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Research Paper

Influence of hydration heat on stochastic thermal regime of frozen soil foundation considering spatial variability of thermal parameters

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HIGHLIGHTS

- A 3D stochastic thermal model of frozen soil foundation with internal heat source is presented.
- Influences of hydration heat on stochastic thermal regime of frozen soil foundation are estimated.
- A sensitivity analysis of coefficient of variation and autocorrelation distance is carried out.

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ABSTRACT

Construction method of cast-in-situ concrete is very popular for the foundation engineering in permafrost regions. But the hydration heat of concrete can lead to the melt of ice in frozen soil zone, and then the temperature variation can lower the bearing capacity of frozen soil foundation. In this study, a three-dimensional (3D) stochastic thermal model of frozen soil foundation with phase change and internal heat source is proposed, and the influences of the hydration heat on the stochastic thermal regime of frozen soil foundation are estimated. Considering the different variability of thermal conductivity, heat capacity and latent heat, a sensitivity analysis for the stochastic thermal regime is presented. The results show that the hydration heat of concrete has a great influence on the stochastic thermal regime of frozen soil foundation in the early days after the base constructed. The variability of temperature is more obvious when the distance from the footing centerline is close. Different variability of the thermal parameters has a different effect on the stochastic thermal regime. These results can improve our understanding of the influences of hydration heat on the stochastic thermal regime and provide a theoretical basis for the safety of cast-in-place construction method.

1. Introduction

Nowadays, a lot of engineering constructions, such as Qinghai-Tibetan Railway, Road, Oil Pipeline and Power Transmission Line, have been carried out in permafrost regions. With the development of economy, more engineering constructions will be implemented in the future [1]. The frozen soil is one of the key factors for ensuring the safety of the engineering constructions in permafrost regions, and its properties are closely related to the temperature, especially for the frozen soil with a high percentage of ice. The temperature variation can leads to corresponding changes in the mechanical properties of the frozen soil. The bearing capacity of the frozen soil foundation is low in the melting state and it will affect the stability of upper engineering [2-4]. For the viaduct pier and bases of transmission line tower in permafrost regions, the cast-in-situ concrete method is more popular than the precast concrete method because of the environmental complexity and transportation difficulty. However, in the cast-in-situ concrete method, the hydration heat of concrete can accelerate the melt of ice in frozen soil and then the temperature variation can lower the bearing capacity of frozen soil foundation [5-7]. Therefore, the Influence of hydration heat on the thermal regime of frozen soil foundation needs to be studied before the engineering constructions are carried out in permafrost regions.

Thus far, some researchers had focused on the influence of hydration heat on the thermal regime of frozen soil foundation by numerical methods [5,8,9], whereas others had employed in-situ monitoring methods [10-12]. However, most of the thermal analysis of frozen soil foundation with phase change and internal heat source were developed under the assumption that the thermal parameters and boundaries were deterministic. In fact, the thermodynamic parameters of frozen soil and

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concrete are uncertain [13-16]. Also, the stochastic climate can lead to the uncertainty of upper boundary conditions of foundation soils [17-19]. The upper engineering in warm permafrost regions will be become more dangerous because of these uncertainties. Therefore, study on the influence of hydration heat on the stochastic thermal stability is very important. A few researchers had paid their attention to these uncertainties in permafrost regions [20-22]. Although these scientific papers can analyze the two-dimensional stochastic thermodynamic issues for the permafrost engineering, they cannot solve the three-dimensional problems. Especially for cast-in-situ concrete method, the uncertain hydration heat will further affect the thermal properties of frozen soil foundation.

In this paper, considering the heat generation of cement hydration, a 3D stochastic thermal model of frozen soil foundation with phase change and internal heat source is proposed, and the influences of the hydration heat on the stochastic thermal regime of the frozen soil foundation are estimated. Taking the different variability of thermal conductivity, heat capacity and latent heat into account, a sensitivity analysis for the uncertain temperature of the foundation soils is presented. The distributions of mean temperature and standard deviation are obtained, and the rules of stochastic heat influence are analyzed. These results can provide a theoretical basis for the safety of cast-in-place construction method.

2. Mathematical model and equations

2.1. Governing equations of transient temperature field

In permafrost regions, 3D thermal analysis without the internal heat source for the frozen soil engineering had been developed [23,24]. Because of the hydration heat of concrete, the proposed thermal model need take the internal heat source into account. The method of sensible heat capacity can deal with the phase change [25]. Therefore, the differential equations of this problem are given by

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

$$C=\begin{cases} C_f & T<T_m-\Delta T \\ \frac{C_u+C_f}{2}+\frac{L}{2\Delta T} & T_m-\Delta T\leqslant T\leqslant T_m+\Delta T_u \\ C_u & T>T_m+\Delta T_u \end{cases} \tag{2}$$

$$\lambda=\begin{cases} \lambda_f & T<T_m-\Delta T \\ \lambda_f+\frac{\lambda_u-\lambda_f}{2\Delta T}[T-(T_m-\Delta T)] & T_m-\Delta T\leqslant T\leqslant T_m+\Delta T \\ \lambda_u & T>T_m+\Delta T \end{cases} \tag{3}$$

where C represents the volumetric heat capacity; λ represents the thermal conductivity; Parameters with subscript f and u represent the frozen and the unfrozen states, respectively; q_v and L represent the internal heat source and latent heat, respectively; T_m and ΔT represent the phase transition temperature and temperature interval, respectively. In this paper, the value of parameter T_m and ΔT are $-0.5\,°C$ and $1\,°C$, respectively [26,27].

2.2. Calculation of cement hydration heat

Cast-in-situ concrete method is very popular for the foundation engineering because of the environmental complexity and transportation difficulty in permafrost regions. One component of the concrete is the cement. The hydration heat of the cement is very obvious after the cast-in-situ concrete constructed. It will raise the thermal effect of the frozen soil and then affect the security and stability of the foundation soil. The exothermic process of the cement hydration heat for the ordinary Portland cement can be expressed as exponential formula [28,29]. Therefore, the computational formula of the hydration heat (Q_t) is given by

$$Q_t=\theta_0 C_c(1-e^{-mt}) \tag{4}$$

where θ_0 is the ultimate adiabatic temperature for the concrete; C_c is the heat capacity for the concrete; m is a constant; t is the time.

Taking the derivative of the Eq. (4), the internal heat source for the cast-in-situ concrete method can be written as

$$q_v=\frac{dQ_t}{dt}=\theta_0 C_c m e^{-mt} \tag{5}$$

2.3. Analysis methods of 3D stochastic thermal regime

The random field method could be used for considering the uncertainty of the thermodynamic parameters of frozen soil and concrete [13,30]. In this study, the thermal conductivity, volumetric heat capacity and latent heat of the frozen soil and concrete are modeled as a 3D random field, respectively. The 3D random field can be divided by cube elements and the 3D local average element is defined as

$$X_e=\frac{1}{V_e}\int_{\Omega_e}X(x,y,z)dxdydz \tag{6}$$

where V_e is the volume of e and Ω_e is the domain of integration of X.

According to Eq.(6), The covariance of two 3D local average elements can be expressed as

$$Cov(X_e,X_{e'})=\frac{\sigma^2}{8V_eV_{e'}}\sum_{j=0}^{3}\sum_{k=0}^{3}\sum_{l=0}^{3}(-1)^j(-1)^k(-1)^l(T_{1j}T_{2k}T_{3l})^2\Gamma^2(T_{1j},T_{2k},T_{3l}) \tag{7}$$

where σ is the standard deviation of the 3D random field; $V_{e'}$ is the volume of e'; T_{1j}, T_{2k}, T_{3l} are the distances of the relative location for the two 3D local average elements and the detailed description is in Appendix A. $\Gamma^2(T_{1j},T_{2k},T_{3l})$ is the 3D variance function and it is decided by the standard correlation function. The detailed calculation formulas of $\Gamma^2(T_{1j},T_{2k},T_{3l})$ is

$$\Gamma^2(T_{1j},T_{2k},T_{3l})=\frac{8}{T_{1j}T_{2k}T_{3l}}\int_0^{T_{1j}}\int_0^{T_{2k}}\int_0^{T_{3l}}(1-\frac{\xi}{T_{1j}})(1-\frac{\eta}{T_{2k}})(1-\frac{\zeta}{T_{3l}})\rho(\xi,\eta,\zeta)d\xi d\eta d\zeta \tag{8}$$

where $\rho(\xi,\eta,\zeta)$ is the standard correlation function of the 3D random field.

In this paper, the uncertain thermodynamic parameters of the frozen soil and concrete are taken as different independent random fields. According to the research results of Zhu and Zhang [31], taking the heterogeneity of the thermodynamic parameters into account, the standard correlation function in the 3D parameter space can be expressed as

$$\rho(\xi,\eta,\zeta)=\exp\left(-2\sqrt{\frac{\xi^2}{\theta_x^2}+\frac{\eta^2}{\theta_y^2}+\frac{\zeta^2}{\theta_z^2}}\right) \tag{9}$$

where θ_x is the autocorrelation distance for x-direction; θ_y is the autocorrelation distance for y-direction and θ_z is the autocorrelation distance for z-direction.

After obtaining the covariance matrices for the 3D local average random field by Eq. (7), the uncorrelated random variables can be calculated by orthogonal transformation method, and the stochastic temperatures of the frozen soil foundation can be calculated by Neumann expansion method [32]. The statistical properties of the stochastic thermal regime can be obtained by mathematical statistics approach. Based on the governing equations of transient temperature field, calculation of cement hydration heat and analysis methods of 3D stochastic thermal regime, a stochastic finite element program was compiled in MATLAB 7.0. The compiled program can directly output