efficiently pump a large amount of heat

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from soils into the atmosphere when the air is colder than the soil [13]. When a thermosiphon begins to work, a frozen bulb forms around the thermosiphon and expands in diameter quickly with the continued operation [19], strengthening the foundation soils as well as reducing the migration of moisture within the soils during the freezing process. The literature indicates that the use of a thermosiphon can both reduce the settlement and frost jacking of an engineering structure, and this technology has accordingly been widely installed to cool and stabilize the soil supporting many types of infrastructure in permafrost regions, such as highways, railways, oil pipelines, transmission lines, tunnels, and houses [2,3,4,16,29,37]. Although the local-cooling effects of thermosiphons have been observed to cause longitudinal cracking along road embankments [19,30], their application has generally been successful, especially in conjunction with the pile foundations widely used for oil pipelines, transmission lines, and houses.

Based on the many successful experiences using thermosiphons in permafrost regions, about 7000 thermosiphons were installed with the tower foundations along the DCPTL to mitigate the likely effects of future tower settlement caused by the degradation and thawing of frozen foundation soils under a warming climate and increasing anthropic activities. These thermosiphons work as passive cooling devices, relying on 0.076-m diameter liquid ammonia-filled sealed tubes to refrigerate the surrounding soil. The thermosiphons used in this project were manufactured by the Jiangsu Sunpower Technology Co., Ltd. in Nanjing, China. The evaporation section of each thermosiphon was installed at depths of 7 m or 9 m and the length of the condensation section above ground was 2.0 m. The methods used to determine the thermosiphon layout allowed for variation in accordance with the properties of each foundation, such as ground-ice content and foundation type. The general layout parameters are described as follows. In warm (≥−1 °C) and high ice-content permafrost regions, four thermosiphons were installed around each excavated footing as shown in Fig. 1a, and two thermosiphons were installed near each pile such that the line between each pair of thermosiphons was orthogonal to that of its neighbors and the direction of pile batter, as shown in Fig. 1c. In cold (<−1 °C) and high ice-content permafrost regions, two thermosiphons were installed near each footing as shown in Fig. 1b, and one thermosiphon was installed near each pile to the outside of the pile batter, as shown in Fig. 1d. No thermosiphons were used for foundations in ice-poor or ice-medium permafrost regions. For excavated footings, the thermosiphons were installed close to the corners of the footing caps, and ~2.5 m from the center of the footing. The thermosiphons were installed by drilling boreholes more than 1 month after the concrete footings were cast. Once the thermosiphons were installed, the boreholes were filled with a sandy soil. Because the boring machine could not be located too close to the concrete footings, for pile foundations, the thermosiphons were installed 0.3–0.5 m away from the footings. Additional details about the thermosiphons used in this research can be found in [2].

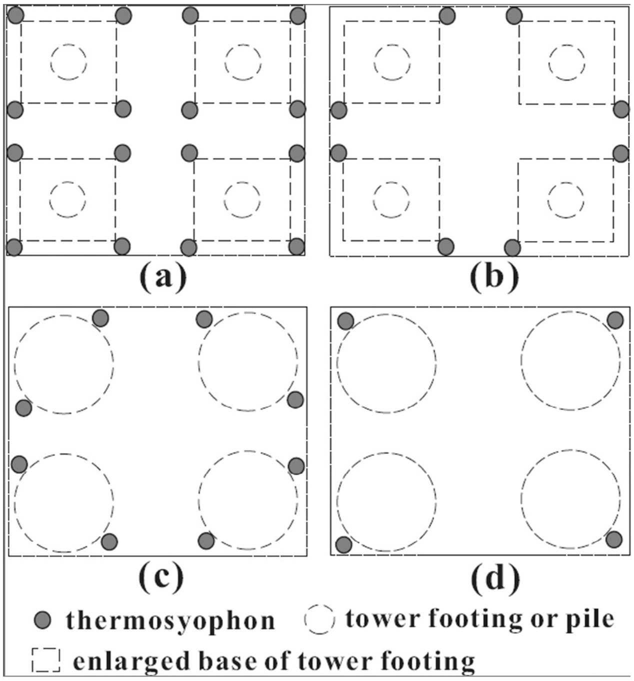

Fig. 1. Layout of thermosiphons used with tower foundations. (a) Four thermosiphons around every excavated footing in warm permafrost regions; (b) two thermosiphons around every excavated footing in cold permafrost regions; (c) two thermosiphons near each pile in warm permafrost regions; (d) one thermosiphon near each pile in cold permafrost regions.

Compared to the linear foundations found on structures such as highways and railways, upon which the application of thermosiphons may trigger the development of cracks [30], thermosiphons may be more suitable for cooling the soils surrounding tower foundations due to their locally-acting characteristics. Studies investigating the cooling performance of thermosiphons have been conducted using many laboratory, on-site, and numerical experiments. Numerical simulations in particular have demonstrated that thermosiphons can efficiently cool the soils surrounding foundations [35,12,14,36], and thus provide a real benefit to the stability of the supported structure in most cases. Indeed, most of the simulated results have been proven generally consistent with data from field monitoring or laboratory tests [2,35,12,14,36].

Notably, however, the application of thermosiphons inevitably results in an increase in the temperature difference between deep and shallow foundation soils, increasing the heat absorption of foundation soil in warm seasons, consequently shindering the cooling efforts of the thermosiphons. Therefore, insulated assistant materials, such as insulation board and ballast, are frequently used in tandem with thermosiphons, typically with good results [4,11]. Yet the extensive use of materials such as insulation board can present a significant threat to the fragile environment of the permafrost regions on the QTP, while the use of ballast layers can result in an undesireable increase in the construction cost, suggesting that a cheaper and more environmentally friendly assistant material must be developed before this technology can be widely applied to engineering structures. Among the potential assitant materials, vegetation is a promising option due to its environment-friendly properties despite some limitations [24]. To test the effectiveness of vegetation as an insulating assitant material, seeds were planted around most completed towers along the DCPTL, some vegetation was transplanted by the authors to the foundation experimentally evaluated in this paper [18,38]. In this study, the authors attempt to (1) illustrate the thermal influence of thermosiphons on the surrounding soil; (2) study the effect of a combination of thermosiphons and vegetation on tower stability; and (3) discuss potential threats to tower stability under the current engineering conditions, based on field-collected data in the Qingshui'he region on the QTP along the DCPTL from 2011 to 2017. It is expected that this investigation will provide useful insights for the future design and construction of infrastructure in cold regions.

2. Study site and data acquisition

The monitoring site used in this study is located at Chumaer'he along the DCPTL, which has been systematically described in [2].