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In-situ experimental and numerical investigation on the cooling effect of a multi-lane embankment with combined crushed-rock interlayer and ventilated ducts in permafrost regions

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ABSTRACT

For the multi-lane expressway embankment constructed in permafrost regions, the width is always over 20 m and asphalt-concrete pavement is adopted, both of which would largely increase the heat absorption of underlying permafrost compared with ordinary highway embankment. The increased heat absorption would result in more severe warming and thawing in underlying permafrost and threat the stability of the embankment. So, traditional cooling measures would not be effective enough to protect the underlying permafrost or to ensure the thermal stability of multi-lane expressway embankment. Based on this, a combined cooling measure composed of crushed-rock interlayer and ventilated ducts at its top was presented by the authors, the cooling mechanism of which was validated under laboratory condition. However, it is of necessity to further investigate the cooling effect of the new combined cooling measure under actual condition and its long-term cooling effect under global warming background. In this study, firstly, the observed temperature data from an in-situ test embankment of the new combined cooling measure were collected and analyzed. The observed data illustrated that the new cooling measure was effective in protecting underlying permafrost under actual condition of the Qinghai-Tibetan Plateau. Secondly, a numerical model was validated by the in-situ test data. Finally, the temperature distributions of ordinary multi-lane embankment, multi-lane embankment with crushed-rock interlayer and multi-lane embankment with combined crushed-rock interlayer and ventilated ducts after 20 years ofconstruction were numerically simulated under global warming background. According to the numerical study result, the long-term cooling effect of single crushed-rock in multi-lane embankment was limited. After the ventilated ducts were added at the top of the crushed-rock interlayer, the cooling effect was greatly enhanced and was effective enough to protect the underlying permafrost.

1. Introduction

On earth, permafrost area is 35,760,000 km^2, accounting for 24% of the earth's land area (French, 1996). In China, 22.4% of the country's territory (Zhou et al., 2000) is permafrost region. Engineering constructed in permafrost regions increases heat income of underlying permafrost by modifying the original (natural) surface. The heat income makes the permafrost warm and thawed, and thus decreases its strength, which threats the stability of the engineering constructed on it. This permafrost problem is one main issue for the engineering construction in permafrost regions. In order to overcome this permafrost problem, several cooling measures have been developed, *e.g.*, the crushed-rock embankment, the duct-ventilated embankment, the shading board embankment, the thermal insulation embankment, and the thermosyphon embankment (Cheng et al., 2008; Song et al., 2013; Wen et al., 2008; Xu and Douglas, 2008; Yu et al., 2008). The application of these cooling measures in many engineering constructions in the Qinghai-Tibetan Plateau (Cheng et al., 2008) has validated their effectiveness.

The traditional cooling measures acted effectively in railway embankment and ordinary highway embankment. However, it should be noticed that the applicable condition is that the embankment width is no more than 10.0 m and the embankment surface absorbs heat weakly. For the case of multi-lane embankments of expressway, the applicable condition changed in two main aspects. On the one hand, the surface width of expressway embankment is commonly over 20.0 m. The heat income of the underlying permafrost increases with embankment width. On the other hand, the asphalt-concrete pavement absorbs heat strongly compared with railway embankment surface and cement-concrete pavement (Li and Sheng, 2008; Wu et al., 2010). Both of these two aspects greatly increase the heat income of expressway embankment and make the permafrost problem more severe.

To solve the permafrost problem of multi-lane expressway embankment, some new cooling measures were presented, the majority of

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which were combination of single traditional cooling measures. Zhang et al. (2007) added thermal insulation to crushed-rock revetment embankment and studied numerically the temperature field of the new embankment. Lai et al. (2009a) combined crushed-rock revetment, L-shaped thermosyphon and thermal insulation and investigated the cooling effect of the new cooling measure by a laboratory test. Zhang et al. (2009) presented a combining cooling measure of crushed-rock revetment and ventilated ducts and studied its temperature characteristics numerically. Zhang et al. (2012) analyzed numerically the thermal characteristics of cinderblock interlayer embankment and pointed out that the cinderblock interlayer embankment with ventilated ducts could be an effective measure to ensure the stability of expressway in warm permafrost regions. By analyzing the heat transfer characteristics of ventilated duct and crushed-rock interlayer, Dong et al. (2010) combined them by adding ventilated ducts at the top of crushed-rock interlayer. To investigate the cooling effect of the new cooling measure, a laboratory test was carried out. The test results showed that the performance of the ventilated ducts decreased the upper boundary temperature of the crushed-rock interlayer, and consequently enhanced its natural convection and cooling effect. In this study, in order to further investigate the cooling effect of the new cooling measure of combined crushed-rock interlayer and ventilated ducts under actual conditions, an in-situ test was carried out in the Qinghai-Tibetan Plateau. Additionally, to examine the long-term cooling effect of the new combined cooling measure under global warming background, the temperature fields of multi-lane expressway embankments without cooling effect, with single crushed-rock interlayer and with combined crushed-rock interlayer and ventilated ducts were comparatively analyzed based on numerical simulation results. This study would supply technological guide for the design of multi-lane expressway in permafrost regions.

2. Cooling effect analysis under actual condition

To examine the cooling effect of the combined crushed-rock interlayer and ventilated ducts under actual condition in the Qinghai-Tibetan Plateau, an in-situ test embankment was constructed. For comparison, the mid cross-section of the embankment with combined crushed-rock interlayer and ventilated ducts and a cross-section of comparative ordinary embankment without cooling measure were instrumented with monitoring system.

2.1. General situation of the test site

The test site was located in the Beiluhe test base, which was in the open area between the Qinghai-Tibetan Highway (K3056 + 500) and Qinghai-Tibetan Railway. According to borehole data, the mean annual ground temperature in the test site was about −1.0 °C to −0.5 °C. In more than half of the test site, there existed 1 m–5 m thick ice-rich soil near the natural permafrost table, the volume ice content of which was over 80%. Thus, the permafrost in the test site was classified as warm and ice-rich permafrost. According to the Technical Standard of Highway Engineering (The Ministry of Transport of the People's Republic of China, 2003) and separated-lane expressway, the embankment width and height was 13.0 m and 3.0 m respectively (Fig. 1). To simulate actual heat absorption of the embankment, asphalt-concrete pavement was constructed. The detailed construction information of the in-situ test embankment was described by Gu et al. (2010).

2.2. Monitoring system

The layout of thermal probes for ground temperature is shown in Fig. 2. Five ground boreholes were drilled at centerline of the embankment, left and right shoulders, and left and right slope toes. The depth of the boreholes was 20.50 m. The space of thermal probes was 0.50 m from $y = 0$ (natural ground surface) to $y = -5.50$ m and was 1.0 m below $y = -5.50$ m. The test embankment construction was finished in mid September 2009, and temperature data were collected soon later.

2.3. Test data analysis

The temperature profile of the embankment with combined crushed-rock interlayer and ventilated ducts on Dec. 20, 2009 is shown in Fig. 3. In Fig. 3, it can be seen that the embankment was totally refrozen in cold season. Near the inlet of the ventilated duct (right side), the soil temperature under the ventilated ducts was about −10 °C, which was close to that under the embankment top surface. This illustrated that the ventilated duct transferred the exterior cold air into the mid part of the embankment, where a cold temperature boundary was formed. The result of this was the reduction of the temperature at the top of crushed-rock interlayer, which would increase its cooling

Fig. 1. A picture of the in-situ combined crushed-rock interlayer and ventilated ducts embankment.