Research Article

Simulation Analysis of the Long-Term Stability for Frozen Soil Roadbed

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Received 9 April 2014; Accepted 6 July 2014; Published 13 August 2014

Academic Editor: Ker-Wei Yu

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The global warming will lead to rising temperature in Tibetan plateau which will cause some trouble to the long-term stability of frozen soil roadbed. Of course, the temperature is the most important to stability analysis and study of frozen soil roadbed. In this paper, taking the frozen soil roadbed in Tibetan plateau as an example, the numerical simulation model is established. Firstly, the characteristics of temperature fields of frozen soil roadbed in the future 50 years are analyzed, and then the vertical and horizontal displacements without load and under dynamic load are analyzed.

1. Introduction

With the rapid development of society and economy in China, many transportation infrastructures in cold regions have been constructed in recent years. However, the engineering stability in cold regions has gained wide attention, especially the long-term stability. We all know that the temperature in cold region, which can be changed by many factors, such as construction and climate warming, is the most important to engineering stability. In Tibetan plateau, the temperature changes significantly with the global warming. According to the 4th IPCC's report, the global average temperature continues to increase, and the temperature has risen about 0.13°C ($0.10\sim 0.16^{\circ}\text{C}$) every ten years in the last 50 years which is almost twice that of the past 100 years. Compared with 1850–1899, the total temperature of 2001–2005 increased by 0.76°C ($0.57\sim 0.95^{\circ}\text{C}$), but the 5th IPPC's report (2013) has said that maybe the global warming is more serious than previous estimation. Assuming that carbon dioxide continues to increase, Qin et al. [1] predicted that the temperature in Tibet plateau will increase by $2.2\sim 2.6^{\circ}\text{C}$ [2, 3] according to the mode of Chinese regional climate.

In recent years, many scholars have studied the stability of frozen soil roadbed [4–8]. Sun et al. [9] analyzed the deformation characteristics of embankment of the Qinghai-Tibet railway, according to the monitored results of the ground

temperature and deformation of 34 monitored sections from 2005 to 2011. Mao et al. [10] put forward the coupling calculation model of the heat-moisture-stress fields based on the control equation of the nonstationary temperature field, the finite element control equation of the moisture movement, and the two-dimensional numerical calculation model of the deformation and stress fields in the subgrade. They found that the temperature field, moisture field, and stress field of the permafrost roadbed were changing all the time, and the redistributing of stress caused by the change of heat and moisture is the key factor to the frost damages. Liu et al. [11] established the stochastic finite element equations for random temperature using the first-order perturbation technique taking into account the random thermal properties and boundary condition, based on heat transfer variational principle. Ma et al. [12] analyzed the deformation and the change of ground temperature of some embankment including the duct-ventilated embankment and the crushed rocks embankment and found that the embankment deformation are not only the behavior of settlement, but also influenced by the change of ground temperature. Zhu et al. [13] put forward a mathematics model and its control equation according to heat transfer, filtration theory, and mechanics of frozen soil. With numerical simulation model established, this paper takes the frozen soil roadbed in Tibetan Plateau as an example. The characteristics of temperature fields of frozen

FIGURE 1: The temperature and time.

soil roadbed in the future 50 years are analyzed, and the vertical and horizontal displacements without load and under dynamic load are analyzed, too.

2. Fundamental Theory

2.1. The Coupling Equations of Temperature Field and Moisture Field. Assuming that there is no dynamic load on roadbed, moisture migration and ice water phase transition are only considered. The heat transport equation can be written as follows [14–16].

In the freezing zone Ω_f is

$$c_f \frac{\partial T}{\partial t} = \text{div} [\lambda_f \text{grad}(T_f)] + L \rho_i \frac{\partial \theta_i}{\partial t}. \quad (1)$$

In the unfrozen zone Ω_μ is

$$C_\mu \frac{\partial T_\mu}{\partial t} = \text{div} [\lambda_\mu \text{grad}(T_\mu)], \quad (2)$$

where the symbols f and μ , respectively, express frozen state and unfrozen state, T_f , C_f , and λ_f are temperature, volumetric heat capacity, and thermal conductivity of soil in the freezing zone, L is the latent heat of ice water phase transition, θ_i is the ice volume, ρ_i is the ice density, and t is time. Parameters with subscript μ are the corresponding

physical components in the unfrozen area Ω_μ , and (1) can be written as

$$\begin{aligned} & \left(C_f + L \rho_w \frac{\partial \theta_\mu}{\partial T} \right) \frac{\partial T}{\partial t} \\ &= \text{div} \left[\left(\lambda_f + \frac{k L^2 \rho_w^2}{T_k} \right) \text{grad}(T_f) \right] \\ &+ \frac{L \rho_w^2}{\rho_i} \text{div} [k^* \text{grad}(P_i)], \end{aligned} \quad (3)$$

where ρ_w is water density, P_i is ice pressure, T_k is absolute temperature, and k^* represents hydraulic conductivity of soil. Not considering the effect of thermal stress in frozen, so

$$C^* \frac{\partial T}{\partial t} = \text{div} [\lambda^* \text{grad}(T)], \quad (4)$$

where

$$\begin{aligned} C^* &= \begin{cases} C_f + L \rho_w \frac{\partial \theta_\mu}{\partial T} & \text{in } \Omega_f \\ C_\mu & \text{in } \Omega_\mu \end{cases} \\ \lambda^* &= \begin{cases} \lambda_f + \frac{k L^2 \rho_w^2}{T_k} & \text{in } \Omega_f \\ \lambda_\mu & \text{in } \Omega_\mu. \end{cases} \end{aligned} \quad (5)$$

FIGURE 2: Vertical displacement.

2.2. Stress-Strain Equations

2.2.1. The Differential Equilibrium of Soil. The equilibrium differential equations of representative elemental volume in the soil under the train load can be represented as [14, 16]

$$[\partial]^T \{\sigma\} - \{f\} + \{c\} + \rho \{\ddot{u}\} = 0, \quad (6)$$

where $[\partial]$ is differential operator matrix, $[\partial] = \begin{bmatrix} \partial/\partial x & 0 & \partial/\partial y \\ 0 & \partial/\partial y & \partial/\partial x \end{bmatrix}^T$, $\{\sigma\}$ is stress, and $\{\sigma\} = \{\sigma_x \quad \sigma_y \quad \tau_{xy}\}^T$, and ρ is calculated damping force. Equation (6) can be expressed by

$$[C] \{\dot{\mu}\} = (\alpha [M] + \beta [K]) \{\dot{\mu}\}, \quad (7)$$

where $[C]$ is damping matrix, $[M]$ is mass matrix, $[K]$ is stiffness matrix, $\{\mu\}$ is displacement vector, $\{\mu\} = \{\mu_x \quad \mu_y\}$, and α and β are damping constants; in this paper, $\alpha = 0.03$, $\beta = 0.01$.

2.2.2. Geometric Equation. The geometric equation can be written as [15]

$$\{\varepsilon\} = -[\partial] \{\mu\}, \quad (8)$$

where $\{\varepsilon\}$ is strain and $\{\varepsilon\} = \{\varepsilon_x \quad \varepsilon_y \quad \tau_{xy}\}^T$.

2.2.3. Physical Equation. Hardin and Drenvich [17] derived the hyperbolic equation under cycle loads which can be written as

$$\tau = \frac{G_0(T) \gamma}{1 + \gamma/\gamma_y(T)}, \quad (9)$$

where $G_0(T)$ is initial shear modulus related to temperature and $\gamma_y(T)$ is strain related to temperature which can be determined by experiment.

3. Simulation Analysis

3.1. Modeling. In this paper, taking one railway roadbed in Tibetan plateau as an example, the numerical simulation model is established. In the model, lithology from top to bottom is ballast, fill, subclay, and weathered mudstone, the slope ratio is 1:1.5, and the road width is 3.4 m [15].

3.2. Boundary Conditions. Considering that the mean annual air temperature will rise 2.6°C in Tibetan plateau in the future 50 years [14], the temperature is expressed as [15–19]

$$T_n = A + B \sin\left(\frac{2\pi}{8760} t_h + \frac{\pi}{2} + \alpha_0\right) + \frac{2.6 t_h}{365 \times 24 \times 50}, \quad (10)$$

where A is the annual average temperature and B is the yearly variation temperature.

FIGURE 3: Horizontal displacement.

On the natural surface AB and IJ are

$$T_n = -1.0 + 12 \sin\left(\frac{2\pi}{8760}t_h + \frac{\pi}{2} + \alpha_0\right) + \frac{2.6t_h}{365 \times 24 \times 50}. \quad (11)$$

On the roadbed slope BCDE and FGHI are

$$T_p = 1.2 + 13 \sin\left(\frac{2\pi}{8760}t_h + \frac{\pi}{2} + \alpha_0\right) + \frac{2.6t_h}{365 \times 24 \times 50}. \quad (12)$$

At the top of the ballast, the temperature change of the EF is as follows:

$$T_s = 2.0 + 15 \sin\left(\frac{2\pi}{8760}t_h + \frac{\pi}{2} + \alpha_0\right) + \frac{2.6t_h}{365 \times 24 \times 50}. \quad (13)$$

ANM and JKL can be assumed as thermal insulating boundary, and the geothermal heat flux through boundary LM is $q = 0.06 \text{ W} \cdot \text{m}^2$.

As the mechanical properties of frozen soil are closely connected with temperature, studies have shown that the elastic modulus of permafrost, Poisson's ratio, and shear

strength relationship with soil temperature reference strain relations can be expressed by [15, 16]

$$\begin{aligned} E &= \alpha_1 + b_1 |T|^m, \\ v &= \alpha_2 + b_2 |T|, \\ \gamma_r &= \alpha_3 + b_3 |T|, \\ \varphi &= \alpha_4 + b_4 |T|, \end{aligned} \quad (14)$$

where α_i and b_i are the experimental coefficients, $b_i = 0$ when the soil temperature is higher than 0°C , T is soil temperature, m is nonlinear exponent which is less than 1, and usually $m = 0.6$.

In frozen soil, there is dynamical equilibrium relation between unfrozen water content and negative temperature [20, 21]. The temperature often effects a change of the soil permeability coefficient, and when the temperature decreases, the unfrozen water content decreased, and vice versa. So the unfrozen water content can be defined as

$$W_\mu = \alpha |T|^{-b}, \quad (15)$$

where W_μ is the unfrozen water content and α and b are both constants which are relative to the nature of the soil.

Assuming that the load loading on the roadbed is uniformly distributed load, the total time of train pass is 12 minutes a day and the time interval is equal, and the maximum

FIGURE 4: Vertical displacement.

train load is 70 kN/m. The boundary of ABCDEFG is free boundary, AM and GL are a roller bearing, and ML is fixed constraints boundary.

3.3. Results and Analysis

3.3.1. The Temperature Field. Using the boundary conditions from (11) to (13), the temperature fields' distribution in the next 50 years is shown in Figure 1.

In Figure 1 it can be known that the roadbed's temperature will increase as time goes by, and the temperature in the roadbed center is higher than that in the roadbed boundary. In 50 years, the maximum temperature will rise from 11.08°C to 16.01°C, and the temperature at roadbed center point (40, 45) increases from -9.80°C to -6.80°C. Overall, the temperature change from 5.0 m to 6.0 m in the roadbed of the natural surface is large.

3.3.2. Displacement without Load. The vertical displacement and horizontal displacement are, respectively, shown in Figures 2 and 3. From Figure 2, it can be known that the maximum vertical displacement is 10.80 cm after 20 years, and it will increase to 14.88 cm after 50 years. From Figure 3, we can know that the horizontal displacement of the toe of roadbed is larger than others as time goes by; the horizontal

displacement of the toe is 8.02 cm after 20 years, and it will increase to 9.01 cm after 50 years.

3.3.3. The Displacement under Load. Assuming that the roadbed surface has the dynamic load that was loaded by the train, the vertical and horizontal displacements are, respectively, shown in Figures 4 and 5.

From the figures we can know that the vertical displacement of the roadbed under load is larger than that without load which is about 1 cm, and the vertical displacement of ballast center is the largest one. The largest vertical displacement of the roadbed surface is 10.80 cm without load 20 years later, and it is 11.92 cm under the dynamic load by the train. When there is no load, the largest vertical displacement of the roadbed surface is 14.88 cm after 50 years; however, it is 15.62 cm under the dynamic load that was loaded by train. It can be seen that the maximum horizontal displacement of the roadbed slope is continuing to increase as time goes by, and the largest horizontal displacement without load is about 0.5 cm larger than that with load. The largest horizontal displacement of the roadbed surface is 8.02 cm without load after 20 years, but it is 8.72 cm under the dynamic load by the train. After 50 years, the largest vertical displacement of the roadbed surface is 9.01 cm without load, and it is 10.21 cm under the dynamic load.

FIGURE 5: Horizontal displacement.

4. Conclusions

- (1) The roadbed's temperature will increase year by year, and the temperature in the roadbed center is higher than that in the roadbed boundary. In 50 years, the maximum temperature will rise from 11.08°C to 16.01°C , and the temperature at roadbed center point (40, 45) increases from -9.80°C to -6.80°C . Overall, the temperature change in the roadbed from the natural surface 5.0 m to 6.0 m is large.
- (2) When the roadbed surface has no load, the horizontal displacement of the toe of roadbed is larger than others as time goes by. The horizontal displacement of the toe is 8.02 cm after 20 years, and it will increase to 9.01 cm after 50 years. The maximum vertical displacement is 14.88 cm 50 years later.
- (3) The vertical displacement of the roadbed under load is larger than that without load which is about 1 cm. The vertical displacement of ballast center is the largest. The largest vertical displacement of the roadbed surface is 14.88 cm without load after 50 years, and it is 15.62 cm under the dynamic load by the train. The maximum horizontal displacement of the roadbed slope is continuing to increase year by year, and the largest horizontal displacement without load is

larger about 0.5 cm than that with load. The largest horizontal displacement of the roadbed surface is 9.01 cm without load after 50 years, and it is 10.21 cm under the dynamic load.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This research is supported by National Natural Science Foundation of China (51104081), Postdoctoral Science Foundation of China (2012M521821), and the Natural Science Foundation of Gansu Province (1010RJZA063).

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