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Thermal regime of frozen soil foundation affected by concrete base of transmission line tower on the Tibetan Plateau

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HIGHLIGHTS

- A 3-D model of frozen soil foundation of concrete base with phase change and internal heat source is presented.
- The thermal regimes of frozen soil foundation affected by concrete base constructed by two different methods were investigated.
- Cast-in-place concrete base has great heat influence on the frozen soil foundation.
- Fabricated construction method is proposed in the concrete base construction in permafrost regions.

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ABSTRACT

Frozen soil is so sensitive to the temperature change. The melt of ice in soil can lower the bearing capacity of foundation. This work aims to investigate the thermal regime of the frozen soil foundation, affected by transmission line tower concrete base which is constructed by two different methods. One is the cast-in-place construction method; another is the fabricated construction method. A three-dimensional model is developed to predict the thermal regime of the frozen soil foundation and the concrete base, considering the hydration heat of concrete. The phase change between water and ice is considered by using the sensible heat capacity method. The results show that the concrete base constructed by the cast-in-place method has great influence on the thermal regime of frozen soil foundation in about one month after the base constructed. The soil surrounding the base experiences severe melting-freezing process in this period. In first four months, the thaw progressing of the two construction cases is significant different. For the cast-in-place construction case, the heat influence area on the frozen soil is along the base side. But for the fabricated construction case, it is only in the active layer. And then, the reasonable construction methods are recommended.

1. Introduction

Frozen soil is extremely sensitive to the change of temperature, especially for which containing a high percentage of ice. The temperature changes can leads to corresponding changes in the mechanical properties of frozen soil. The bearing capacity of frozen soil foundation is low in the melting state. Furthermore, in the process of soil freezing, the frost heaving will happen. All of these phenomena will affect the security and stability of upper engineering [1]. So, for the above reasons, the thermal regime and stability of frozen soil foundation must be studied before the construction of the engineering in permafrost regions. (Note: permafrost is soil at or below the freezing point of water 0 °C for two or more years [2]).

The Qinghai-Tibet DC transmission line is one of the key project of the Western China Development. Along the transmission line, the average altitude is 4500 m, the highest altitude is 5300 m, and there distributions of large area of permafrost because of the high altitude. As shown in Fig. 1, the line across the 550 km in permafrost regions. Most bases of transmission line tower were constructed with concrete in this area, and it may affect the temperature regime of frozen soil foundation. For transmission line tower bases on the frozen soil foundation, some works have been completed. Q.H. Yu et al. [3,4] monitored the temperature regimes of frozen soil foundation of tower with concrete base, and analyzed the heat transfer characters of frozen soil foundation. Besides, there are many scholars studied the influence of cement hydration heat on

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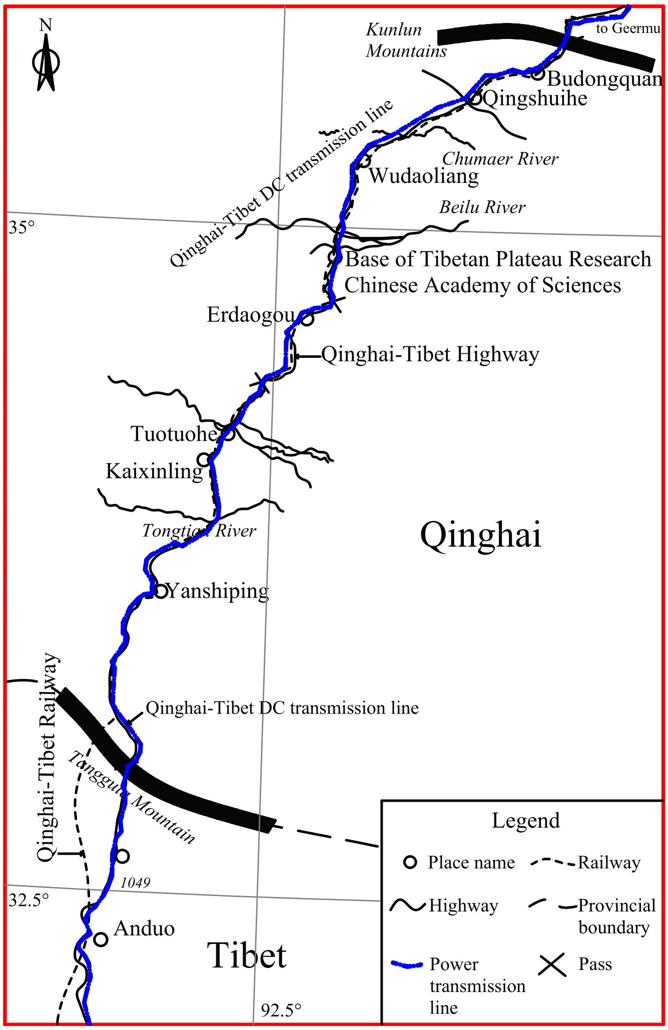

Fig. 1. Route of the Qinghai-Tibet DC transmission line.

temperature distributions of engineering foundations. Y.P. Wu et al. [5] established the single concrete pile model in permafrost and analyzed the influence of casting temperature of single pile on temperature distribution of ground using finite element method. X.F. Zhang et al. [6] studied the culvert cast-in-situ concrete foundation of Qinghai-Tibet Railway and derived the heat balance differential equation for this transient heat transfer process considering the phase change and heat generation, and the finite element formula was also derived in Galerkin method. On that basis, the temperature distributions of culvert foundation with and without heat preservation measures were calculated. C.X. Guo et al. [7] analyzed the influence of concrete hydration heat on the melting and refreezing processes of surrounding rock of tunnels in permafrost regions. In addition, H. Ma et al. [8] studied the influence of construction of single pile in cold season on ground temperature in permafrost regions.

Although much works have been conducted on the influence of engineering on the frozen soil foundation, there are barely work aims at the heat influence on the frozen soil foundation caused by construction method. In the Tibetan Plateau permafrost regions, some construction methods are employed in the construction of concrete base, and the heat influence caused by them are different. So, based on the above-mentioned truth, it is worth studying of what form and degree and how the duration time of heat influence of concrete base on the frozen soil foundation in different construction methods. In this work, based on the heat transfer theory, a three-dimensional model of frozen soil foundation of transmission line tower is developed. The ice-water phase change and the heat generation of cement hydration are considered in the calculation. Through temperature distributions, temperature curves and thaw progressing diagram, the heat influence of concrete base on the frozen soil foundation is analyzed in different construction methods, and the rules and process of influence are obtained. Finally, the reasonable concrete base construction methods on the frozen soil foundation are proposed.

2. Modeling

2.1. Physical model

In Fig. 2(a), a transmission line tower on the frozen soil foundation on the Tibetan Plateau is presented. The base of transmission line tower is constituted with 4 concrete bases in horizontal plane (Fig. 2(b)). These 4 concrete bases are symmetric about two axes. Because of this character, the model of tower foundation is heat isolated at the plane of symmetric. Therefore, a quarter of area can be taken as the computation model. As shown in Fig. 2(c), the depth of model is 30 m, the horizontal width is 26 m. The soil in the model is divided into three layers. Each stratum is assumed to be uniform and isotropic. As Fig. 2(d) shows is the ice-rich soil revealed by drilling. In some areas of foundation, there contains this kind of soil, which is so sensitive to the temperature change.

The thermal parameters of different strata can be obtained according to field testing data and related documents [1]. In this work, the concrete was made using C30 ordinary Portland cement, and the thermal parameters can be obtained [9]. All of the parameters are listed in Table 1.

2.2. Mathematical model

2.2.1. The governing differential equations and finite element method of transient temperature field

Heat transfer of frozen soil foundation is a kind of unsteady process with phase change. There are some hypotheses in this process, which are isotropic of soil, inexistence of convection, quality migration, evaporation heat and chemical potential. The only considered factors are heat transfer of soil skeleton and medium water, and the ice-water phase change. The calculated area can be divided into frozen area (Ω_f) and unfrozen area (Ω_u), the whole calculated area is $\Omega = \Omega_f + \Omega_u$. This unsteady three-dimensional heat transfer process can be described by the following differential equations and initial and boundary conditions [10–12]:

In Ω_f,

$$C_f \frac{\partial T_f}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_f \frac{\partial T_f}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_f \frac{\partial T_f}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_f \frac{\partial T_f}{\partial z}\right) \tag{1}$$

In Ω_u,

$$C_u \frac{\partial T_u}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_u \frac{\partial T_u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_u \frac{\partial T_u}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_u \frac{\partial T_u}{\partial z}\right) \tag{2}$$

In Eqs. (1)–(2), subscripts f and u represent the soil states frozen and unfrozen, respectively. T, C, and λ are the temperature, volumetric heat capacity, and thermal conductivity of soil, expressed in °C, J/m^3·°C, and W/m·°C, respectively.

At each phase front position $s(t)$, the continuous condition and the conservation of energy should be met, i.e.,