Cold Regions Science and Technology 101 (2014) 73–80

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

A mathematical optimization model of insulation layer's parameters in seasonally frozen tunnel engineering

Yuanfu Zhou [a,*], Xuefu Zhang [b], Jianhui Deng [a]

[a] State Key Laboratory of Hydraulics and Mountain River Engineering, College of Water Resource & Hydropower, Sichuan University, Chengdu 610065, China
[b] College of Civil and Architectural Engineering, Chongqing Jiaotong University, Chongqing 400074, China

ARTICLE INFO

Article history:
Received 19 July 2013
Accepted 27 January 2014
Available online 13 February 2014

Keywords:
Seasonally frozen soils
Insulation layer
Optimization design
Tunnel engineering

ABSTRACT

The insulation layer is often used in seasonally frozen tunnel to prevent from frost damages caused by the freeze–thaw cycles. In order to investigate the rationality and economic benefits of insulation layer's parameters when it is used in seasonally frozen tunnel, based on the characteristics of seasonally frozen soils and optimization theory, a mathematical optimization model of insulation layer's parameters is constructed by taking Daban mountain tunnel for an example. The example shows that the mathematical optimization model is reasonable and the solution method is feasible. And then the relationships between the cost and the insulation layer's parameters, depth of tunnel, boundary conditions and phase transition are discussed and they show that all these parameters could affect the optimization results. Therefore, the mathematical optimization model could contribute to choosing the best insulation layer's parameters for the designers when they design seasonally frozen tunnel because it contains all these important parameters and the enormous economic benefits could be obtained.

1. Introduction

In seasonally frozen soils, the negative temperature, which could cause many frost damages, periodically appears with the change of atmospheric temperature. The damages (Chen and Zan, 2001; Lai, 1999) may threaten traffic safety and shorten the life of tunnel. The maintenance cost also will be increased year by year. So the theory and practice about permafrost have been developed rapidly in last decades. On theoretical aspect, some difficult problems about temperature, stress, seepage and so on in permafrost have been solved, for example, the coupled problem of temperature, seepage and stress fields (Lai et al., 1998, 1999), temperature field including phase transition (Xuefu et al., 2002), freezing–thawing situations under different conditions (Zhang et al., 2002) and coupled problem of heat transfer and heat convection (Xuefu et al., 2006). In practice, analyses of the refreezing on Fenghuo mountain tunnel and Kunlun mountain tunnel were forecasted by Zhang et al. (2004a,b). Some technologies to prevent permafrost from thawing, have been studied in Qinghai–Tibetan highway, for example, the thermal-insulation and two-phase closed thermosyphon (Wen et al., 2005), the extruded polystyrenes (EPS) and polyurethane (PU) (Liu and Tian, 2002; Sheng et al., 2006). Although the theory and practice about permafrost have been significantly developed, the economic benefits are often ignored in the design of seasonally frozen tunnel. It is even more unfortunately that the cost has not been researched deeply. Therefore, it is worth to investigate the insulation layer's cost because installing insulation layer is still the most important and universal tool to prevent the frost damages by now and the designers and managers may want an optimization method about cost as soon as possible since more and more tunnels will be constructed in seasonally frozen soils in the future. A mathematical optimization model of insulation layer's parameters is constructed due to the above reasons, and it is examined by an example in this paper.

2. Mathematical optimization model of insulation layer's parameters

2.1. Partial differential equations of temperature field and finite element formulations

In seasonally frozen tunnel, as the tunnel structure and surrounding rock undergo freeze–thaw cycles every year, this problem can be described by the phase transition. The differential equations of the transient temperature field with phase transition are given by the following expressions (He and Wu, 1996; Lai et al., 1998, 2000):

In the frozen domain Ω_f,

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

---

* Corresponding author. Tel.: +86 28 85401807.
E-mail address: zhouyf-666@163.com (Y. Zhou).

http://dx.doi.org/10.1016/j.coldregions.2014.01.009
0165-232X/© 2014 Elsevier B.V. All rights reserved.

In the unfrozen domain Ω_u,

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

Where, f and u represent the state of frozen and unfrozen respectively. C, T and λ are the surrounding rock's volumetric heat capacity, temperature and thermal conductivity, respectively. Over the border between frozen domain and unfrozen domain, the continuity condition and conservation condition must be satisfied:

$$T_f(s(t), t) = T_u(s(t), t) = T_m \tag{3}$$

$$\lambda_f \frac{\partial T_f}{\partial \mathbf{n}} - \lambda_u \frac{\partial T_u}{\partial \mathbf{n}} = L \frac{ds(t)}{dt}. \tag{4}$$

Where, $s(t)$ is the boundary between frozen domain and unfrozen domain, L is the volumetric latent heat and T_m is the temperature over the border between frozen domain and unfrozen domain.

The first and third boundary conditions are:

$$T = T_a, \frac{\partial T}{\partial \mathbf{n}} = \alpha(T_a - T). \tag{5}$$

Where, α is the coefficient of heat convection and T_a is the equilibrium temperature.

The initial condition is:

$$T|_{t=0} = T_0. \tag{6}$$

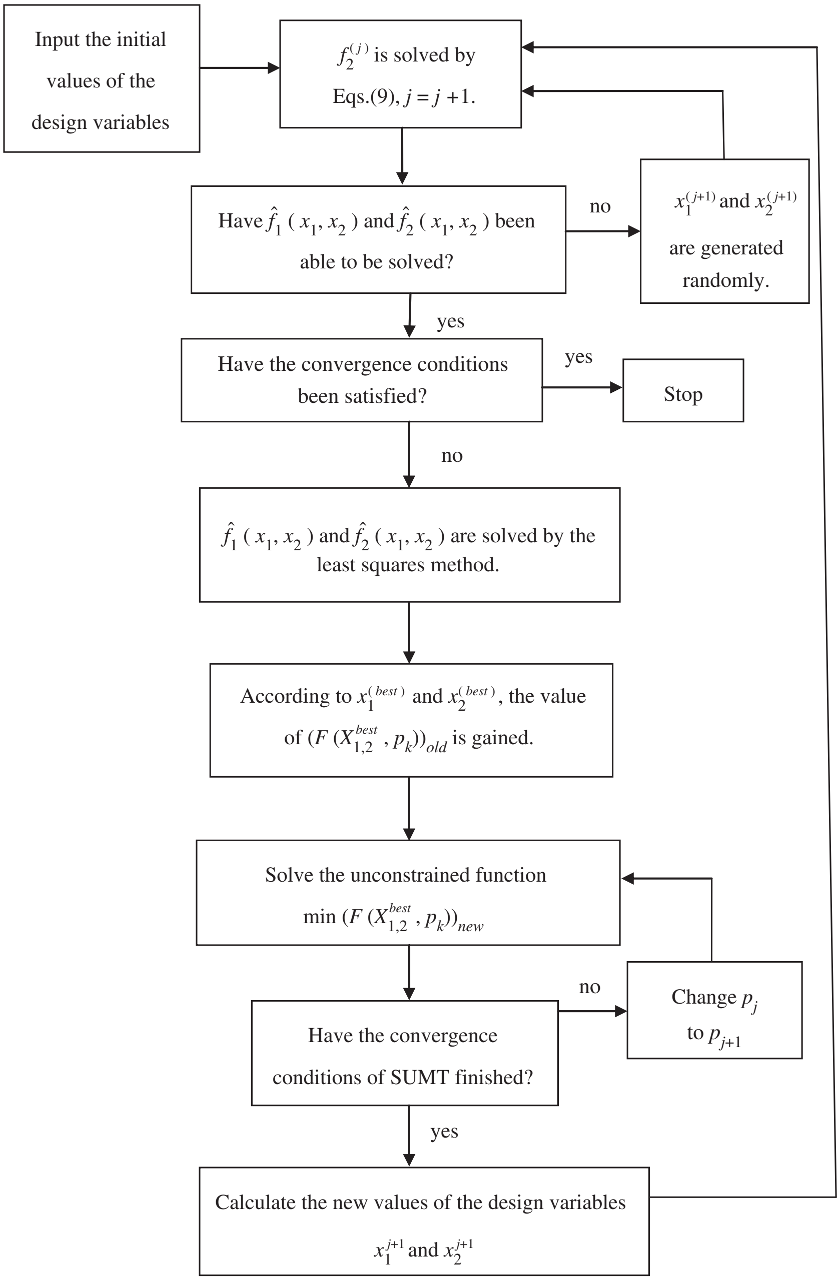

Fig. 1. Procedure of the optimization.