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Research Paper

Thermal regime of paved embankment in permafrost regions along the Qinghai-Tibet Engineering Corridor

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HIGHLIGHTS

- Numerical and statistic methods are used to study the thermal regime of embankment.
- The south-facing slope effect and other factors are considered.
- The mean annual air temperature is key factor determining the heat influence scope of embankment.
- The distance between the proposed and existed highway should be controlled to prevent the thermal interactions.

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ABSTRACT

Heat influence among infrastructures is one of the key factors that will determine the route of the proposed Qinghai-Tibet Expressway (QTE) in the permafrost regions of the Qinghai-Tibet Plateau Engineering Corridor. Considering the south-facing slope effect and other factors, the dynamic variation of heat influence scope of paved embankment is investigated by numerical method and statistic approach. Results indicate that at the south-facing slope side heat influence scope at the horizontal direction is positive correlation with embankment height and pavement width, while it is negatively correlated with the mean annual air temperature (MAAT). At the north-facing slope side heat influence scope at the horizontal direction is positive correlation with pavement width, while it is negatively correlated with embankment height and the MAAT. After 50 years for the south-facing and north-facing slopes the maximum distance of heat influence scope from the foot of the embankment slope will be to 35.95 m and 31.84 m, respectively. The difference of heat influence scope at the horizontal direction between the south-facing and north-facing slope enlarges with increase of embankment height and pavement width. The grey-relation analyses show that the sensitivity of the heat influence scope to the factors is the MAAT, the embankment height and the pavement width in turn. The results are expected to serve as a reference for the design of the proposed QTE.

1. Introduction

The permafrost has remarkable characteristics of poorly thermal stability and highly sensitive to the temperature change, which is served as bearing foundation of engineering in permafrost regions [1]. Several major infrastructures have been completed such as the Qinghai-Tibet Railway, Qinghai-Tibet Highway, Golmud-Lhasa Oil Pipeline etc, which are restricted in the Qinghai-Tibet Plateau Engineering Corridor (QTPEC) narrowed to a few hundred meters in some places (Fig. 1) [2]. The proposed QTE will be designed along the existing infrastructures for the sake of convenient construction and environmental protection. The interactions of thermal regime among engineering projects have an obvious impact on permafrost environment, and gradually strengthens with time in the QTPEC [3]. So the thermal regime of paved embankment must be studied before the construction of the proposed QTE.

Engineering projects can change heat exchange conditions between the nature ground surface and atmosphere, which could generate the redistribution of thermal regime for the underlying permafrost of embankment [4]. Researches have indicated that the thermal regime of embankment is affected by multiple factors, such as the size, the type and the varying MAAT [5–7]. Meanwhile due to the strong solar radiation on the Tibetan plateau, the south-

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Nomenclature

A_i	the grey relational grade
C	volume specific heat, J m^{-3} °C^{-1}
L	latent heat, J kg^{-1}
N_i	the shape function
N_j	the shape function
n	the direction vector of the moving boundary, m
$n1$	the normal direction at the fixed boundary, m
T	temperature, °C
T_a	the mean annual air temperature, °C
T_m	phase change temperature, °C
T_∞	the environmental temperature, °C
ΔT	phase transition temperature range, °C
t	time, h
t_f	the failure time, min
W	water content, %
X	the comparability sequence
Y	the reference sequence
x	x axis, m
y	y axis, m

Greek symbols

ρ	density, kg m^{-3}
λ	thermal conductivity, W m^{-1} °C^{-1}
α	the coefficient of heat convection, W m^{-2} °C^{-1}
σ	stress intensity, MPa
θ	the failure temperature, °C
γ	the grey relation coefficient
Δ	the deviation sequence
ξ	identification coefficient

Subscripts

f	frozen state
u	unfrozen state

facing slope effect will aggravate the asymmetric thermal state for embankment and underlying permafrost [8,9]. Furthermore the superposition of thermal influence between the new and existing engineering structures will surely accelerate degradation of the permafrost and ecological environment [10]. Induced permafrost disasters will be unfavorable to the safe operation of engineering projects. But for the previous papers mentioned a single factor is adopted to investigate the thermal regime of permafrost in lack of quantitative evaluation of the thermal influence of embankment.

Heat influence among infrastructures is one of the key factors that will determine the route of the proposed QTE in the permafrost regions of the QTPEC. Numerical method and statistic approach are adopted to investigate the thermal regime of embankment, considering the south-facing slope effect and other factors. According to the results, designer can propose techniques to mitigate interactions of heat influence between the proposed QTE and the existing infrastructures.

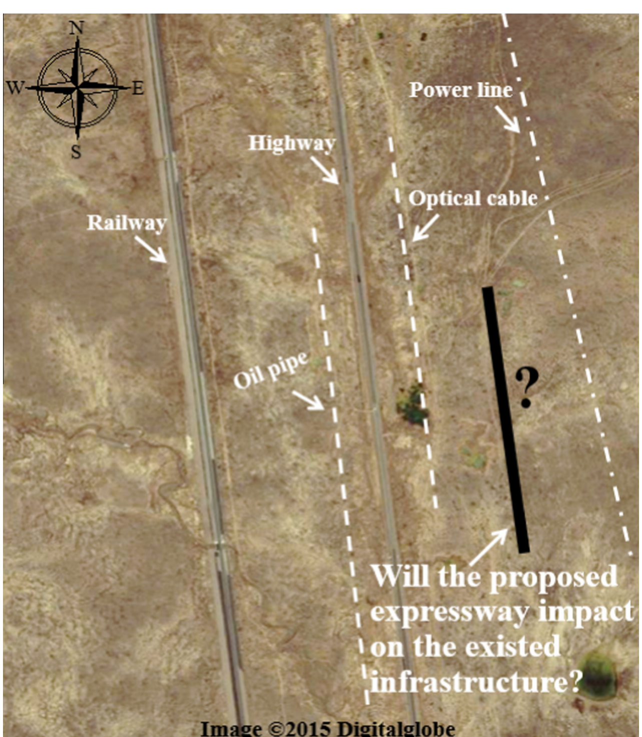

Fig. 1. Key engineering projects in the QTPEC.

2. The computational model

2.1. Governing differential equations and finite-element formula

Heat transfer of a permafrost embankment is an unsteady process that includes phase changes. There are some hypotheses for this process, which are isotropy of the soil, nonexistent convection, the quality of migration, heat of evaporation, and chemical potential. The only factors considered are the heat transfer of the soil skeleton and medium water and the ice to water phase change. The transient two-dimensional heat transfer process can be expressed as follows [11,12]:

$$\rho C\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) \tag{1}$$

where ρ is soil density (kg m^{-3}), C is equivalent thermal capacity (J/kg × °C) of soil, λ is thermal conductivity of soil (W m^{-1} × °C), t is time variable (h), x, y is space variable (m).

At the moving boundary $s(t)$, the continuity condition and the conservation of energy should hold, i.e.,

$$T_f(s(t),t) = T_u(s(t),t) = T_m \tag{2}$$

$$\lambda_f\frac{\partial T_f}{\partial n} - \lambda_u\frac{\partial T_u}{\partial n} = L\frac{ds(t)}{dt} \tag{3}$$

where f and u denote frozen and unfrozen states, respectively. L is latent heat of water (J m^{-3}), Tm is the temperature on the freeze-thaw interface (°C), n is direction vector of the moving boundary $s(t)$ (m).

The conditions are described as follows at the fixed boundary:

$$T = T_\infty, \quad \lambda\frac{\partial T}{\partial n_1} = \alpha(T - T_\infty) \tag{4}$$

Here, T_∞ is the environmental temperature (°C), n_1 is the normal direction at the fixed boundary (m), α is the coefficient of heat convection W m^{-1} × °C.

The initial conditions are given as

$$T_u|_{t=0} = T_0, \quad \Omega_u|_{t=0} = 0 \tag{5}$$