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Experimental study on heat transfer of upright pipes in cold regions

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HIGHLIGHTS

- A new technique for cooling permafrost embankment is presented.
- Laboratory experiment is conducted to investigate the heat transfer characteristic.
- The up-right pipe can cool the surrounding soil.

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ABSTRACT

Laboratory experiments are conducted to investigate the heat transfer characteristics of upright pipes under periodic ambient temperatures. The results provide evidence to support the use of upright pipes in permafrost engineering. This paper presents two models with different inlet pipe diameters. The results indicate that the mean periodic temperatures at the bottom of the pipe and soil decrease with increasing freeze-thaw cycles and ultimately remain in a frozen state. Natural convection is the dominant mode of conducting heat exchange between the upright pipe and air. The inlet diameter greatly affects both the cold energy accumulation at the pipe bottom and the cooling efficiency. Furthermore, the lateral thermal disturbance distance of the upright pipe is approximately more than one fold of the inlet diameter. Therefore, the upright pipe enhances the cooling effect to the surrounding soil and is recommended for the cooling of permafrost foundations.

1. Introduction

Permafrost degradation affects the structural and functional capacities of infrastructures built due to the climate change and anthropogenic activities [1,2]. The thaw settlement and cracking patterns for permafrost embankment are commonly observed in areas of permafrost [3,4]. The proactive cooling strategies were used to lower the underlying ground temperature in order to mitigate the settlement problem [5]. For example, thermosyphon, crushed-rock layers, and forced ventilation ducts have been adopted along the Qinghai-Tibet Engineering Corridor [6–8]. Composite embankment incorporated adaptive strategies mentioned above has better cooling effect validated by field observations, laboratory tests, and numerical simulations [9–11].

At present, old infrastructure and planned wide pavement embankments are facing new problems associated with local warming of the infrastructures. Because of multi-lane and high-temperature asphalt surfaces, heat spread is difficult in the atmospheric environment, resulting in concentrated heat accumulation at the centerline of the embankment [12,13]. Concrete tower footings along the Qinghai-Tibet DC transmission line are good thermal conductors and strengthen the heat input to frozen foundations, accelerating thermal increase of the surrounding soil [14,15]. Due to the significant south-facing slope effect in Qinghai-Tibet Plateau, the foot of the south-facing slope can be deepened the permafrost table caused the uneven settlement of embankment [16,17]. The mentioned above could accelerate thaw of the underlying permafrost producing serious threat to the stability of engineering structures. However, the existing cooling strategies could not be completely applied for kinds of problems. Although thermosyphon can adjust the local infrastructural thermal regime, the exposed

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finned-condenser sections of thermosyphon are high cost and working fluid is unstable performance [18]. The installation of traditional thermosyphon adjacent to a roadway is also a safety concern for transportation. Crushed-rock layers under sand-filling generated that natural convection intensity weakened gradually with the increasing thickness of sand-filling, which cannot cool the permafrost anymore under the scenarios of sand-filling and climate warming [19,20]. Current forced ventilation ducts allow heat extraction beneath the embankment by wind-driven convection in a pipe installed through embankment cross section [1]. But they cannot be applied to cool local parts of infrastructures. Therefore, how to cope with local warming of the infrastructures should be investigated.

This paper presents a new technique, involving the use of upright pipes, to cool local parts of infrastructure, such as the center median divider of wide pavement highways, the foot of the south-facing slope, and the tower foundation. The heat transfer characteristics of the proposed structure were investigated in a laboratory under the conditions of periodic-changes in the air temperature and a negative mean air temperature.

2. Experimental design

2.1. Experimental equipment

The environmental testing box consisted of four parts: the experimental modeling box, the auto-temperature controller system, the ventilation system, and the data acquisition system. The interior dimensions of the modeling box are $8.0 \times 1.84 \times 2.7$ m and the box walls contain 10-cm-thick the rock wool insulation layer with 0.032 W/m °C of the thermal conductivity.

The auto temperature controller system consists of a double-head SANYO compressor (7.5 kW), an automatic temperature controller (precision: ±0.3 °C), an evaporator, and a temperature sensor (precision: ±0.1 °C). The temperature controller can manually change the modeling box air temperature to reach the desired steady state temperature. The control temperatures range from -60 °C to +50 °C.

The ventilation system consists of cooling fans, speeding fans, a wind-velocity-controlling instrument, and a passage for wind circulation. The wind is parallel to the longitudinal direction of the modeling box and is regulated by adjusting the direction of the window shades.

The data acquisition system consists of 18 temperature sensors (precision: ±0.05 °C), a data logger (CR3000) and a desktop computer. The monitoring data were collected at intervals of 10 min.

2.2. Experimental model

In order to investigate the cooling effect and heat-transfer properties of the upright pipe, two models with different inlet diameters (denoted by the symbols M_1 and M_2) were designed for comparison under the same ambient temperature (Fig. 1). Case M_1 has an orifice inlet diameter of 7 cm and case M_2 has an inlet diameter of 15 cm. The pipe bodies for both cases have a uniform diameter of 15 cm. The height between the inlet and the soil surface is 20 cm for the two cases. The bottom and sides of the model have a 10-cm-thick thermal insulation layer to reduce the mutual boundary heat flux. The upright pipes were made of steel material, whose wall thickness was 0.6 cm.

The dimensions of the two models are $100 \times 87 \times 100$ cm. The filled soil in the test models is clay from the Qinghai-Tibet plateau. The soil water content and the dry density are approximately 13.4% and 1.8 g/cm^3, respectively. Considering the symmetry of the models, six thermistors have been installed to investigate the temperature field of the soil. Furthermore, three thermistors were distributed at the inlet, midpoint, and bottom of the pipe body to observe the temperature distribution along the pipe. The distributions of temperature sensors on the two monitored sections are shown in Fig. 1.

The controlled ambient temperature in the modeling box $T = -3.2 + 12.7\sin(2\pi t/15)$, where t is in days, was adopted based on long-term monitoring of the in-situ air temperature in the permafrost region and similarity constants [21]. During the tests, the wind velocity in the modeling box was kept at 2.8 m/s based on field data for wind on the Qinghai-Tibetan Plateau [22]. Before starting the experiments, the test models of the pipe were kept in the modeling box for 72 h to ensure that the soil temperature becomes stable. Then, the test was started from 0 °C and repeated periodically. The test cycle was 15 days and each test was performed for 4 cycles (60 days) [23]. Thermistor monitoring data were obtained from September 30 to November 29, 2014.

3. Results and analysis

3.1. The heat transfer property of pipe

In order to illustrate the heat transfer properties of the upright pipe, the time-varying temperature curves for cases M_1 and M_2 were selected for analysis in the test cycles. The temperatures of sensors 1, 3, 6, and 9 are plotted for case M_1, and those of sensors 10, 12, 15 and 18 are plotted for case M_2 in Fig. 2, representing the inlet, pipe bottom, and soil bottom, respectively.

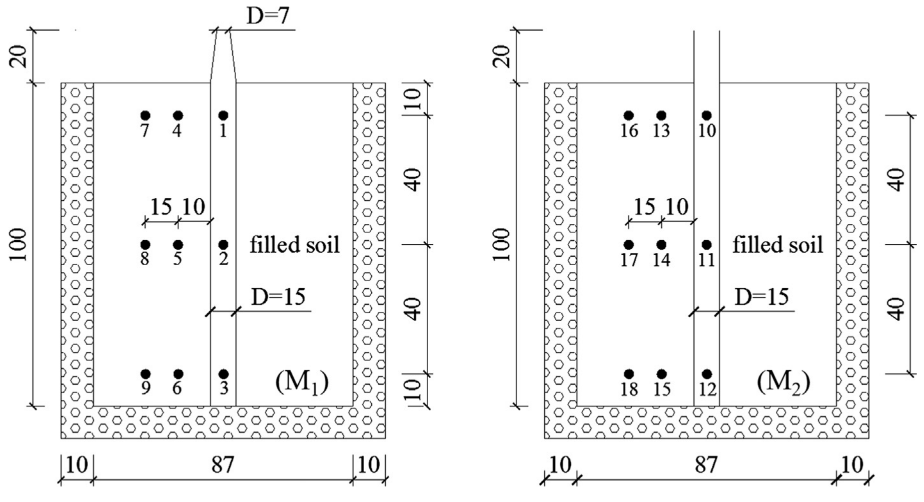

Fig. 1. Experimental models of the upright pipes (Unit: cm).