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MODELING AND PREDICTING PERMAFROST DEGRADATION DUE TO CLIMATIC WARMING IN THE HUASHIXIA VALLEY, EASTERN QINGHAI-TIBET PLATEAU

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Abstract

The depth and temperatures of continuous permafrost in the Huashixia Valley in the eastern Qinghai-Xizang Plateau in China, and the future trend of the permafrost degradation are modeled and predicted by computer for the natural geographic and geologic conditions in the Huashixia Valley. The modeling results indicate that the position of the permafrost base in the Huashixia Valley is about 56 m deep, with a mean annual air temperature of -4.5ºC. Degradation of the continuous permafrost in the Huashixia Valley is predicted using a mean annual warming rate of 0.04ºC for air temperatures. After one hundred years, the depth to the permafrost base would decrease to 19.5 m, but the position of the permafrost table would be changed by only about 0.50 m. The maximum rate of decrease at the base of permafrost is 0.56 m/a.

Introduction

The Qinghai-Sichuang Highway, i.e., National Road 214, crosses the eastern part of the Qinghai-Xizang Plateau, China. It is one of the most important highways connecting the three provinces of Qinghai, Sichuang and Xizang. It ranges between latitudes 33.5°and 36°N, and longitudes 96°and 99°E, with elevations from 3,000 to 5,000 m. Because of the high elevations and low mean annual air temperatures, many large areas are underlain by permafrost. The highway crosses about 300 km of permafrost, which has been degrading in this region since the 1960's. Zhu Linnan et al. (1995) thought that the degradation could continue for 30-40 years into the future. Thus, good reasons exist to study and predict the degrading trend of the permafrost under conditions of climate warming, along the Qinghai-Sichuang Highway. This is particularly important for road fill and surfacing specifications in the Huashixia Valley area.

Heat and mass transfer model

Since Harlan (1973) presented the first model for the coupled heat and mass transfer in freezing soils, his strategy has been referred to and further developed by many other researchers (Guyman and Luthin, 1974; Nixon, 1975; Outcalt, 1977; Taylor and Luthin, 1978; Jame and Norum, 1980). These authors applied two partial differential equations, in terms of temperature, water (ice) content or water pressure, to describe the transient processes of heat and water flows in freezing soils. In this section, the two equations are coupled through the characteristic relationship between the unfrozen water content and the temperature. The essential ideas of heat and mass transfer model will be discussed theoretically.

Assuming that vapor transfer and heat convection are omitted, the application of the laws of heat balance to saturated or unsaturated soil and the mass conservation of water in soil pores results in the following two equations:

$$\frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) = C\rho \frac{\partial T}{\partial t} - L\rho_i \frac{\partial \theta_i}{\partial t}$$

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial \psi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial \psi}{\partial y}\right) = \frac{\partial \theta_u}{\partial t} + \frac{\rho_i}{\rho_w}\frac{\partial \theta_i}{\partial t}$$

[1] [2]

Where ρ_w, ρ and ρ_i are respectively the densities of water, soil and ice; t, x and y denote the time and two space coordinates; θ_i and θ_u are the volumetric fractions of the ice content and the unfrozen water content; λ_x (λ_y) and K_x (K_y) are the thermal and the hydraulic conductivities in the x and y directions; T is the temperature; C is the specific heat; L is the latent heat; ψ is the total potential of water in soil; $\psi = \varphi + Z$, where φ and Z denote, respectively, the volumetric potential of water in the soil and the gravitational potential. In general, Z can be omitted and therefore $\psi = \varphi$.

According to the characteristic relationship $\theta_u = f(T)$ between the unfrozen water content θ_u and the temperature T, we obtain the following differential relationship:

$$\frac{\partial \theta_u}{\partial t} = \frac{\partial \theta_u}{\partial T}\frac{\partial T}{\partial t} \qquad [3]$$

Substituting the differential relationship into equation (1) and reducing (1), we can derive :

$$\left(C\rho + L\rho_w \frac{\partial \theta_u}{\partial T}\right)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + L\rho_w\left[\frac{\partial}{\partial x}\left(K_x \frac{\partial \psi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial \psi}{\partial y}\right)\right] \qquad [4]$$

Equations (2) and (4) can be solved when the function ψ is given, and the characteristic relationship between the unfrozen water content and the temperature is determined by testing. Therefore, in terms of the different types of potential functions, we can derive different types of calculated models.

Some studies of volumetric potential of unfrozen water in frozen soil have proposed that it can be determined using the characteristic relationship between the unfrozen water content and the temperature, similar to the volumetric potential of unfrozen soil, when the action of ice in the frozen soil is omitted, i.e., the characteristic relationship of moisture for unfrozen soil is suitable for frozen soil (Taylor and Luthin, 1976, 1978).

Introducing a new differential relationship:

$$\frac{\partial \varphi}{\partial T} = \frac{\partial \varphi}{\partial \theta_u}\frac{\partial \theta_u}{\partial T} \qquad [5]$$

In terms of the differential water capacity $c = \frac{\partial \theta_u}{\partial \varphi}$, and the soil-water diffusivity $D = \frac{K}{c}$, we reduce equation (4) to:

$$C(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\beta_x(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\beta_y(T)\frac{\partial T}{\partial y}\right) \qquad [6]$$

where

$$C(T) = C\rho + L\rho_w \frac{\partial \theta_u}{\partial T} \qquad [7]$$

$$\beta_x(T) = \lambda_x + L\rho_w D_x \frac{\partial \theta_u}{\partial T} \qquad [8]$$

and

$$\beta_y(T) = \lambda_y + L\rho_w D_y \frac{\partial \theta_u}{\partial T} \qquad [9]$$

Since the characteristic relationship between the unfrozen water content and the temperature can be determined by testing of core samples, the set of nonlinear equations (2) and (6) can be solved using several methods. In this paper, we used the implicit finite difference method.

Boundary conditions

In order to model and predict the permafrost and its degradation under climatic warming in the Huashixia Valley, the 60-meter-deep ground temperature gradient at the lower boundary was assumed to be $\frac{\partial T}{\partial x} = \frac{3}{100}$, i.e., 0.03°C per meter. According to the drilling records on temperature and temperature gradients, the heat flux at the base of permafrost is a stable value. Using the meteorological information from the Huashixia Valley and from Ma Duo County, and using the regression analysis of the sine function, we can reduce the upper boundary temperature to the following sine function:

$$T = T_s + g(t) + 12.2\sin\left(\frac{2\pi}{8640}t + \frac{4\pi}{3}\right) \qquad [10]$$

where $g(t) = At$, and T_s and A are respectively the mean annual temperature at the ground surface (Wu Ziwang, 1988) and the rate of temperature increase per annum. The values are, respectively, -2.0°C and 0.04°C/a. As for the continuous permafrost region in the Huashixia Valley (Drill Hole No.2), the hydrogeologic conditions are shown as follows:

(1) 0-1.20 m, organic clayey soil, water content of 40.0%, dry density 0.9 g/cm^3,

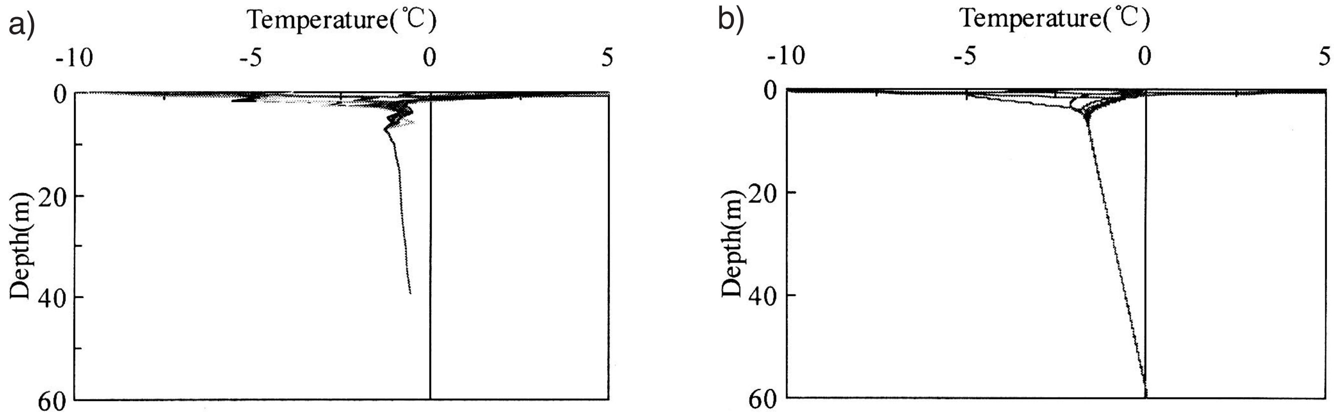

Figure 1. a) Ground temperature profiles in frozen soil (measured 1996). b) Ground temperature profiles in frozen soil (calculated 1996).

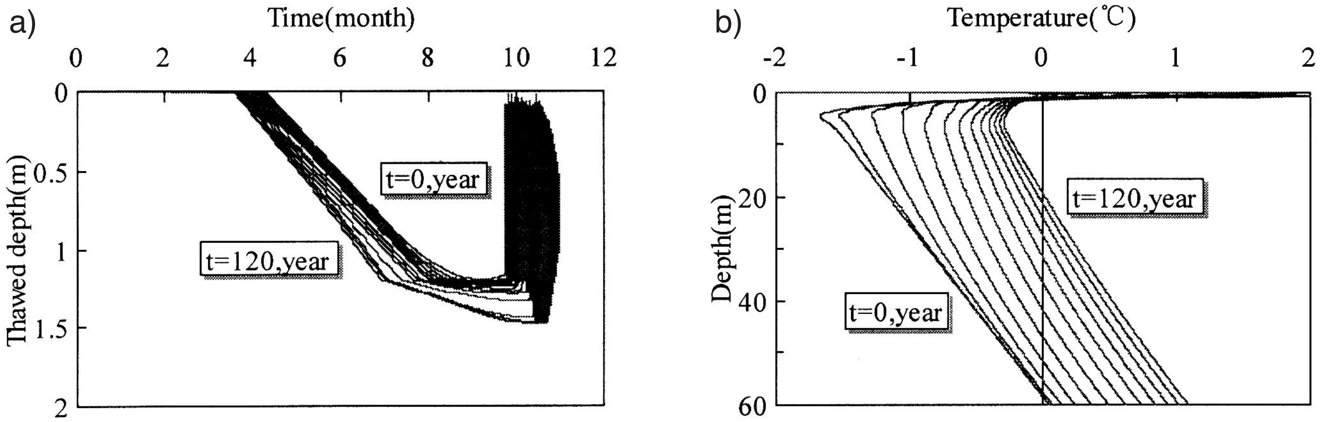

Figure 2. a) Changing curves of seasonally thawed depths with time. b) Ground temperature profiles for October every ten years.

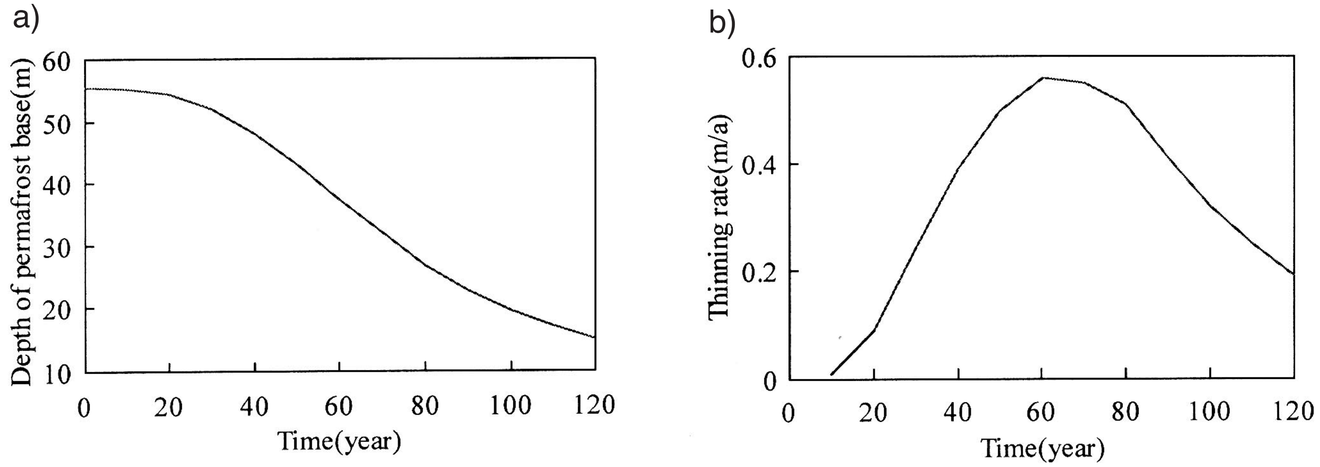

Figure 3. a) Relationship between the depth of the permafrost base and time. b) Relationship between the thinning rate of permafrost from the base and time.

(2) 1.20-3.30 m, clayey soil, water content of 178.5%, dry density 0.355 g/cm^3,

(3) 3.30-7.60 m, gravel, water content of 24.5%, dry density 1.52 g/cm^3,

(4) below 7.60 m, bedrock, water content of 4%.

The relationship between the unfrozen water content, temperature, total moisture and the heat parameters are taken from a book of the experimental research on moisture transfer in frozen soil (Xu and Deng, 1991).

Results and conclusion

The results of the modeling are shown in Figures 1-4. Figure 1a and Figure 1b show the ground temperature profiles for the frozen soil, denoting respectively the results of field observations and calculations. Under a

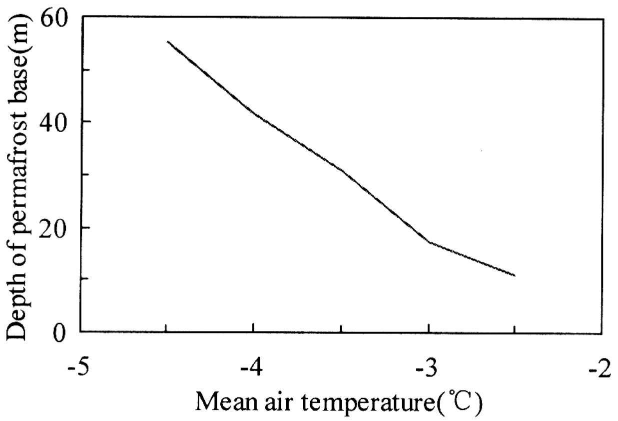

Figure 4. Relationship between the depth of the permafrost base and the mean annual air temperature.

mean annual air temperature warming at a rate of 0.04°C/a, the active layer depth and the ground temperature distribution in October for each ten-year period are plotted in Figure 2a and Figure 2b. The relationship between the permafrost thickness (depth) and the rate of thinning from the base, and time are plotted in Figure 3a and Figure 3b. Using the meteorological properties and hydrogeologic conditions of the Huashixia Valley, the relationship between the modeled thickness of permafrost and the mean annual air temperature is plotted in Figure 4.

The modeling and predicted results indicate that the thickness of the continuous permafrost in the Huashixia district is about 56.0 m, under a local mean annual air temperature of 4.5°C. After one hundred years, the depth of the continuous permafrost base would move upwards to 19.5 m under conditions of climatic warming at a rate of 0.04°C per annum. In the permafrost degradation process, not only has the continuous permafrost contracted vertically, but the amplitude of the maximum seasonal thaw depth is about 0.50 m smaller. The reason is that the permafrost degradation process is influenced by moisture and the soil properties. Finally, the peak rate of permafrost thinning, about 0.56 m/a, appears during the middle period (after about 60 years, Figure 3b).

From the relationship between the air temperatures and the thicknesses (depths) of permafrost (Figure 4), we can examine the relationship between modern climate and the developing permafrost, trace the distribution of permafrost during other historic times, and analyse the principles of zoning among continuous and discontinuous permafrost and seasonally frozen regions.

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