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Stochastic analysis of uncertain temperature characteristics for expressway with wide subgrade in cold regions

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ABSTRACT

In cold regions, it is more difficult to ensure the stability of wide embankment than ordinary embankment because of a larger heat absorption area. Also, the soil properties and the upper boundary conditions are stochastic because of complex geological processes and changeable atmospheric environment. However, the conventional finite element analysis of temperature characteristics for embankment is always deterministic, rather than taking stochastic parameters and conditions into account. In this paper, the upper boundary conditions are considered as stochastic processes and the soil properties are considered as random fields. A stochastic analysis model for the uncertain temperature characteristics of expressway embankment is presented. The stochastic finite element program is compiled by Matrix Laboratory (MATLAB) software, and the random temperature fields of an expressway embankment in a cold region are investigated by Neumann stochastic finite element method (NSFEM). The results show that the randomness of soil properties and boundary conditions play a different role at different times. NSFEM can solve the random temperature field for expressway embankment when the perturbations of random variables are more than 20%. It can improve our understanding of the random temperature field of expressway embankment and provide a theoretical basis for actual engineering design in cold regions.

1. Introduction

In China, a lot of engineering constructions, like Qinghai–Tibetan railway, road and tunnel have been built in the permafrost regions. These constructions have resulted in a warmer surface condition, and tend to warm the permafrost and make it susceptible to thaw. Many researches have indicated that thaw settlement of permafrost can result in instability and failure of construction (e.g., Lai et al., 2004; Mu, 1988; Zhang et al., 2005, 2009). Under the global warming, these constructions of cold regions will face many severe problems from permafrost degradation (Lai et al., 2003). Especially, for the expressway with a wide surface, it is easier to cause the degeneration of the underlying permafrost and lead to their failure because of higher heat absorption capacity (Yu et al., 2007). Owing to the wide subgrade of expressway, the heat transfer between embankment and nearby frozen soil becomes more difficult and the effect of heat accumulation in embankment rapidly leads to a degradation of permafrost, which means permafrost under embankment tends to thaw and the permafrost table to decline. So, the construction of expressway with wide subgrade in cold regions faces a more complicated engineering problem than that of ordinary roads (Yu et al., 2010).

The thermal stability of embankment is analyzed through numerical methods because the analytical solution is complicated (Lai et al., 2003, 2004; Zhang et al., 2005, 2009). It is well known that the correct value of soil properties and boundary conditions directly affects the results. Up to now, most of the thermal analysis of engineering construction is developed under the assumption that the soil properties and boundary conditions are deterministic; therefore, their results are deterministic. In fact, the property parameters of soil are variable because of the complex geological processes (Dasaka and Zhang, 2012; Elkateb et al., 2003; Ramly et al., 2002; Soulie et al., 1990). Also, the upper boundary conditions of an expressway embankment are stochastic due to the changeable atmospheric environment (Hasselmann, 1976; Majda et al., 1999, 2001). In warm permafrost regions, the random soil properties and boundary conditions can truly make the states of warm frozen soil become stochastic. Therefore, it is significantly important to consider the random aspects of the parameters and conditions. Liu et al. (2006, 2007, 2014) investigated the random temperature fields of an ordinary embankment and a wide embankment in a cold region by first-order perturbation technique. However, the results obtained from first-order perturbation technique were not accurate when the perturbation was more than 20% to 30% and the calculation formulas of local average random field were not mentioned.

In this paper, based on the earlier studies of stochastic analysis model for uncertain temperature characteristics of ordinary embankment (Wang et al., 2015), considering the soil properties as random fields and the upper boundary conditions as stochastic processes, the random temperature fields of a expressway embankment in a cold region are investigated by NSFEM. The mean and standard deviation of

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the random temperature field are obtained and analyzed given climatic warming. The results can provide a theoretical basis for the engineering reliability analysis and design of actual expressway in cold regions.

2. Deterministic governing equations

In cold regions, the temperature fields of embankment are considered as a nonlinear problem of heat transfer with phase change (Lai et al., 2004; Zhang et al., 2005). Based on the method of sensible heat capacity (Bonacina et al., 1973; Lai et al., 1998), the differential equations of this problem are given by

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

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

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

where f and u represent the frozen and the unfrozen states, respectively; C_f and λ_f are the volumetric heat capacity and thermal conductivity of embankment in the frozen area, respectively; Parameters with subscript u are the corresponding physical components in the unfrozen area; L is the latent heat per unit volume; T_m is the freezing point of soil; ΔT is the temperature range of the phase transition; t is the time and x, y, z are the distances.

The boundary conditions and initial conditions of wide embankment are similar to ordinary embankment. The detailed formulas of ordinary embankment were introduced by Wang et al. (2015). It is very difficult to obtain the analytical solution for this problem. We obtain a solution by the Galerkin method (Lai et al., 2003, 2004; Zhang et al., 2005). The following finite element formulae are obtained.

$$[K]\{T\}_t+[C]\left\{\frac{\partial T}{\partial t}\right\}_t=\{F\}_t \tag{4}$$

where $[K]$ is the stiffness matrix; $[C]$ is the capacity matrix; $\{T\}_t$ is the column vector of temperature; $\{F\}_t$ is the column vector of load; and t is the time.

Based on the backward difference method (Lewis et al., 1996), Eq. (4) can be written as

$$\left([K]+\frac{[C]}{\Delta t}\right)\{T\}_t=\frac{[C]}{\Delta t}\{T\}_{t-\Delta t}+\{F\}_t \tag{5}$$

where Δt is the time step.

Both $[K]$, $[C]$ and $\{F\}_t$ are deterministic variables in the conventional deterministic finite element analysis, so $\{T\}_t$ of Eq. (5) is a deterministic result. In this paper, $[K]$ and $[C]$ are not deterministic because soil properties are stochastic, and $\{F\}_t$ is not deterministic because boundary conditions are random. Therefore, $\{T\}_t$ of Eq. (5) is a random result.

3. Stochastic analysis methods of uncertain temperature characteristics

3.1. Stochastic processes for boundary conditions

According to the meteorological information and the regression analysis, we can reduce the boundary temperature to an annual sine function (Lai et al., 2003, 2004; Zhang et al., 2005). Considering the climate warming and its randomness in the future 50 years (Qin, 2002), the air temperature is assumed as following formulation

$$T=A+B\sin\left(\frac{2\pi}{8760}t_h+\frac{\pi}{2}+\alpha_0\right)+\frac{C}{365\times 24\times 50}t_h \tag{6}$$

where A is the yearly average temperature; B is the yearly variation temperature; C is the rise rate of air temperature; α_0 is the phase angle; and t_h the is time, and its unit is h.

The upper boundary conditions for the expressway embankment are stochastic because of the changeable atmospheric environment. We consider the temporal variability and didn't consider the spatial variability, i.e., the upper boundary conditions are modeled as stochastic processes (Wang et al., 2015). In this paper, the mean values of A, B and C are −4 °C, 11.5 °C and 2.6 °C, respectively (Lai et al., 2003, 2004). We assume that A, B and C follow a normal distribution and their coefficients of variation are 0.2.

3.2. Random fields for soil properties

Based on the random field theory (Phoon and Kulhawy, 1999; Vanmarcke, 1977; Vanmarcke et al., 1986), we consider the uncertain soil properties as random fields and describe the correlation by autocorrelation function. The local average method is popular with researchers because it converges rapidly, has high precision, and it needs less statistical information than other methods (Vanmarcke, 1983). We modeled the thermal conductivity, volumetric heat capacity and latent heat as a 2D continuous random field, respectively. $P(x, y)$ is a point on the plane, and the random function, $X(P)$, constitutes a 2D continuous random field.

Based on the random field theory, the autocorrelation function is

$$R_X[P,P']=E[X(P)X(P')]=R_X(|x-x'|,|y-y'|) \tag{7}$$

where the position of $P'(x', y')$ is different from $P(x, y)$.

The standard correlation function is

$$\rho[P,P']=R_X[P,P']/\sigma^2=\rho(|x-x'|,|y-y'|). \tag{8}$$

According to Wang and Zhou (2013), we assume the mean function, $E[X(x, y)]$, is zero and the variance is constant, i.e., $E[X(x, y)] = 0$ and $Var[X(x, y)] = \sigma^2$. It is the local average method of triangular elements when the 2D random field is divided by triangular elements. Fig. 1 is

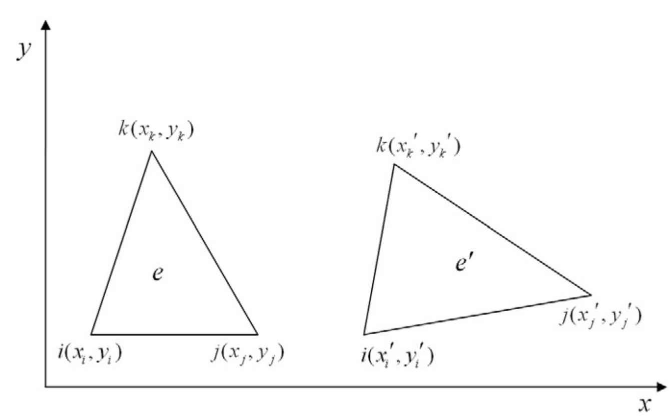

Fig. 1. The 2D triangular random field elements.