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寒区隧道围岩导温系数及其冻深分析*

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摘 要: 本文根据一寒区强风化花岗岩隧道实测围岩温度, 采用一维热传导模型、古典显式差分格式和最小二乘法, 对该隧道围岩导温系数进行了反分析。用解析方法和数值计算法分析了影响隧道围岩冻深的主要因素, 所得结论有一定的工程实用价值。

关键词: 寒区; 围岩; 导温系数; 防水层; 冻深

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1 引言

寒冷地区隧道的冻胀危害近年来引起人们的普遍重视, 虽然在设计和施工中采取了种种措施加以预防, 但往往不尽人意。据文献[1]报道, 在我国东北和西北地区有 33 座铁路隧道和多座公路隧道, 由于地处寒区, 这些隧道都有不同程度的冻害。有些隧道由于冻害的影响, 每年有 8~9 个月不能正常使用; 有些隧道因冻胀使衬砌产生裂缝宽达 5cm, 严重影响正常运营。

随着自然界四季交替变化, 隧道围岩经历着从非冻结状态到冻结状态以及再次融化的过程。动态变化的温度场、水分场给工程建设及运营带来极大危害, 因此, 围岩冻胀机理的研究对解决实际工程冻胀问题具有重要意义, 而围岩的导温系数是研究围岩冻胀机理的重要参数[2-5]。迄今为止, 我国还没有对寒区隧道围岩的温度场进行过系统的实测, 渗流和冻胀对寒区隧道围岩温度场和应力场的影响也未开展[1]。为此, 本文结合小盘岭工程实际, 应用有限差分法得到了该隧道围岩的导温系数, 应用解析法分析了影响隧道围岩冻深的主要因素, 获得了有益的结论。

2 工程实例

延吉—图们二级公路上的小盘岭隧道, 双向两车道行车, 长 600 余米, 围岩为华力西晚期花岗岩, 主要造岩矿物为石英、正长石、斜长石、黑云母角闪石和辉石等。衬砌混凝土平均厚 650mm。隧道内围岩温度量测断面的测点布置如图 1 所示。测点 1 位于混凝土衬砌内, 测点 2、3、4、5 位于围岩内。现场测得各点的温度变化情况如图 2 所示。

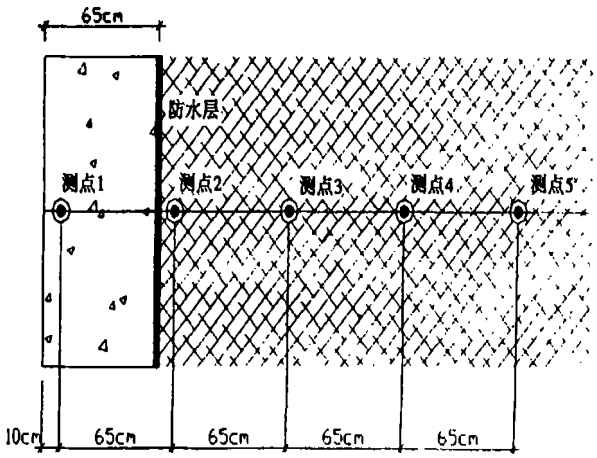

图 1 围岩温度测点布置图

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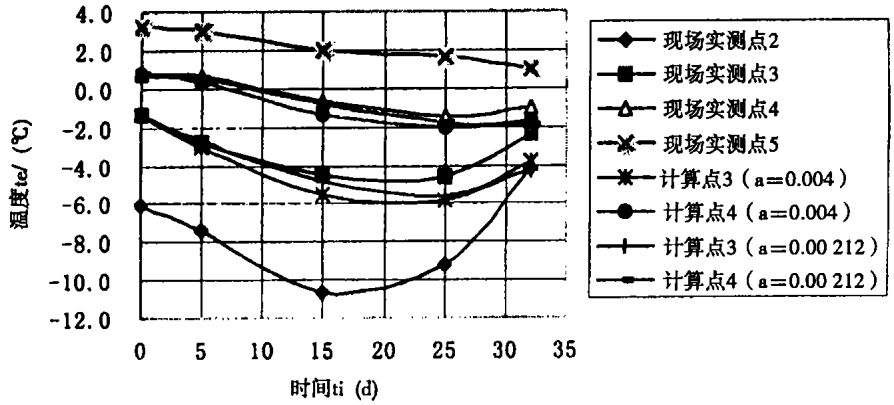

图 2 实测与计算隧道围岩温度—时间曲线

3 问题描述

3.1 热传导方程

假设导温系数为常数，因隧道长度很长（600 余米），沿轴向的热传导可略去不计，而温度仅沿半径方向变化，故将隧道围岩视为半无限体，其内温度变化可简化为沿隧道深度方向上的一维热传导问题。该问题的热传导方程为[4][8][9]：

$$\frac{\partial u(x,\ t_e)}{\partial t_e} = \alpha \cdot \frac{\partial^2 u(x,\ t_e)}{\partial x^2} \qquad (1)$$

式中：$u(x, t_e)$——距隧道围岩内部边界 x 米处围岩的温度，℃；

α ——围岩的导温系数，m^2/h。

3.2 定解条件

3.2.1 初始条件

该热传导问题的初始条件即为初始时刻（$t_i=0$）围岩内距边界不同深度处的温度分布 $f(t_e)$，表达式(2)，参见图 3。

$$u(x,\ t_e)_{t_i=0} = f(t_e) \qquad (2)$$

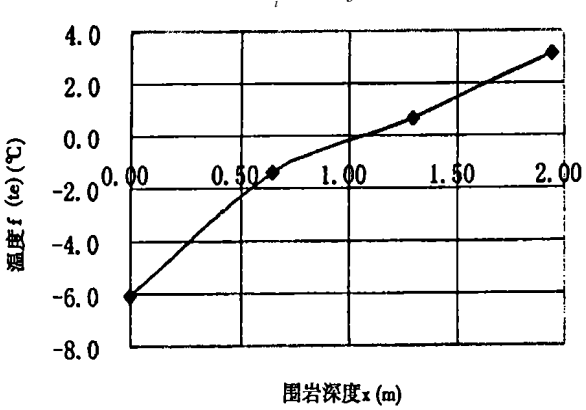

图 3 初始时刻（$t_i=0$）围岩内温度分布 $f(t_e)$

3.2.2 第一类边界条件

研究围岩的热传导过程，还必须考虑围岩所处的特定环境，而周围环境的影响常体现为边界上的物理状况[8]。实测得到围岩在内边界 x＝0m 处温度分布 $g_1(t_e)$和围岩内一定深度 x＝1.95m 处的温度分布 $g_2(t_e)$，如图 4 所示，表达式如下：

$$u(x,\ t_e)_{x=0} = g_1(t_e) \qquad (3)$$

$$u(x,\ t_e)_{x=1.95} = g_2(t_e) \qquad (4)$$

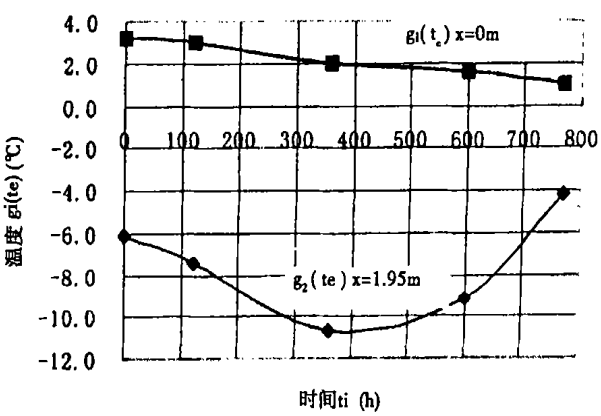

图 4 不同时刻实测围岩温度分布

由于隧道围岩的导温系数是未知的，求解定解问题时先假定其值再进行试算，然后比较给定时刻的计算温度和实测温度，反复调整导温系数，最终使在某个导温系数下，计算预测温度与实测温度最为接近，则此导温系数即为围岩的导温系数。

4 数值计算比较

原则上，热传导问题的求解就是对热传导微分方程在规定的定解条件下积分求解。然而对于许多实用场合，定解条件的复杂性排除了理论解的可能性。这时采用有限差分法迭代求解是有效的途径[9]。用有限差分法求解偏微分方程，必须把连续问题离散化。对热传导问题的离散化方法参见文献[6]，构造热传导方程(1)的差分格式如下：

$$\frac{u_j^{n+1} - u_j^n}{\tau} - \alpha \cdot \frac{u_{j+1}^n - 2u_j^n + u_{j-1}^n}{h^2} = 0$$

$(j = 0, \pm 1, \cdots ; \quad n = 0, 1, \cdots)$　　(5)

式中: τ — 时间步长; h—空间步长; u_j^n—第 n 个时刻第 j 个空间点上的温度, 其余类推。式(5)为古典显式差分格式, 所用到的节点如图 5 所示。现将式(5)写成便于计算的形式:

$$u_j^{n+1} = u_j^u + \alpha \cdot \lambda \cdot (u_{j+1}^n - 2 \cdot u_j^n + u_{j-1}^n) \quad (6)$$

式中: 网格比 $\lambda = \tau / h^2$, 此格式的稳定性条件为: $\alpha \cdot \lambda \leq 1/2$。

最后利用最小二乘法确定最接近实际的导温系数。即对于每个 α_i, 计算 2-范数[10]:

$$H_i = \sqrt{\sum_{j=1}^{m} (u_j^* - u_j)^2} \quad (i = 1, 2, \cdots, n) \quad (7)$$

式中: H_i—与 a_i 有关的 2-范数;

u_j^*—围岩内给定点、给定时刻的实测温度;

u_j—围岩内给定点、给定时刻的计算温度;

m—实测温度 u_j^* 的点数。

则与 $\min(H_i)$ 对应的 a_i, 即是围岩的导温系数。

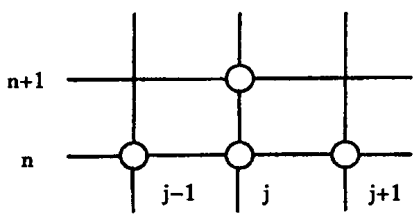

图 5　古典显式差分格式节点图

差分所用空间步长 h=0.065m, 时间步长 τ=0.24h, 其中 $a\tau/h^2 = 0.1136 \sim 0.2272$, 满足显式差分格式的稳定性条件[9], 边界条件用线性插值确定, 初始条件用 Seidel 插值确定, 并用 Gauss 法检验[10]。经理论分析, 此插分格式的截断误差为 $O(\tau + h^2)$。与多种差分格式(如隐式格式, Richardson 格式, Crank-Nicholson 格式等)及多种插值方法(如代数三次插值, Newton 插值, Lagrange 插值等)反复计算比较后, 选定该隧道围岩的导温系数为 $a = 2.12 \times 10^{-3} m^2/h$。

图 2 为按此系数和按文献[6]提供的花岗岩导温系数 $a = 4.00 \times 10^{-3} m^2/h$, 分别反算所得围岩内的温度分布与实测值对比。显见按本文所得围岩的导温系数的反算值与实测温度分布值更为接近。

5　隧道围岩冻深影响因素

5.1　导热微分方程

实测得到隧道内表面的温度时间曲线如图 6 所示(实线为拟合余弦曲线), 设平均气温为 t_m, $\theta = t - t_m$, 则导热微分方程为[9]:

$$\frac{\partial \theta}{\partial z} = a \frac{\partial^2 \theta}{\partial x^2} \quad (8)$$

内表面温度可表示为:

$$\theta(0, \tau) = \theta_w = A_w \cos \frac{2\pi}{T} \cdot \tau \quad (9)$$

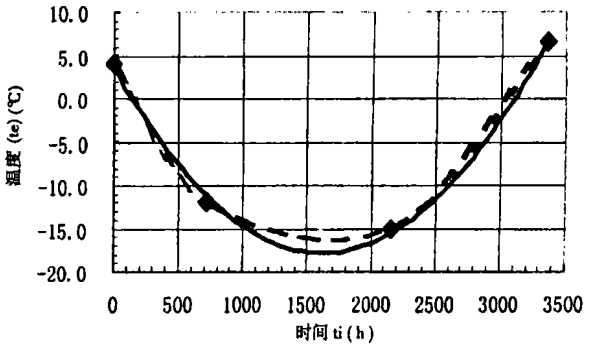

图 6　设防水层后隧道围岩实测时间-温度曲线

这样可以得到半无限空间体在周期性变化边界条件下温度场的表达式:

$$\theta(x, \tau) = A_w e^{-\sqrt{\frac{\pi}{aT}} \cdot x} \cos\left[\frac{2\pi}{T}\tau - x\sqrt{\frac{\pi}{aT}}\right] \quad (10)$$

该地区最高气温 $t_{max} = 34.6$℃, 最低气温 $t_{min} = -18.6$℃, 平均气温 $\bar{t} = 8.0$℃。最低温度出现的时间为 1614h, 即第 67 天, 则:

$$t(0, \tau) = 26.64 \cos\left[\frac{2\pi}{8760}(\tau + 2766)\right] + 8 \quad (11)$$

5.2　混凝土层

取混凝土层的导温系数 $a_1 = 2.4 \times 10^{-3} m^2/h$, 厚 $\delta = 0.60m$, 内部各断面的温度分别为:

$$t(x, \tau) = 26.64 e^{-\sqrt{\frac{\pi}{8760 a_1}} \cdot x} \cdot \cos\left[\frac{2\pi}{8760}(\tau + 2766) - x\sqrt{\frac{\pi}{8760 a_1}}\right] + 8 \quad (12)$$

将 x = 0.60m 代入上式, 可得最低温度为 −13.13℃, 出现的时间为 1936h, 即第 81 天。

5.3　防水层

防水层的导温系数 $a_2 = 4.45 \times 10^{-5} m^2/h$, 厚 $\delta = 0.002m$, 内部各断面的温度分别为:

$$t(x, \tau) = 26.64\, e^{-\sqrt{\frac{\pi}{8760 a_1}} \cdot 0.6} \cdot e^{-\sqrt{\frac{\pi}{8760 a_2}} \cdot (x - 0.6)} \cdot \cos\left[\frac{2\pi}{8760}(\tau + 2866) - 0.6\sqrt{\frac{\pi}{8760 a_1}} - (x - 0.6)\sqrt{\frac{\pi}{8760 a_2}}\right] + 8 \quad (13)$$

将 x = 0.60m 代入上式, 可得最低温度为 −12.9℃, 出现的时间为 1944h, 即第 81 天。

5.4　围岩

围岩的导温系数 $\alpha_3=2.12\times10^{-3}m^2/h$，内部任意断面 x 处的温度为：

$$t(x,\tau)=26.64\cdot e^{-\sqrt{\frac{\pi}{8760a_1}}\cdot0.6}\cdot e^{-\sqrt{\frac{\pi}{8760a_2}}\cdot0.002}\cdot e^{-\sqrt{\frac{\pi}{8760a_3}}(x-0.602)}\cdot\cos\left[\frac{2\pi}{8760}(\pi+2766)-0.6\sqrt{\frac{\pi}{8760a_1}}-0.002\sqrt{\frac{\pi}{8760a_2}}-(x-0.602)\sqrt{\frac{\pi}{8760a_3}}\right]+8 \quad (14)$$

x 断面处温度最低时满足：

$$\cos\left[\frac{2\pi}{8760}(\tau+2766)-0.6\sqrt{\frac{\pi}{8760a_1}}-0.002\sqrt{\frac{\pi}{8760a_2}}-(x-0.602)\sqrt{\frac{\pi}{8760a_3}}\right]+8=-1 \quad (15)$$

则最低温度为：

$$t_{\min}(x)=-26.64e^{-\sqrt{\frac{\pi}{8760a_1}}\cdot0.6}\cdot e^{-\sqrt{\frac{\pi}{8760a_2}}\cdot0.002}e^{-\sqrt{\frac{\pi}{8760a_3}}(x-0.602)} \quad (16)$$

计算冻结圈的位置，即令最低温度为 0℃，则可算得布设 2mm 的防水层时冻深线的位置 x＝2.929m，入岩层 2.327m。最低温度出现的时间是 3284.7h，即 137 天。

5.5 若没有防水层

即 0.60m 以后为岩层，同理可算得围岩的冻线在 x＝2.951m，入岩层 2.351m。用有限差分法计算，也可得到类似结论。

总之，隧道围岩温度场的衰减呈负指数关系：$\exp[(\pi/Ta)^{0.5}\cdot x]$，即围岩温度随 x 增大或 α 减小而衰减。若布设 0.002m 的防水层，则使得围岩的冻深线外移：2.351－2.327＝0.024m。

6 结论

隧道围岩导温系数是影响其温度场的重要参数，确定围岩中冻深线是分析隧道冻胀的基础。本文利用实测围岩温度资料，分析了隧道围岩的导温系数和影响隧道围岩冻深的主要因素，可得结论：

(1)小盘岭隧道围岩的导温系数 $\alpha=2.1\times10^{-3}$～$2.2\times10^{-3}m^2/h$，随围岩含水率的变化有小动。为研究冻胀力对隧道衬砌的影响提供了参数准备。

(2)隧道围岩温度场与导温系数 α 和距离 x 呈负指数衰减关系，x 增大或 α 减小都可引起温度场衰场。小盘岭隧道工程，布设 0.002m 厚防水层，使得围岩的冻深线外移了 0.024m。

(3)防水层的保温性能取决于两个因素：其一，防水层导温系数。本工程防水层导温系数 $\alpha_2=4.45\times10^{-5}m^2/h$，远小于围岩的导温系数 $\alpha_3=2.12\times10^{-3}m^2/h$，其传热性相对而言惰性较大，对温度的衰减能力较强。其二，防水层厚度。本工程防水层有一定的保温性能，虽然其导温系数很小，但厚度有限，则保温效果不显著。

(4)为减少冻胀对寒区隧道工程的危害，应采取良好的保温措施，缩小冻结圈。一方面要选取导温系数小的材料做防水层，另一方面防水层还要有一定的厚度。

(5)在寒区兴建铁路、公路和各类输送管道等隧道工程时，只有充分掌握隧道围岩的导热特性和冻胀规律，才能确保设计方案合理和隧道工程安全运营。

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[Keywords] underground structure; interaction; vertical earthquake; vibration table test

[Abstract] In this paper the Displacement Discontinuity Method (DDM) was applied to solve the rupture propagation of two-dimensional combined crack under any load. According to the characteristics of damage progress of two-dimensional crack, the DDM tracking of dynamic process of crack propagation has been developed for external load increment and automatic unit addition along the direction of crack propagation under the criteria of maximum tensile stress. The calculation results for the theoretical solution of the single crack are coincident with the experiment ones for double cracks arranged regularly. The procedure is simple with fewer units and it is easy to simulate multiple crack propagation on the computer.

[Keywords] two-dimensional combined crack; progress of elastic rupture; DDM dynamic tracking

[Abstract] In this paper the selection of sliding plane during slope stability analysis and design of slope supporting was discussed. An analytical solution for sliding plane angle for slope stability analysis was given. Some conclusions from qualitative analysis have been obtained by comparing the results with variation of parameters for soil bodies and slopes. It will be helpful to the engineering practice.

[Keywords] sliding plane; stability analysis; support structure

[Abstract] In this paper, the performance of rigid pavement of the tunnel is studied by couple analysis of multi-slab system with joint and the foundation. It is assumed that the foundation is Winkler one and the joints are shear spring elements; the multi-slab system is calculated by compressed matrix. The load-flexure curve of the tunnel pavement can be obtained by FEA program, which can judge the tunnel pavement performance in corporation with nondestructive test method by deflector.

[Keywords] multi-slab; compressed matrix; FEA

[Abstract] Based on the sealing principle of the sealing cushion and the statistical theory of cross-linked rubber, an experiment was carried out on expansion and resistance to hydraulic pressure under different conditions for hydro-expansive rubber sealing cushion in the shield tunnel. Its water proof mechanism was analyzed and water proof capability in tunnel was evaluated. Some suggestions were given to design and construction of hydro-expansive rubber sealing cushion in the shield tunnel.

[Keywords] shield tunnel; hydro-expansive rubber sealing cushion; resistance to hydraulic pressure

Disaster Prevention , Environment

[Abstract] Results of temperature measurement for the underground pace in Beijing subway are summarized. The variation of air and wall temperature and in ticket hall was analyzed. The results show that the air and wall temperature rises instantly with high amplitude of temperature variation, when the train moves through the tunnel. The temperature in ticket hall is influenced not only by atmosphere temperature but by piston action induced ventilation due to the train movement.

[Keywords] subway; underground space; thermograph; temperature

[Abstract] Based on the temperature measured from the surrounding weathered granite of tunnel in cold region, the thermal conductivity of the rock is analyzed by means of the one-dimensional thermal conducting model, the classic difference scheme and the least square method. The influences of the main factors on the frost depth of the enclosure rocks are analyzed by the analytic and numerical methods. Finally, some referable conclusions are obtained from engineering practice.
[Keywords] cold region; surrounding rock; thermal conductivity; damp-proof course; frost depth

Academic Discussion, Research Development

[Abstract] One of the obstacles in development and utilization of underground space is the psychological problem of people; application of atrium is an effective way to solve this problem. In this paper, the characteristics, form of enclosure, interface design and geographical characters of atrium in underground space are analyzed and some problems for its design are discussed.
[Keywords] atrium; underground construction; space form

[Abstract] With development of economy, the development and utilization of underground space will be a trend for the construction of residential areas in 21-th century. In this paper the trend and future of construction of residential areas in 21-th century are studied. To realize the task for development of residential areas, the underground space resource should be utilized and the development and utilization should be in coordination with the residential areas in respect of their function and disposition. In this paper, based on discussion of function and disposition of underground space in residential areas, the mode of development and utilization of underground space in coordination with the structure and form of residential areas is suggested
[Keywords] residential area; underground space; function; disposition

[Abstract] A primary study on suitability of underground space was carried out in this paper and a multilevel evaluation for complex decision was suggested. By this method with using a series of decision indexes, three problems could be solved, namely: (1) the function suitable for realization underground, (2) determination of areas with large potential, (3) evaluation of the urban development proposal whether it is a promotion or prevention for the utilization of underground space. Some examples were given in illustration of this method
[Keywords] complex decision; multilevel evaluation; suitability

[Abstract] With development of high grade highway in China, the three-lane highway tunnel with large cross section will be an important component for high grade highway. In this paper, the present situation of the study on three-lane highway tunnel with large cross section both at home and abroad is expounded in respect to design, construction and surrounding rock stability as well as dynamic construction process, technique for emulating physical simulation and numerical simulation.
[Keywords] highway tunnel; three lane; design construction; surrounding rock stability; emulating simulation

[Abstract] In this paper the ground settlement due to leakage and crack of pipe joint in running sand area in Shanghai is introduced. The treatment of damaged sewage in running sand area is introduced and analyzed based on experience both at home and abroad especially the experience in Shanghai. The groove cutting of pipe and the technique of renovation inside the pipe were introduced, which provide the basis for renovation of sewage in large area and non-excavation technique application.
[Keywords] urban sewage; settlement of pipeline; groove cutting and pipe embedment; non-excavation technique