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Research Paper

Evaluation of cooling effects of crushed rock under sand-filling and climate warming scenarios on the Tibet Plateau

Wenbing Yu [a], Weibo Liu [a,b,*], Lin Chen [a,c], Xin Yi [a,b], Fenglei Han [a,b], Da Hu [a,b]

[a] State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, CAS, Lanzhou, Gansu 730000, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Geography Department, University of Montreal, 520, ch. Côte Ste-Catherine, Montreal, QC, Canada H2V 2B8

HIGHLIGHTS

- Field test was conducted to validate the numerical heat transfer model.
- Natural convection decreases with increasing of sand thickness.
- Thermal regime of permafrost beneath porous media is investigated.

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ABSTRACT

Crushed rock has been applied to cool the permafrost foundation on the Tibet Plateau. It is facing the challenges of sand-filling and climate warming. Desertification and climate warming are a definite trend on the Tibet Plateau, which has affected the permafrost and infrastructures. This study investigated the influence of sand-filling and climate warming on the cooling effect of crushed rock on the Tibet Plateau, on the basis of a coupled finite element model of convective heat transfer and heat conduction with phase change. The model is calibrated by field measurements. The field experiment and numerical simulation reveal that natural convection in rock layer only occurs in winter season. With the increasing thickness of sand in rock layer, the critical temperature difference between the sand-free layer increases, and the Ra number decreases, and the natural convection intensity weakens gradually. At the climate warming rate of 0.052 °C a^{-1}, the cooling effect of rock layer can counteract the negative effect of climate warming and raise the permafrost table for about the former 20 years. However, the permafrost will eventually degrade continuously, which means the crushed-rock can't be applied to maintain the permafrost foundation stability anymore under these conditions.

1. Introduction

Observations of air and ground temperature in cold regions indicate that the mean annual ground temperatures are cooler in blocky materials than that in adjacent mineral soils [1–4]. Thus, numerous studies have been conducted to study the cooling mechanisms and cooling characteristic of coarse rock layers and its natural convection property in cold season has been used to maintain infrastructure stability in permafrost areas. Goering and Kumar [5] developed an unsteady finite element model to analyze characteristics of heat transfer in highly porous roadway embankments. Wang et al. [6] conducted field experiments on a coarse rock embankment. The crushed rock embankment has been experimented at Beaver Creek experimental road site in Canada [7]. Yu et al. [8,9] carried out some laboratory experiments on the thermal characteristics of coarse rock layers. Lai et al. [10,11] discussed impacts of boundary conditions on cooling characteristics and mechanism of rock layers. Cheng et al. [12] reported on the operation of crushed-rock embankment. Thus, the knowledge of the cooling effect of surficial coarse rock material has been successively used to keep permafrost foundation stable [13–15]. However, climate warming and human activities had significantly led to the grassland degradation and desertification on the Tibet Plateau [16–18]. According to a survey [19], the Qinghai–Tibet Railway affected by sand was about 270 km long by 2008, which represents 25% of the total length of the Golmud–Lhasa Section of the railway (Fig. 1).

The crushed rock embankment has been used as a mainstream technology to maintain road foundation stability on the Tibet Plateau. Now a new problem has to be faced, i.e., aeolian sand fills the pore spaces of rock layer and may influence the cooling effect of blocky

* Corresponding author. Tel.: +8615002634765; fax: 86-931-4967292.
E-mail address: liuweibo980@163.com (W. Liu).

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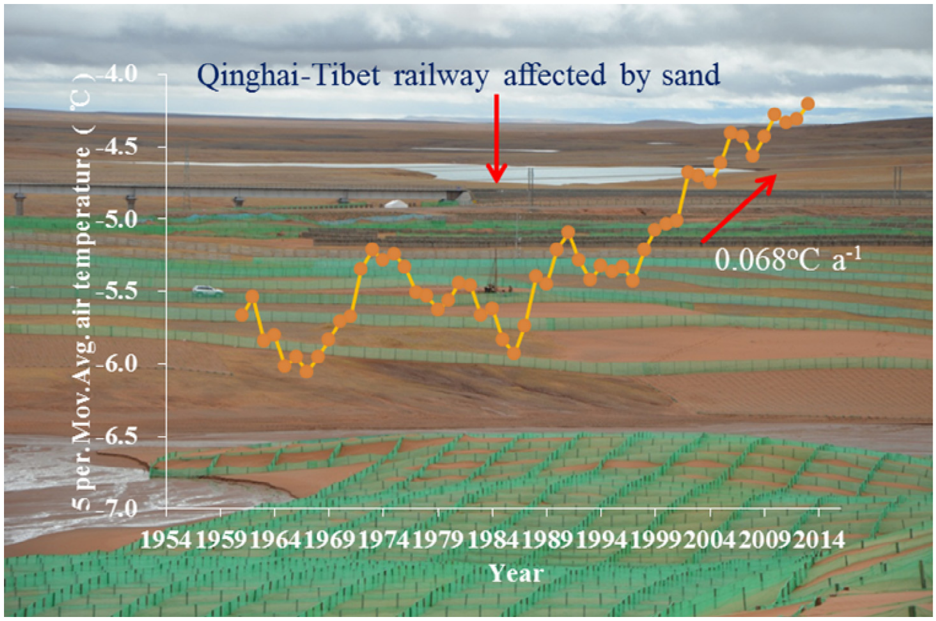

Fig. 1. Sand prevention facilities along the Qinghai–Tibet railway and the 5 per. Mov.Avg. air temperature at Wudao Liang on the Tibet Plateau. Notes: There are several facilities used for sand prevention along the Qinghai–Tibet railway, but they can't prevent the sand from filling the crushed-rock layer of the railway embankment. A rapid warming tendency has been occurring on the Tibet Plateau since 1997. The data in Fig. 1 are from the Share Center of Chinese Meteorology Data.

material and thus warm permafrost thermal regimes. There are currently no studies of this phenomenon in peer reviewed scientific literature. This paper tries to answer this question with field experiment and numerical simulations. To evaluate the effect of aeolian sand and the role of climate warming on the heat transfer properties of rock layers in permafrost regions, field measurements are used to calibrate the numerical model, and then several simulated cases are conducted to predict the thermal regimes of permafrost beneath sand-filled rock layer, under climate warming scenario. This study can supply scientific evidence for the long-term stability evaluation of the application of crushed-rock in permafrost engineering on Tibet Plateau.

2. Methods

2.1. Governing differential equations and finite element method

Air will flow in coarse rock layers according to the principle of fluid flow in porous media. In practical permafrost engineering problem, the rock layer can be considered infinitely long in the longitudinal direction. Thus, the problem studied in this work can be approximated as a 2D problem. According to the theories of transient heat transfer with phase change and thermodynamic equilibrium, and (1) not considering the thermal dissipation during the evaporation of the moisture in soil and (2) accounting for closed upper boundary of the rock layer, the 2D differential equations of the problem are given as [20].

Mass conservation (Continuity) equation:

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}=0 \tag{1}$$

Here, U and V are flow velocities ($\mathrm{m\,s^{-1}}$) in the direction x, y, respectively.

Momentum conservation equation:

$$U=-\frac{k}{\mu}\cdot\frac{\partial p^*}{\partial x} \tag{2}$$

$$V=-\frac{k}{\mu}\left[\frac{\partial p^*}{\partial y}+\rho_a g\right] \tag{3}$$

Here, ρ_a is the air density ($\mathrm{kg\,m^{-3}}$). P^* is the effective pressure of air ($\mathrm{kg\,s^{-1}}$). k is the permeability coefficient of the media ($\mathrm{m\,s^{-1}}$). μ is the dynamic viscosity of the interstitial air ($\mathrm{kg\,m^{-1}\,s^{-1}}$). g is the acceleration due to gravity ($\mathrm{m^2\,s^{-1}}$).

Energy conservation equation:

$$C^*\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda^*\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda^*\frac{\partial T}{\partial y}\right)-C_a\rho_a\frac{\partial}{\partial x}\left(U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}\right) \tag{4}$$

Where T is temperature (°C), t is time (h), ρ is the density of the media ($\mathrm{kg\,m^{-3}}$), C is the specific heat capacity ($\mathrm{J\,m^{-3}\,K^{-1}}$) and λ is the thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$) of soil expressed as follows according to the temperature range and corresponding freezing-thawing status. According to experimental data, the phase transition is largely concentrated on a narrower transition temperature range ($T_m+\Delta T$). Therefore, when the temperature is out of range, the conductivity and specific heat influence of phase transition between ice and water could be neglected. The function is built as follows [21]:

$$C^*=\begin{cases} C_f & T<(T_m-\Delta T^*) \\ \dfrac{L}{2\Delta T^*}+\dfrac{C_u+C_f}{2} & (T_m-\Delta T^*)\le T\le(T_m+\Delta T^*) \\ C_u & T>(T_m+\Delta T^*) \end{cases} \tag{5}$$

$$\lambda^*=\begin{cases} \lambda_f & T<(T_m-\Delta T^*) \\ \lambda_f+\dfrac{\lambda_u-\lambda_f}{2\Delta T^*}[T-(T_m-\Delta T^*)] & (T_m-\Delta T^*)\le T\le(T_m+\Delta T^*) \\ \lambda_u & T>(T_m+\Delta T^*) \end{cases} \tag{6}$$

Where f and u denote the frozen and the unfrozen status, respectively. ΔT^* is a small temperature range (°C). W is the water content (%). L is latent heat in ice phase transition ($\mathrm{J\,m^{-3}}$).