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Analytical and numerical modeling for the effects of thermal insulation in underground tunnels

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ABSTRACT

The heat flow generated from the infinite rock mass surrounding the underground tunnels is a major cause for the increasing cooling demands in deep mine tunnels. Insulation layers with lower thermal conductivities on tunnel walls and roof ceilings are believed to supply a thermo-barrier for heat abatement. However, it is found that no systematic theoretical investigations were made to predict and confirm the effectiveness of underground thermal insulation. Specifically, investigations on the underground insulation problems involving heat flows through the semi-infinite hot rock mass and insulation layer were not sufficient. Thus, in this paper, the thermal characteristics, accompanied with heat flow through the semi-infinite rock mass and the insulation layer, were modeled by both analytical and numerical methods with focus on underground mine tunnels. The close agreements between models have indicated that the thermal insulation applied on tunnel surfaces is able to provide promising heat abatement effects.
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1. Introduction

Nowadays, underground mines are going increasingly deeper to keep up with the larger demand for minerals. The geothermal heat emanated from the rock mass rises significantly with greater mining depth [1,2]. Also, geothermal heat is considered to be the primary contributor [3,4] of total heat loads in deep mines. Therefore, requirements for ventilation and mine-cooling systems also go up proportionately, which makes substantial costs of the operational and cooling system. One possible way of reducing this heat load is to use appropriate materials to insulate the rock surface of mine openings. The insulation layer functions as a thermo-barrier to abate the heat flow from the rock mass to the atmosphere inside the mine.

In underground mines, heat flows radially and transiently from the infinite rock mass region into cylindrical mine tunnels and shafts which have the internal boundary. As shown in Fig. 1a, rock temperature profile experiences a drop near the tunnel surface while the virgin rock temperature (T_v) far away from the tunnel maintains constant. One of the difficulties in applying theoretical and empirical models is the determination of the outer boundary in the infinite rock mass region. The application of insulation makes the model even more complicated. To simplify the analysis, the thermal flow problem in cylindrical systems is considered as a one-dimensional transient heat conduction problem in a two-layer slab with infinite-long rock mass. Even with this assumption, the analytical solutions of simplified transient conduction in composite slabs are found to be too sophisticated to solve, in particular with the solutions relating to eigenvalues [5–8].

Some theoretical attempts have been made to address the principle of using thermal insulation in underground mines, but usually only one single model was used to explain the effect of underground thermal insulation in each of these attempts. Thus, so far none of these previous attempts has generated a systematic and comprehensive investigation. For instance, Bottomley [9] used an equivalent surface heat transfer coefficient to predict thermal flow effects. This method assumed that thermal capacity of insulation layer could be neglected. However, no proof was performed to show the reliability of this assumption. Ashworth [10] established and solved an analytical conduction model only for the steady-state heat flow, which cannot represent the transient phenomenon in reality. Furthermore, the definition of the outer boundary may strongly influence the modeling result. For example, Chellam [11] simulated the thermal insulation in underground openings assuming a 50 m outer boundary. On the other hand, Rao et al. [12] assumed a 32 m outer boundary. In all such cases, the boundary dimensions were arbitrary without further justifications. Therefore, existing reports have not established a solid theoretical foundation to predict the effectiveness of underground thermal insulation, in particular, the heat flow abatement percentage after the application of insulation layer on tunnel surface. In this study,

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Nomenclature

T	temperature (K)	C_p	specific heat capacity (J/(kg K))
T_0	initial temperature (K)	α, α_1, α_2	thermal diffusivity (m^2/s)
T_V	virgin rock temperature (K)	λ	dimensionless parameter α_2/α_1
T_R	reference temperature (K)	h	heat transfer coefficient (W/(m^2 K))
T_a	air temperature (K)	h_{eff}	equivalent overall heat transfer coefficient (W/(m^2 K))
T_s	tunnel surface temperature (K)	ϑ	dimensionless temperature: $\vartheta = (T - T_V)/(T_a - T_V)$
T_{in}	interface temperature (K)	ξ	dimensionless length: $\xi = x/\delta$
x	space coordinate (m)	Fo	dimensionless time, known as *Fourier number*, $Fo = (\alpha t)/\delta^2$
r	distance with respect to axis of cylindrical opening (m)	Bi	dimensionless heat transfer coefficient, known as *Biot number*, $Bi = (h\delta)/k$
r_o	cylindrical opening radius after insulation (m)	q_s	surface heat flux (W/m^2)
r_{in}	cylindrical opening radius before insulation (m)	Q_s	total accumulated heat flow through surface (J/m^2)
δ	thickness of the insulation layer (m)	$\bar{q}_s$	average surface heat flux (W/m^2)
L	outer boundary length (m)	β	eigenvalues
t	time (s)	p	a number in the integral of Laplace transformation
τ	ending time (s)		
k, k_1, k_2	thermal conductivity (W/(m K))		

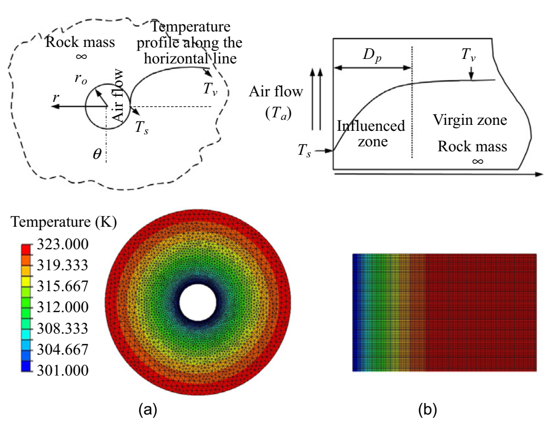

Fig. 1. Schematic of underground temperature distribution.

Table 1
Models descriptions.

	Model	Method	Wall surface BC	Outer BC scale	Layers	Thermal insulation
Slab	A	Analytical	Dirichlet	Semi-infinite	1	No
	B	Analytical	Dirichlet	Semi-infinite	2	Yes
	C	Analytical	Neumann	Semi-infinite	1	No
	D	Analytical	Neumann	Semi-infinite	2	Yes
	E	Analytical	Dirichlet	Finite length	1	No
	F	Analytical	Dirichlet	Finite length	2	Yes
	G	Numerical	Dirichlet	Finite length	1	No
	H	Numerical	Dirichlet	Finite length	2	Yes
	I	Numerical	Neumann	Finite length	1	No
	J	Numerical	Neumann	Finite length	2	Yes
	K	Empirical	Neumann	Semi-infinite	2	Yes
Cylinder	M	Analytical	Neumann	Semi-infinite	1	No

Note: BC means boundary condition.

analytical solutions are discussed and compared to predict the effectiveness of underground insulation. In addition, the finite element method (FEM) software ABAQUS® was chosen to establish the numerical models. Rather than ABAQUS®, other FEM software can also be utilized in the thermal analysis. The FEM is currently the mainstream numerical tool in rock engineering, because of its benefits and maturity in processing the non-linearity and non-homogeneity of rock mass, the complexity of opening geometry, rock/structure interaction and the tunneling method [13–15].

The aim of this study is to conduct systematic theoretical investigations through the comparisons of various analytical and numerical methods to predict the effectiveness of underground thermal insulation.

2. One-dimensional slab model

The one dimensional slab model [16] describes heat conduction through isotropic solid materials such as rock mass and shotcrete. The fundamental governing equation is given below:

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \quad (1)$$

As shown in Fig. 1b, the right side of the boundary (outer boundary) in the rock mass is defined as infinite. Before ventilation and cooling, the initial temperature (T_0) of the whole model is the same as the virgin rock temperature (T_V), which is the temperature of the rock mass at certain depth before excavations. After cooling, the left boundary of rock mass (tunnel surface) is cooled by the air flow with air temperature (T_a), thus the heat flows from the high temperature rock mass toward the tunnel, developing into two different zones, namely, the influenced zone and the virgin zone. The influenced zone is the area affected by the cooling process, whereas the virgin zone is the area where the temperature is kept constantly at the virgin rock temperature (T_V). The distance between the tunnel surface to the interface of two zones is called penetration depth (D_p). These one-dimensional models are important to understand the heat transfer in the rock mass and the applied thermal insulation. The description of these models is given in Table 1, in which the model names are defined in the following sections.

2.1. Heat flow through one-dimensional slab model with a semi-infinite boundary

2.1.1. Analytical models without insulation

For the model without insulation, the rock–air interface (tunnel wall surface) experiences three heat transfer processes at the same time, namely, (i) conduction, (ii) convection and (iii) radiation. The *Dirichlet* boundary condition [17] is based on the assumption that the heat transfer coefficient is large enough to be considered as infinity, thus the temperature at the rock–air interface is maintained at the air temperature (T_a). Whereas, the *Neumann* boundary condition [17] is the more realistic case, solutions of this

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