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# A NUMERICAL SIMULATION OF HEAT LOSS FROM A BASEMENT WITH VARIABLE SOIL THERMAL CONDUCTIVITY

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## ABSTRACT

A numerical simulation of two-dimensional heat loss from an uninsulated concrete basement surrounded by two soils with different textures is performed to illustrate the importance of the effective soil thermal conductivity on underground heat transfer problems. The system is assumed to be at steady-state, with a uniform moisture distribution within the soil, and having moisture contents of completely dry, field capacity and full saturation. It is determined that underground heat transfer is significantly influenced by soil thermal conductivity, which in turn depends primarily on texture, temperature and moisture content. It is concluded that moisture content has the most significant effect on underground heat transfer, causing up to a 132% variation relative to a dry soil condition. The soil texture is the second most influential factor, resulting in up to a 62% variation with respect to a fine soil condition. Temperature has the least effect, leading up to a 22% variation relative to a condition of constant thermal conductivity.

## INTRODUCTION

The heat transfer of the above-ground portion of a building from the walls exposed to ambient air is generally well-predictable and its mechanisms are well understood. However, the prediction of heat transfer of the earth-coupled portion is more complex being primarily influenced by soil thermal conductivity, which in turn depends on a wide variety of properties related to soil. Among these factors, soil texture, temperature and moisture content have by far the greatest impact upon it [Becker et al., 1992; Salomone et al., 1984; Salomone and William, 1984]. Nevertheless, depending on the type of construction, heat loss from an uninsulated basement can account for 20 to 35% of the total heat loss of a house [NRCan, 2003].

The focus of this paper is the performance of a numerical simulation of the heat loss from a basement surrounded by two soil types: Ottawa sand and Richmond Hill clay-loam. The objective is to improve understanding of the influence of variable soil thermal conductivity on underground heat transfer problems.

## BACKGROUND

One of the early studies on basement heat loss was by Latta and Boileau [1969]. Average heat loss coefficients for insulated and uninsulated basement walls were determined based on a constant value of soil thermal conductivity. Until recently, some major textbooks (e.g., McQuiston et al., 2005) are still using the calculated heat loss coefficients for evaluating heat losses through basement walls and floors.

Many investigations of thermal systems involve heat loss through soils and thus require a good understanding of soil thermal properties and their dependences on physical and chemical parameters. For instance, the evaluation of heat losses from partially buried and bermed heat storage tanks requires a knowledge of soil properties, and was investigated by Rosen [1990, 1991]. Rosen [1998a] also developed a semi-empirical model for assessing the effects of soil berms on the heat loss from partially buried heat storage tanks, and investigated the economics of use of berms in thermal energy storage systems [Rosen, 1998b].

The effects on underground thermal storages of soils having spatially varying thermal properties have been examined by Rosen et al. [1994]. Also, the impact has been investigated of soil properties on evaluations of a ground thermal energy storage system for heating and cooling of dwellings [Leong et al., 2006], and of building systems that integrate cogeneration and district heating and cooling [Rosen et al., 2001].

As computing and storage capacities of personal computers become more readily abundant, as well as computer modelling techniques become more advanced, it may soon be unacceptable to evaluate an underground heat transfer problem without taking into account the effects of soil texture, temperature and moisture content on the effective soil thermal conductivity.

## APPROACH AND MODEL

The simulation is carried out using the FEHT finite-element software package in 2-D. A 2-D approach is reasonable for such a problem considering its symmetry and continuous constant cross-section over a relatively long length before reaching a corner. Corner effects in the third dimension are thus neglected. The system is assumed to be at steady-state, with a uniform moisture distribution within the soil. The thermal conductivity, $\lambda$, of the ground, accounting for soil texture, moisture content and temperature, is estimated using a similar empirical correlation developed by Tarnawski and Leong [2000]:

$$\lambda = \frac{a_1 + a_2 T + a_3 \theta + a_4 \theta^2}{1 + a_5 T + a_6 \theta + a_7 \theta^2} \qquad (1)$$

where $T$ is the temperature in °C, $\theta$ is the moisture content in $m^3/m^3$, and the correlation coefficients $a_1$ to $a_7$ are tabulated in Table 1 for Ottawa sand and Richmond Hill clay-loam for the temperature range of $2 \leq T \leq 92$°C and moisture content range of $0 \leq \theta \leq \theta_{FS}$, where $\theta_{FS}$ is the moisture content at full saturation [Nikolaev, 2007].

Table 1: The correlation coefficients for Eq. (1) [Nikolaev, 2007].

| Correlation coefficient | Ottawa sand | Richmond Hill clay-loam |
|---|---|---|
| $a_1$ | 0.3039 | 0.2079 |
| $a_2$ | $-1.3300\times10^{-3}$ | $-9.4004\times10^{-4}$ |
| $a_3$ | -0.6934 | -0.7811 |
| $a_4$ | 42.9621 | 6.9407 |
| $a_5$ | $-6.1050\times10^{-3}$ | $-5.8852\times10^{-3}$ |
| $a_6$ | -3.8360 | -2.7028 |
| $a_7$ | 17.6166 | 7.0293 |

The basement-soil system is modelled as shown in Figure 1. That model includes a 3 m high (DE) and 0.2032 m thick (CD) basement wall made of concrete which is 2 m below grade (BM). The concrete basement floor is 0.1016 m thick (FN) and 2.5 m long (EF). The soil domain extends 5 m from the wall (AB) and about 3 m deep (AH). The inside basement temperature, $T_{inside}$, is 20°C. The outside temperature of ambient air, $T_\infty$, is 0°C. With these two temperatures, there will be no freezing of soil moisture involved in simulation.

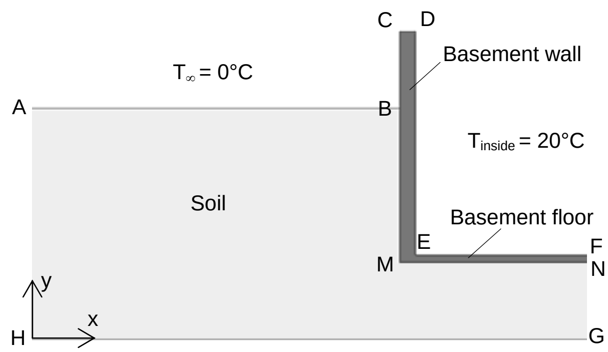


Figure 1: Model of basement surrounded by soil.

## MATHEMATICAL FORMULATION AND BOUNDARY CONDTIONS

The system is governed by the heat conduction equation in two dimensions, assuming steady state conditions, isotropic conductivity, and no heat storage or heat generation within the elements:

$$\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) = 0 \qquad (1)$$

where the thermal conductivity $\lambda$ is assumed to be homogeneous and constant for the concrete wall and floor, and a function of temperature for a given uniform moisture distribution in the soil.

The far-field boundary condition is applied to lines AH and CD in Figure 1, and an adiabatic boundary condition is applied to line FG, which is the centerline of the basement:

$$\left.\frac{\partial T}{\partial x}\right|_{AH,FG} = \left.\frac{\partial T}{\partial y}\right|_{CD} = 0 \qquad (2)$$

The temperatures and heat fluxes on all interfaces (BM-MN) between different materials are conjugated. The Dirichlet constant temperature condition is applied along line HG to simulate the constant deep ground temperature of 10°C. Natural convection boundary conditions are assumed along the inside wall surface (DE-EF), the outside portion of the wall surface above the ground (BC), and the ground surface (AB). The outside ambient and inside air temperatures are set to 0 and 20°C, respectively, with a convective heat transfer coefficient, $h$, of 4 $W/m^2K$ for all convective surfaces.

## DISCRETIZATION OF DOMAIN AND GRID SENSITIVITY

The computational domain (Figure 1) is discretized into linear triangular elements using the automatic meshing algorithm available in FEHT. The finite-element grid is then modified manually and made denser in regions where high temperature gradients are expected as well as in areas of sudden geometrical changes where the boundaries need to be described in detail.

To ensure that numerical solutions are independent of the grid density, a grid sensitivity study is conducted. The problem, considering dry Ottawa sand, is initially solved on the basis of a coarse grid comprising 224 nodes and 372 elements (coarse grid density, Figure 2). Then, the mesh is made finer to 819 nodes and 1488 elements (medium grid density, Figure 3), and then even finer to 3125 nodes and 5952 elements (high grid density, Figure 4).

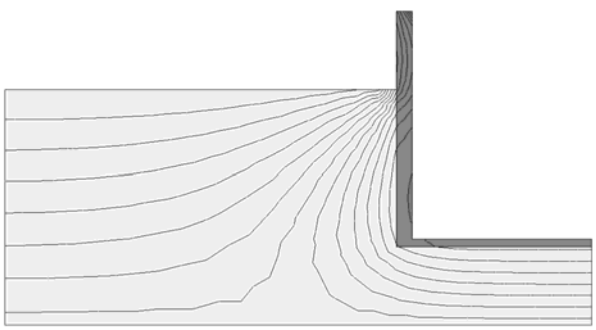

Figure 2: Temperature field for a coarse grid density. 15 isothermal lines are shown with $T_{min}$=0.28°C, $T_{max}$=20°C

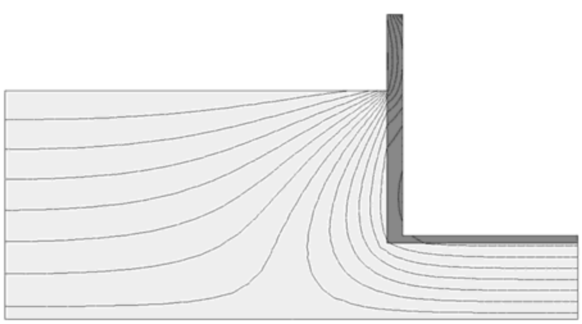

Figure 3: Temperature field for a medium grid density. 15 isothermal lines are shown with $T_{min}$=0.29°C, $T_{max}$=20°C

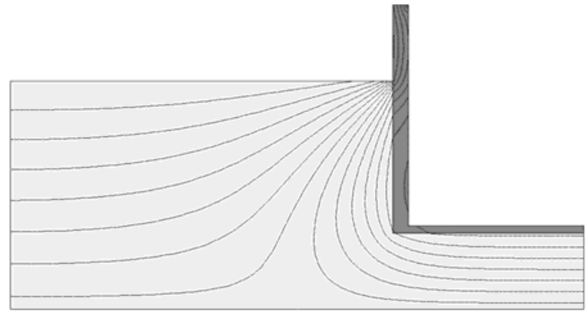

Figure 4: Temperature field for a high grid density. 15 isothermal lines are shown with $T_{min}$=0.29°C, $T_{max}$=20°C

Although converged solutions are obtained successfully without any numerical instabilities for all three mesh densities, there are insufficient nodes in the coarse grid to closely represent the temperature field. The quantitative analysis is based on the relative percentage difference (RPD) between the heat flows through the outside underground surfaces of the wall and the floor (BM-MN) for the three mesh densities. The heat flows are determined to be 21.37, 18.68 and 18.41 W/m for coarse, medium and fine grids, respectively. The RPDs are computed as follows:

$$RPD = \frac{q_{grid\,1} - q_{grid\,2}}{\left(\frac{q_{grid\,1} + q_{grid\,2}}{2}\right)} \cdot 100\% \qquad (3)$$

where $q_{grid\,1}$ and $q_{grid\,2}$ are the heat flows (per unit length in z direction) for coarse and medium, and then medium and fine grids. The RPD between coarse and medium grids is 15%; meanwhile the RPD between the medium and fine grids is less than 1.4%, illustrating close convergence. Hence both medium and fine grids can be used for the analysis; but since the difference in computational time between the medium and fine grids is not significant, the high grid density is employed for all simulations.

## ANALYSIS OF VARIATION OF HEAT TRANSFER AND RESULTS

The heat transfer analysis is based on a comparison of the heat flows through the below-grade wall and the floor (BM-MN) for Ottawa sand (coarse texture) and Richmond Hill clay-loam (fine texture), at several moisture contents. In particular, both soils are considered at dry, field capacity (FC) and full saturation (FS) conditions, as given in Table 2.

Table 2: Volumetric moisture contents at dry, field capacity (FC) and full saturation (FS) conditions for Ottawa sand and Richmond Hill clay-loam.

| Soil | $\theta$ ($m^3/m^3$) | | |
|---|---|---|---|
| | Dry | FC | FS |
| Ottawa sand | 0 | 0.183 | 0.366 |
| Richmond Hill clay-loam | 0 | 0.290 | 0.571 |

First, the heat transfer is analyzed to investigate the effect of variation in thermal conductivity for the coarse (Ottawa sand) and fine (Richmond Hill clay-loam) soil textures. To make a quantitative comparison of numerical results regarding the texture variation, the relative percentage difference between the heat flows is calculated as follows:

$$RPD = \frac{q_{course} - q_{fine}}{\left(\frac{q_{course} + q_{fine}}{2}\right)} \cdot 100\% \quad (4)$$

where $q_{coarse}$ and $q_{fine}$ are the heat flows (per unit length in the z direction) through the underground wall (BM-MN) surrounded by coarse and fine soils (see Table 3).

Table 3: Heat flows through the below-grade wall and the floor for coarse and fine soil textures at three moisture contents.

| | Dry | FC | FS |
|---|---|---|---|
| $q_{coarse}$ (W/m) | 18.4 | 64.0 | 90.6 |
| $q_{fine}$ (W/m) | 12.3 | 33.7 | 52.6 |
| RPD between coarse and fine textures (%) | 40.1 | 62.0 | 53.1 |

The highest RPD is calculated to be 62% at field capacity condition, with heat flows of 33.7 and 64 W/m in the cases of fine and coarse textures, respectively. This relatively large variation indicates the significance of using correct soil texture properties for estimating the effective soil thermal conductivity and, consequently, for accurate modeling of the ground heat transfer. Based on this finding, in order to have low heat loss from a basement, fine soil can be used as a backfill between the basement walls and the surrounding soil.

The effect of moisture content is discussed next. The quantitative comparison for dry, FC and FS moisture contents of Ottawa sand and Richmond Hill clay-loam with respect to the variation in moisture content is based on the below defined RPD between two heat flows of interest at different moisture contents:

$$RPD = \frac{q_{\theta_2} - q_{\theta_1}}{\left(\frac{q_{\theta_2} + q_{\theta_1}}{2}\right)} \cdot 100\% \quad (5)$$

where $q_{\theta_1}$ and $q_{\theta_2}$ are the heat flows (per unit length in the z direction) through the below-grade wall and the floor for a moisture content $\theta_2$ relative to $\theta_1$. The results in Table 4 demonstrate that moisture content has a strong influence on the heat transfer. For instance, the relative percentage difference between the dry and full saturation conditions of Ottawa and Richmond Hill soils can be as high as about 132% and 124%, respectively. It is clear that moist soils can cause much greater heat loss from a basement than dry soils.

Table 4: RPD in heat flow regarding variation of moisture content of Ottawa sand and Richmond Hill clay-loam.

| | $\theta_1$=Dry $\theta_2$=FC | $\theta_1$=Dry $\theta_2$=FS | $\theta_1$=FC $\theta_2$=FS |
|---|---|---|---|
| RPD between moisture contents of Ottawa sand (%) | 110.6 | 132.5 | 34.5 |
| RPD between moisture contents of Richmond Hill clay-loam (%) | 93.3 | 124.4 | 43.8 |

Finally, the underground heat transfer is analyzed along with the impact of the variation of thermal conductivity as a function of temperature. The problem is solved twice: first, on the basis of thermal conductivity being a function of temperature for the three moisture contents, and then considering the thermal conductivity at a fixed temperature taken as an average of the inside and outside temperatures, $T_{ave} = (T_{inside} + T_{\infty})/2$, for the three moisture contents for Ottawa and Richmond Hill soils, respectively. As in the previous cases, the quantitative analysis regarding the temperature variation is based on the RPD as follows:

$$RPD = \frac{q_{\lambda=f(T,\theta)} - q_{\lambda=f(T_{ave},\theta)}}{\left(\frac{q_{\lambda=f(T,\theta)} + q_{\lambda=f(T_{ave},\theta)}}{2}\right)} \cdot 100\% \qquad (6)$$

where $q_{\lambda=f(T,\theta)}$ and $q_{\lambda=f(T_{ave},\theta)}$ are the heat flows (per unit length in z direction) through the below-grade wall and floor regarding thermal conductivity as a function of temperature $T$ for a moisture content $\theta$, and of average temperature $T_{ave}$ for a moisture content $\theta$, respectively. The results presented in Table 5 indicate that the assumption of thermal conductivity as a function of $T_{ave}$ for a moisture content might lead to a significant error in heat transfer estimation (up to about 22% in the case of dry Richmond Hill clay-loam). But compared with the effects due to soil texture and moisture content, the effect due to temperature is relatively insignificant.

Table 5: RPD between the heat flows for the thermal conductivity as a function of temperature and as a function of $T_{ave}$ for three moisture contents ($T_{ave}$=10°C).

| Ottawa sand | | | |
|---|---|---|---|
| | Dry | FC | FS |
| $q_{\lambda=f(T,\theta)}$ (W/m) | 18.4 | 64.0 | 90.6 |
| $q_{\lambda=f(T_{ave},\theta)}$ (W/m) | 16.2 | 60.3 | 77.6 |
| RPD (%) | 12.8 | 6.04 | 15.5 |
| Richmond Hill clay-loam | | | |
| | Dry | FC | FS |
| $q_{\lambda=f(T,\theta)}$ (W/m) | 12.3 | 33.7 | 52.6 |
| $q_{\lambda=f(T_{ave},\theta)}$ (W/m) | 15.3 | 36.3 | 46.4 |
| RPD (%) | 21.9 | 7.35 | 12.6 |

## CONCLUSIONS

The numerical simulation demonstrates that underground heat transfer is significantly influenced by soil thermal conductivity, which in turn depends primarily on texture, temperature and moisture content. Over the ranges of parameters studied here, it appears that the moisture content has the most significant effect on underground heat transfer (up to 132% with respect to the dry soil condition), followed by soil texture (up to 62% with respect to the fine soil condition). Although temperature has the smallest effect (up to 22% with respect to $T_{ave}$ condition), it may become significant if the temperature is high, say greater than 40°C, combined with moderately-to-highly moist soils, i.e. ranging from the permanent wilting point (PWP) to the full saturation ($\theta_{PWP} < \theta \leq \theta_{FS}$).


## ACKNOWLEDGEMENTS

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## REFERENCES


Becker B., Anil Misra P. and Fricke B. (1992), ‘Development of Correlations for Soil Thermal Conductivity’, *Int. Comm. of Heat and Mass Transfer*, 19 59-68.

Latta J.K. and Boileau G.G. (1969), ‘Heat Losses from House Basements’, *Canadian Building* XIX(10) 39-42.

Leong W.H., Lawrence C.J., Tarnawski V.R. and Rosen M.A. (2006), ‘Evaluation of a Ground Thermal Energy Storage System for Heating and Cooling of an Existing Dwelling’, *Proc. Can. Conf. on Building Performance Simulation (eSim 2006)*, 3-5 May, Toronto, 141-148.

McQuiston F.C., Jerald D.P. and Spitler J.D. (2005), *Heating, Ventilating, and Air Conditioning Analysis and Design*, John Wiley and Sons.

Natural Resources Canada (NRCan) (2003), *Chapter 5 Basement Insulation*, in *Keeping the Heat In*, Office of Energy Efficiency (accessed via www.oee.nrcan.gc.ca/ keep_ heat_in/index.cfm?PrintView=N& Text=N)

Nikolaev I.V. (2007), ‘GHP Apparatus Design and Construction for Thermal Conductivity Measurements’, MASc Thesis, Department of Mechanical and Industrial Engineering, Ryerson University, Toronto, Ontario.

Rosen M.A. (1998a), ‘A Semi-Empirical Model for Assessing the Effects of Berms on the Heat Loss from Partially Buried Heat Storage Tanks’, *Int. J. Solar Energy* 20(1) 57-77.

Rosen M.A. (1998b), 'The Use of Berms in Thermal Energy Storage Systems: Energy-Economic Analysis', *Solar Energy* 63(2) 69-78.

Rosen M.A. (1990), 'Evaluation of the Heat Loss from Partially Buried, Bermed Heat Storage Tanks', *Int. J. Solar Energy* 9(3) 147-162.

Rosen M.A. (1991), 'A New Empirical Method for Assessing the Effects of Berms on Partially Buried, Bermed Thermal Energy Storage Tanks', *Proc. 5th Int. Conf. on Thermal Energy Storage (Thermastock 91)*, 13-16 May, Scheveningen, The Netherlands, 3.11.1-3.11.6.

Rosen M.A., Hanford G.C. and Gunnewiek L.H. (1994), 'Heat Loss Analysis of Bermed Thermal Storages with Spatially Varying Thermal Properties', *Proc. 6th Int. Conf. on Thermal Energy Storage (Calorstock 94)*, Espoo, Finland, 255-262.

Rosen M.A., Leong W.H. and Le M.N. (2001), 'Modelling and Analysis of Building Systems that Integrate Cogeneration and District Heating and Cooling', *Proc. Can. Conf. on Building Performance Simulation (eSim 2001)*, 13-14 June, Ottawa, 187-194.

Salomone L., William D. and Kusuda T. (1984), 'Thermal Performance of Fine-Grained Soils', *Journal of Geotechnical Engineering*, ASCE, 110(3) 359-374.

Salomone L. and William D. (1984), 'Thermal Resistivity of Soils', *Journal of Geotechnical Engineering*, ASCE, 110(3) 375-389.

Tarnawski V. and Leong W.H. (2000), 'Thermal Conductivity of Soil at Very Low Moisture Content and Moderate Temperatures', *Transport in Porous Media*, 41 137-147.