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Thermal stability analysis of crushed-rock embankments on a slope in permafrost regions

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ABSTRACT

Highways/railways often pass across slope areas and their embankments are often built on the slopes in permafrost regions. It is difficult to ensure the thermal stability of the embankments at the slopes due to the effect of slopes. To protect the underlying permafrost, the crushed-rock embankments are often used in the slope areas. Therefore, it is very necessary to explore the thermal state of crushed-rock embankments located on the slopes. In this study, we studied numerically the temperature characteristics of three kinds of crushed-rock embankments located on a slope under global warming, i.e. crushed-rock interlay embankment, crushed-rock interlayer-revetment embankment and crushed-rock base embankment. Numerical results indicate that the crushed-rock interlayer embankment and the crushed-rock interlayer-revetment embankment, located on a slope with a ratio of 1:3.73 (about 15° from the horizontal), cannot effectively eliminate the negative effect of climate warming and construction-induced warming, and the effect of slope is still obvious on the thermal stability of permafrost under the crushed-rock interlayer embankment. However, the crushed-rock base embankment can significantly reduce the temperature of underlying permafrost and keep the underlying permafrost table stable for a long term; furthermore, the ground temperatures under the long side slope are far lower than those under the short side slope, and this will be more advantageous to control the slide of the embankment located on a slope and increase its stability. We also find that the three kinds of embankments cannot all remove the thermal effects of construction from themselves in a short term. Generally speaking, the crushed-rock base embankment structure can be very advantageous to the thermal stability of the embankment on a slope.

1. Introduction

A crushed-rock layer, as a highly porous medium (Lai et al., 2003), has been widely used to protect the underlying permafrost in the embankment engineering in cold regions. Examples include many important highway and railway engineering projects, such as the Qinghai–Tibet Highway and Qinghai–Tibet Railway in China, the Alaska Highway in the USA and the Baikal–Amur Railway in Russia (Cheng, 2005; Cheng and He, 2001). Typical construction methods include crushed-rock embankments, crushed-rock base (interlayer) embankments, crushed-rock revetment embankments and U-shaped (interlayer and revetment) crushed-rock embankments (Cheng et al., 2009; Lai et al., 2009; Zhang et al., 2005). The cooling mechanism results from the fact that the high permeability of such material would allow air convection to occur within it when unstable air pressure/temperature gradients exist. At present, the heat and mass transfer theories have been developed in cold region engineering. The convective heat transfer effect in crushed-rock layer has been applied to control thaw settlement of permafrost embankment. The cooling effects of highly porous media embankments made from crushed rocks have been evaluated previously using numerical simulation, laboratory tests and in-situ observation. In detail, Goering (2003) numerically researched the convective heat transfer of crushed-rock embankment with an unsteady two dimensional finite-element model that is capable of solving the coupled governing equations of pore air flow and energy transport. Lai et al. (2006) analyzed numerically the velocity and temperature characteristics of open-boundary crushed-rock embankment under wind action based on the climatic and geological conditions of the Qinghai–Tibet Plateau. Zhang et al. (2009a, 2009b) found that the geometrical parameters including sloped angle, aspect ratio and so on have significant influence on the natural convection cooling effect of crushed-rock revetment by numerical calculations. Yu et al. (2005) researched the temperature properties of a traditional embankment and a ripped-rock revetment embankment by laboratory experiments and found that the

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ripped-rock revetment could cool embankment and adjust the temperature difference between the north-facing slope and the south-facing slope. Zhang et al. (2006) studied experimentally heat transfer mechanisms of a trapezoidal crushed-rock layer under two boundary conditions, i.e. cyclic temperature, air-flow, air-permeable/impermeable at the two side slopes and closed at both top and bottom, and found that the former is forced convective heat transfer and the latter is nature convective heat transfer. Sun et al. (2005) concluded that the cooling capacity of the coarse rock revetment excelled that of the fine rock revetment by analyzing the temperature fields of the experimental embankments with crushed rock slope protection in field. Wu et al. (2008) performed lots of in-situ observations and found that crushed rock-based embankment could effectively cool the roadbed, resulting in the decrease of permafrost temperatures and the rise of permafrost table, however the cooling effects were significantly different in warm and relatively cold permafrost areas. From these studies, we can conclude that crushed-rock layer can have a good cooling effect on the underlying soil layers.

However, the previous researches usually focus on the crushed-rock embankments located on the flat open areas. In fact, the highway/railway often passes across slope areas, e.g. valley and hillside, and thus their embankments are often built on the slopes. Because of the asymmetry thermal boundary conditions and the effect of gravity, it will be difficult to ensure the thermal stability of the embankments located on the slopes. Especially for the side slope of the embankment on the downward slope, the longer slope absorbs more heat energy than that on the upward slope, and this will not benefit the thermal stability of the embankment. To protect the underlying permafrost, the crushed-rock embankments are also often used on the slope areas. Therefore, it is very important to explore the thermal state of crushed-rock embankments at the slopes. In this paper, we focused on the influence of slope for crushed-rock embankments and proposed a model for crushed-rock embankments on a slope. In order to quickly research the effect of crushed-rock embankments on the underlying permafrost on a slope, we have used a numerical method. A large number of numerical simulations were carried out during the course of this study. However, only three kinds of embankment structures are presented in this paper. Namely, the temperature characteristics of crushed-rock interlay embankment, crushed-rock interlayer-revetment embankment and crushed-rock base embankment, located on a slope with a ratio of 1:3.73 (about 15° from the horizontal), have been analyzed for 20 years based on the assumption that the warming rate of air temperature on the Qinghai–Tibet Plateau will be 0.052 °C (Qin, 2002).

2. Description of the models

The computational domain of crushed-rock embankment model on the slope is shown in Fig. 1. The ratio of slope OJ is 1:3.73 (about 15° from the horizontal). The embankment height is 3.1 m from the left slope toe. The computational domain is extended 30 m horizontally from the side slope toe (A and I) of the embankment, and 30 m downward from the natural ground surface at the left and right lateral boundaries, respectively. Three crushed-rock embankment structures are designed in the model.

Case 1 Crushed-rock interlayer embankment. Namely, Parts I and III are the embankment fill, Part II is the crushed-rock interlayer with a thickness of 1.5 m, and Parts V and VI are the natural soil layers and they are subclay and weathered mudstone, respectively.
Case 2 Crushed-rock interlayer-revetment embankment. Based on case 1, a crushed-rock revetment (Part IV) is added at the right side of the embankment with a horizontal width of 1.6 m.
Case 3 Crushed-rock base embankment. Similarly, based on case 1, Part III is filled with crushed rocks.

In the calculational domains, shown in Fig. 1, the specific heat of air at an elevation of more than 4500 m is $C_a = 1.004 \times 10^3$ J/(kg ·°C), the thermal conductivity is $\lambda = 2.0 \times 10^{-2}$ W/(m · °C), the air density is $\rho_a = 0.641$ kg/m^3, and the dynamic viscosity is $\mu = 1.75 \times 10^{-5}$ kg/(m · s).

The mean particle size of crushed rock is about 20.0 cm and the permeability and inertial resistance factor (*Beta* factor of non-Darcy flow) are $k = 1.66 \times 10^{-5}$ m^2 and $B = 41.20$ m^{-1}, respectively (Zhang et al., 2013). The thermal parameters of all media are listed in Table. 1 (Lai et al., 2009).

3. Governing equations

According to the Design Specifications for Highway Alignment (2006) and actual embankment geometries in permafrost regions, the crushed-rock embankment structures on a slope at an elevation of 4500 m are taken as computational models (Fig. 1) in this paper. Considering the direction of geothermal heat flux and rationality of boundaries, the bottom boundary (ML) is set parallel to the natural ground surface (OJ) and the lateral boundaries (ONM and JKL) are perpendicular to the natural ground surface (OJ) and the bottom boundary (ML). According to the different heat transfer characteristics of different media, the embankment model is divided into two zones, i.e. crushed-

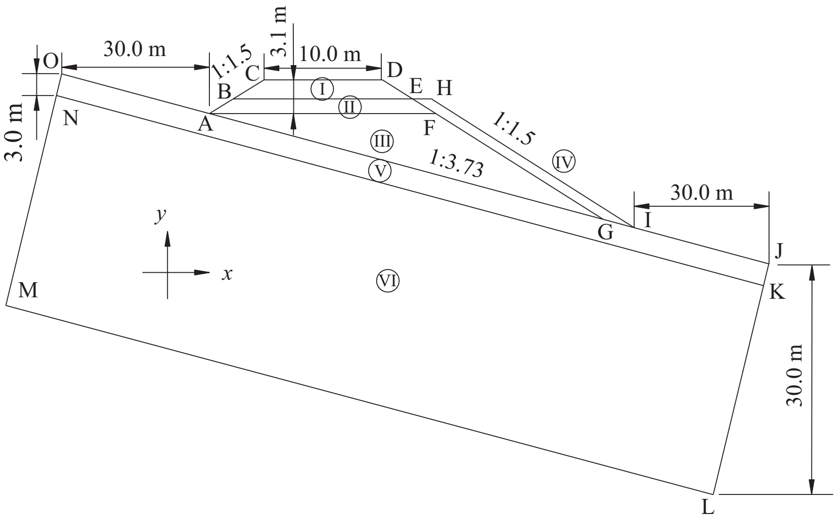

Fig. 1. Computational domain of crushed-rock embankment.