Energy 93 (2015) 874–881

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Evaluating the cooling performance of crushed-rock interlayer embankments with unperforated and perforated ventilation ducts in permafrost regions

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ARTICLE INFO

Article history:
Received 7 March 2015
Received in revised form
11 August 2015
Accepted 19 August 2015
Available online 22 October 2015

Keywords:
Cooling performance
Crushed-rock interlayer embankment
Perforated ventilation duct
Expressway
Permafrost region

ABSTRACT

The crushed-rock interlayer embankment with ventilation ducts has been advocated to stabilize the permafrost stratum under expressways in permafrost regions. This embankment must render better cooling effect than railway embankments because the expressway surface is wider and hotter. To this purpose, the walls of the ventilation ducts need to be perforated. This study evaluates the cooling performance of the rushed-rock interlayer embankments with unperforated and perforated ventilation ducts along an expressway in permafrost regions of the Qinghai-Tibet Plateau. A three-dimensional numerical model is developed based on heat and mass transfer theories. The model includes the coupled heat transfer between air and ventilation duct wall, the air convective heat transfer in crushed-rock layer, and the heat conduction with phase change in soil layers. The numerical results indicate that if the ventilation ducts are perforated and embedded at the top of the crushed-rock interlayer, the cooling effect of the embankment can be greatly enhanced. A good cooling performance can still be achieved even if the centerline spacing of the perforated ventilation ducts is enlarged to 4 m to facilitate the construction. The crushed-rock interlayer embankment with perforated ventilation ducts is a better candidate structure for expressways in permafrost regions of the Qinghai-Tibet Plateau.

1. Introduction

The permafrost regions are about 22.4% of the land area of China [1]. An increasing railway/highway projects that had been constructed or are under plan in the special regions in China will face the problem of permafrost degradation due to global warming [2]. The problem can be remedied by introducing proactively cooling approach to the roadbed design, an approach focusing on proactively decreasing the underlying ground temperature rather than simply insulating the permafrost stratum [2–4]. For examples, duct-ventilated embankments, crushed-rock embankments and thermosyphon embankments have effectively cooled the permafrost stratum under the Qinghai-Tibet Railway [5–10]. A single proactively cooling approach, however, is sometimes insufficient to protect the underlying permafrost under some highways in the Qinghai-Tibet Plateau (e.g. Qinghai-Tibet Highway and Qing-Kang Highway). The reason may be that the mean annual surface temperature of an asphalt pavement surface can be up to 6.5 °C higher than surrounding air temperature [11] and that a full expressway (beyond 20 m wide) [12] is far wider than that of the Qinghai-Tibet Railway. It is thus necessary to design new embankment structure to proactively cool the permafrost stratum under expressways in permafrost regions of the Qinghai-Tibet Plateau.

A crushed-rock interlayer embankment embedded with ventilation ducts has been found to be an economical and effective technique to stabilize the permafrost stratum under expressways in permafrost regions [13–15]. This embankment structure provides a good cooling effect when the ventilation ducts are embedded on the top of the crushed-rock interlayer with a spacing of 1.0–2.0 m on centerline along the expressway embankment. However, it is practically difficult to uniformly compact the fill materials between ventilation ducts because of the small duct's spacing [13–15]. Recently studies have attempted to optimize this composite embankment structure by perforating the ventilation ducts embedded in a crushed-rock interlayer [16,17]. Laboratory results indicated that those perforated ventilation ducts can enhance the

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http://dx.doi.org/10.1016/j.energy.2015.08.059
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cooling capacity of the crushed-rock interlayer embedded in embankments [16,17]. It remains unknown if the embankment setup can provide a desirable long-term cooling performance, especially under the global warming.

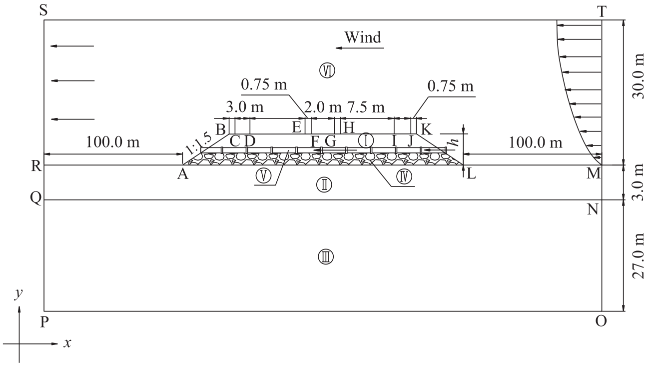
This study develops a three-dimensional numerical model to simulate the temperature evolution of the crushed-rock interlayer embankments with unperforated and perforated ventilation ducts. On the basis of heat and mass transfer theories, the model includes the coupled heat transfer between air and ventilation duct wall, the air convective heat transfer in crushed-rock layer, and the heat conduction with phase change in soil layers. We simulate the temperature distributions and heat flux changes of three crushed-rock interlayer embankments with unperforated ventilation ducts of 2-m centerline spacing, with unperforated ventilation ducts of 4-m centerline spacing, and with perforated ventilation ducts of 4-m centerline spacing, respectively, in permafrost regions of the Qinghai-Tibet Plateau. To simulate the influence of global warming, we assume that the air temperature in the Qinghai-Tibetan Plateau will warm by 0.052 °C/year in the future 50 years [18].

2. Model description

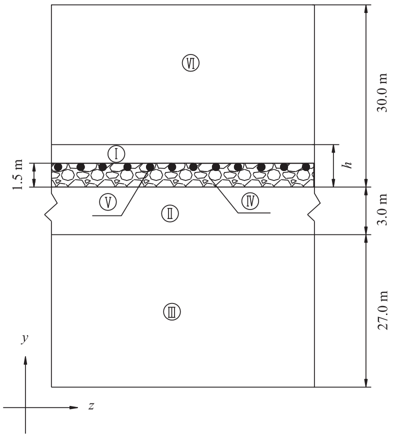
2.1. Computational domain

According to the Design Specification for Highway Alignment in China [12] and related references [2,14], the physical structure of a crushed-rock interlayer embankment with unperforated/perforated ventilation ducts whose inner diameters are 0.40 m, is shown in Fig. 1(a, b). The unperforated/perforated ventilation ducts are embedded at the top of crushed-rock interlayer (Fig. 1b). The perforated ventilation duct is illustrated in Fig. 2.

The embankment height h is 4.0 m. The computational domain is extended for 100 m from the toe of the embankment (A and L), and 30 m above and under the natural ground surfaces (RA and LM) (Fig. 1a). The interfaces ABC and JKL are the embankment fill layer surfaces; FG is the median strip with embankment fill layer surface; and CDEF and GHIJ are the asphalt pavement surfaces.



(a) Cross section



(b) Longitudinal section

①-embankment fill layer, ②-silty clay layer, ③- strongly weathered mudstone layer, ④-crushed-rock interlayer, ⑤- unperforated/perforated ventilation duct, ⑥-air

Fig. 1. Physical structure of a crushed-rock interlayer embankment with unperforated/perforated ventilation ducts.

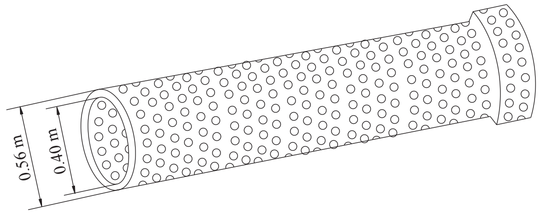


Fig. 2. Schematic of the perforated ventilation duct.

2.2. Governing equations

The embankment model is divided into three zones, including the air zone inside and outside the ventilation ducts (fluid zone); the crushed-rock interlayer and perforated ventilation duct wall zones (porous media zone); and the soil layer and the unperforated ventilation duct wall zones (solid zone). The air can be treated as an incompressible fluid. The governing equations of different zones are described as follows:

1) Air zone inside and outside the ventilation ducts (VI zone)

The airflow or wind is considered as turbulent flow outside the ventilation ducts, and the airflow can be considered to be fully developed turbulent flow inside the ventilation ducts [19,20]. As an incompressible fluid, the influence of air temperature on the velocity of airflow is negligible. Hence, we have the following equations for the turbulent heat transfer problem of airflow (Effect of gravity is ignored) [14,19–21]:

$$\rho_a\frac{\partial\varphi}{\partial t}+\rho_a\left[\frac{\partial(\upsilon_x\varphi)}{\partial x}+\frac{\partial(\upsilon_y\varphi)}{\partial y}+\frac{\partial(\upsilon_z\varphi)}{\partial z}\right]=\frac{\partial}{\partial x}\left(\Gamma_\phi\frac{\partial\varphi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_\phi\frac{\partial\varphi}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_\phi\frac{\partial\varphi}{\partial z}\right)+S_\varphi \tag{1}$$

Continuity: $\varphi=1,\ \Gamma_\varphi=0,\ S_\varphi=0$

Momentum: $\Gamma_\varphi=\mu+\mu_t$,

x-direction:

$$\varphi=\upsilon_x,\ S_\varphi=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left[(\mu+\mu_t)\frac{\partial\upsilon_x}{\partial x}\right]+\frac{\partial}{\partial y}\left[(\mu+\mu_t)\frac{\partial\upsilon_y}{\partial x}\right]+\frac{\partial}{\partial z}\left[(\mu+\mu_t)\frac{\partial\upsilon_z}{\partial x}\right]$$

y-direction:

$$\varphi=\upsilon_y,\ S_\varphi=-\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left[(\mu+\mu_t)\frac{\partial\upsilon_x}{\partial y}\right]+\frac{\partial}{\partial y}\left[(\mu+\mu_t)\frac{\partial\upsilon_y}{\partial y}\right]+\frac{\partial}{\partial z}\left[(\mu+\mu_t)\frac{\partial\upsilon_z}{\partial y}\right]$$

z-direction:

$$\varphi=\upsilon_z,\ S_\varphi=-\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left[(\mu+\mu_t)\frac{\partial\upsilon_x}{\partial z}\right]+\frac{\partial}{\partial y}\left[(\mu+\mu_t)\frac{\partial\upsilon_y}{\partial z}\right]+\frac{\partial}{\partial z}\left[(\mu+\mu_t)\frac{\partial\upsilon_z}{\partial z}\right]$$