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Thermal performance of a novel crushed-rock embankment structure for expressway in permafrost regions

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ABSTRACT

The current crushed-rock interlayer structure, which was successfully adopted in construction of the Qinghai-Tibet Railway, cannot maintain the foundation stability of expressways in permafrost regions because of the strong heat absorption of the wide and dark-colored asphalt pavement surface. To satisfy the higher cooling requirement of expressways, a novel crushed-rock interlayer structure, which especially focuses on enhancing the cooling performance on the embankment core, is presented. A heat transfer model, which includes air convection in the crushed-rock interlayer and the heat conduction with a phase change in the soil layers, was developed to simulate the temperature evolution of a full-scale testing expressway embankment section built in Huashixia, the Qinghai-Tibet Plateau. The numerical results indicated that the new structure has a significant cooling performance and especially plays an effective role in lowering the permafrost temperature beneath the centerline of the expressway. Moreover, the new structure has the benefit of maintaining symmetry of the embankment temperature distribution. Therefore, it can be concluded that the new structure is an effective method to prevent permafrost degradation under expressways and can ensure the long-term thermal stability of embankments under the climate warming. The study provides reference and guidance for expressway design and construction in permafrost regions, such as the planned Qinghai-Tibet Expressway.

1. Introduction

The Qinghai-Tibet Plateau (QTP), which has an average elevation of more than 4000 m a. s. l., contains the largest low-latitude permafrost area on the earth [1] (Fig. 1). With the rapid economic development in China, many pivotal engineering projects have traversed the special regions of the QTP, e.g., the Qinghai-Tibet Railway (QTR), the Qinghai-Tibet Highway, and the Qinghai-Tibet Power Transmission Line. However, engineering problems frequently occur, including frost heave and thaw settlement of foundation soils, leading to damage, malfunction or infrastructure failures [2,3], and the problems will be exacerbated under the climate warming [4,5]. Under combination of the climate warming and thermal disturbances from engineering constructions, infrastructures on the degrading permafrost in the QTP are at a clear risk [6]. The QTR is the first transportation infrastructure designed in the plateau permafrost region of China to take climate warming into consideration [6]. This roadway project has resulted in the introduction of a roadbed cooling approach and the development of various special embankment structures with cooling features, including crushed rocks, ventilation ducts, thermosyphons, and sun-shadings, to protect the permafrost from warming and thawing beneath the railway embankments [7,8].

A crushed-rock embankment, which is a cost-effective mitigation technique to reduce the effects of permafrost degradation, has been widely applied in the QTR construction in permafrost regions, and its ability of protecting the underlying permafrost has been validated by numerous field experiments and numerical simulations [9–12]. Experimental embankments with crushed-rock materials on the Alaska Highway in the USA and at the Beaver Creek test site in Canada have also demonstrated the excellent cooling performances [13,14]. A crushed-rock embankment is usually constructed using coarse, poorly-graded rocks with a high porosity, which allows natural/forced air convection to occur within them and can accelerate heat extraction from the embankment and underlying soil during winter. In summer, the heat transfer within the porous layer primarily occurs through conduction because the crushed-rock layer has a lower thermal conductivity than the typical embankment material [13], and thus less heat is conducted to the underlying soil. In summary, its cooling mecha-

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Nomenclature

v	velocity ($m{\cdot}s^{-1}$)
μ	dynamic viscosity (Pa·s)
ρ	density ($kg{\cdot}m^{-3}$)
P	pressure (Pa)
λ	thermal conductivity ($W{\cdot}m^{-1}{\cdot}°C^{-1}$)
c	specific heat capacity ($J{\cdot}kg^{-1}{\cdot}°C^{-1}$)
B	inertial resistance factor (m^{-1})
k	permeability of the medium ($m{\cdot}s^{-1}$)
T	temperature (°C)
β	thermal expansion coefficient of air
C	volumetric heat capacity ($J{\cdot}m^{-3}{\cdot}°C^{-1}$)
L	latent heat ($J{\cdot}m^{-3}$)
t	time (s)
q	heat flux ($W{\cdot}m^{-2}$)

Subscripts/superscripts

x	x-direction
y	y-direction
a	air
$*$	equivalent
f	frozen
u	unfrozen
H	height

nism results from the increased winter cooling rates and decreased summer warming rates [15].

Although a crushed-rock embankment has been used as a mainstream technique to maintain the road foundation stability of railways and ordinary highways on the plateau [9–11], the current structure used for the QTR cannot satisfy the higher cooling requirement of an expressway, which has a wider and dark-colored asphalt pavement. This is mainly because of the adoption of an asphalt pavement and the much wider (more than 20 m wide) road surface [16,17], both of which significantly increase the heat absorption and decrease the heat dissipation from the top surface compared with railway and ordinary highway embankment, causing more severe permafrost thaw settlement [18]. Based on the data from several monitoring units installed along the newly built Gonghe-Yushu Expressway in the east part of the QTP, obvious permafrost warming trends were observed under some crushed-rock embankments, especially under the centerlines [19], indicating that the crushed-rock configuration used for the QTR cannot be directly applied to expressway construction in permafrost regions. According to the proposed development project by China's Ministry of Transport, the plan is for the Qinghai-Tibet Expressway (QTE) to run across the largest plateau permafrost region in China, and it is expected to play an important role in promoting the economic development of Tibet [18]. The QTE will face more severe permafrost degradation problems than the QTR, especially under impacts of the climate warming.

Some composite embankments that combine crushed-rock and other cooling measures such as a forced-air ventilation duct, L-shaped thermosyphons, and insulating material for better cooling performances have been developed, and their effects in increasing the thermal stability of expressway embankments have been verified by laboratory tests or numerical experiments [20,21]. However, the combining of two or more cooling measures multiplies the construction costs. Nanofluid can be selected as an ideal working fluid to enhance the convection heat transfer efficiency in porous media [22–24], but such a material at present cannot be directly applied in the construction of crushed-rock embankment in permafrost regions.

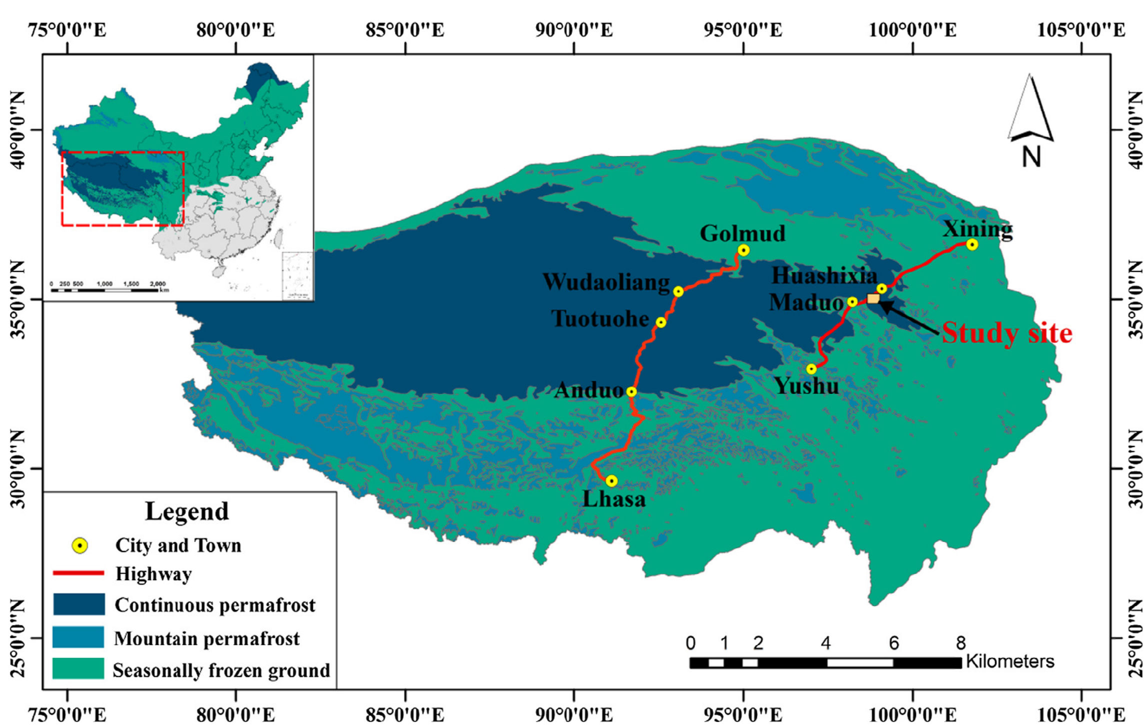

Fig. 1. Permafrost distribution and embankment section with new design at Huashixia in QTP. The data in this permafrost map was from the China Cold and Arid Scientific Data Center (http://westdc.westgis.ac.cn/).