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Numerical analysis for critical height of railway embankment in permafrost regions of Qinghai–Tibetan plateau

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Abstract

In permafrost regions of Qinghai–Tibetan plateau, the critical embankment height must be considered in the process of the construction of railway, especially for the global climatic warming. In this paper, the two-dimensional numerical analysis for the critical embankment height (for coarse-grained soil) has been performed by using the finite element method. The mean annual air temperatures used in the calculation are −6.5, −6.0, −5.5, −5.0, 4.5 and −4.0 °C, respectively, and the value of temperature rise is taken as 1.10 °C in the coming 50 years. The minimum embankment heights derived from the analysis are 0.85, 0.92, 1.01, 1.18, 1.60 and 2.66 m for the different mean annual air temperatures, and the maximum embankment heights are 7.68, 7.55, 7.34, 7.00, 6.45 and 5.85 m, accordingly. On condition that the service life of railway embankment is 50 years, the critical value of the mean annual air temperature is −3.5 °C. Namely, in the areas where the mean annual air temperature is higher than −3.5 °C, the critical embankment height does not exist. Furthermore, by calculating, we can find that no matter whether high or low embankment is constructed, the ground temperature under the embankment will rise, and the permafrost will be in a degradation situation, which has been confirmed by the field observation data at Qinghai–Tibetan railway test sites.

Keywords: Railway embankment; Mean annual air temperature; Critical embankment height; Numerical analysis

Introduction

The construction of embankments in permafrost regions will induce disturbance to the thermal balance between ground surfaces and atmosphere. Usually, the temperature of embankment surfaces is higher than that of natural ground surfaces, as this directly causes the change of the permafrost table under embankments (Wu and Cheng, 1988). When the embankments are too low, the stability of the embankments will be affected by the decline of the permafrost table; when the embankments are too high, which are constructed especially in summer

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because much more heat energy is contained in the embankments, the local climate fails to remove the surplus heat in the following winter, and the residual thawed layer in the embankments will exist for some time after the embankments have been finished. Similarly, the permafrost table below the embankments will move down, and the stability of the embankments will be influenced. To solve the problems, as early as the 1980s, people have begun to study the critical embankment height in permafrost regions. Huang (1983) has simulated the statistical relationship between the critical embankment height for clay soil and the change of permafrost table by thorough investigation and research on the embankment of Qinghai–Tibetan highway. Dai (1983) has summarized the experience from the railway construction in Daxing'an Mountains and concluded that the critical embankment height is 1.5 m in continuous permafrost area and 2.0 m in the areas with isolated taliks. Wu and Zhu (1998) have investigated Qinghai–Kangding highway after it has been running for 35 years and pointed out that the critical embankment height is 1.6 and 2.0 m for gravel and concrete road surfaces in the regions, respectively, analyzing such factors synthetically as changing characteristics of permafrost table under the embankment, the influence of climate and highway grade. Ding and He (2000) have concluded that the critical mean annual air temperature is −3.8 °C for fine-grained soil, which shows that the critical embankment height does exist in the areas where the mean annual air temperature is lower than the critical value. At present, in situ experiments on the critical embankment height are being carried out at Beiluhe test sites of Qinghai–Tibetan railway.

Although a number of studies on the critical embankment height in permafrost regions have been done, until now, most of them still rely on empirical formulas to solve the problem. As far as the global warming is concerned, those empirical formulas cannot meet the design requirements of railway embankment. In this paper, we aim to obtain the critical embankment heights for different mean annual air temperatures in permafrost regions of Qinghai–Tibet plateau using finite element method, considering both global warming and 50-year service life of the railway. It is hoped that the calculation results can serve the design and construction of Qinghai–Tibetan railway.

2. Governing equations and their finite element formulae

In the problem, we assume that the soil layers of the embankment and below are homogeneous and isotropic, and there is no water infiltration into or out of the embankment; subsequently, water migration is negligible in the active layer. According to the data (An et al., 1990), we can conclude that, in the process of freezing and thawing, the ratio of thermal conduction is much larger than that of convection in soil (above 100–1000 times), so the convection can be neglected. Thus, when only the conduction and phase transition problem are considered, the heat transfer process in the soil layers can be described as follows (An et al., 1990; Yang and Tao, 2000):

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

$$C^* = C + \frac{L}{(1+w)} \frac{\partial w_{\mathrm{i}}}{\partial T} \tag{2}$$

where, ρ—soil density; λ—heat conductivity of soil; C^* and C—equivalent specific heat capacity and composite specific heat capacity of soil; L—latent heat of water; t—time; w_{i}—ice content in soil expressed as $w-w_{\mathrm{u}}$; w, w_{u}—the total water content and unfrozen water content of soil, respectively.

The main difference between frozen soil and thawed soil is that frozen soil contains ice. Depending on its physical state (frozen or thawed), the composite specific heat capacity C of soil can be obtained in the following way (Xu et al., 2001):

$$C_{\mathrm{u}} = \frac{C_{\mathrm{su}} + wC_{\mathrm{w}}}{1+w} \tag{3}$$

$$C_{\mathrm{f}} = \frac{C_{\mathrm{sf}} + (w-w_{\mathrm{u}})C_{\mathrm{i}} + w_{\mathrm{u}}C_{\mathrm{w}}}{1+w} \tag{4}$$