ENERGY PERFORMANCE OF BELOW-GRADE ENVELOPE OF STANLEY-PAULEY BUILDING IN WINNIPEG

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ABSTRACT
This paper aims to study the energy performance of basement structure of the currently under-construction Engineering Building of the University of Manitoba. The building is located at Fort-Garry campus in Winnipeg. A total of eighteen soil samples were collected at different locations and depths based on the geological profile of the ground. Thermal properties of the collected soil samples were obtained in the Geotechnical Engineering Lab using a K2-Pro device by Decagon. Heat losses are predicted for the below-grade envelope by considering thermal properties of soil and building materials. For that purpose, a numerical model was created based on construction drawings using COMSOL Multiphysics software. The applied approach includes the calculation of heat loss due to heat transfer through conductive mechanism. Different alternatives for insulation are suggested and compared.

RÉSUMÉ
Cet article vise à étudier la performance énergétique de la structure du sous-sol du bâtiment de la faculté de génie de l'Université du Manitoba. Le bâtiment est actuellement en construction et situé au campus Fort-Garry à Winnipeg. Au total, dix-huit échantillons de sol ont été prélevés à différents endroits et à différentes profondeurs en fonction du profil géologique du sol. Les propriétés thermiques des échantillons de sol collectés ont été obtenues dans le laboratoire géotechnique en utilisant un dispositif K2-Pro de Decagon. Ensuite, les pertes de chaleur sont calculées pour l'enveloppe souterrain du bâtiment en tenant compte des propriétés thermiques du sol et des matériaux de construction. À cette fin, un modèle numérique a été créé à partir des plans structuraux à l'aide du logiciel COMSOL Multiphysics. L'approche appliquée inclut le calcul des pertes de chaleur dues au transfert de chaleur par la conduction. Différentes alternatives d'isolation sont suggérées et comparées.

1 INTRODUCTION

Buildings in cold regions often encounter problems regarding insulation efficiency of the entire building envelope which attempts to maintain suitable indoor conditions all year long. In fact, a significant component of total global energy demand relates to energy used to heat and cool buildings. In Canada in 2009, 63% of all residential energy use was for space heating. Although gains in efficiency produced a 24% decrease in energy needed for space heating of a single family dwelling between 1990 and 2009, a 36% increase in the number of households in Canada resulted in a 13% net increase in required total for heating (NRC, 2011).

A significant amount of heat dissipates due to ventilation purposes during air exchange while another part of it is released through the wall, floor and ceiling's built-up (M. Deru, 2003). To date, most efforts to decrease the energy loss in buildings have been concentrated primarily on the above-grade envelope of buildings such as walls and roofs, since they initially posed the most substantial potential. However, it is also recognized that significant heat losses may occur due to the flow of heat from the inside of a building through the ground floor slab and into the foundation soils. As this value might reach to the extent of 30% to 50% of the total heat loss, this fact has encouraged many researchers to study energy performance of basements more deeply.

Engineering practice sometimes consist of simplified thermal calculations of structural build-up interacting with the ground. Apart from structural materials, it is often assumed in building energy simulation programs, such as EnergyPlus and TRNSYS, that thermal properties of soils are constant, which means that they do not depend on such factors as seasonal freeze-thaw cycles and variations in water content. However, it is shown that this assumption cannot appropriately predict the actual heat loss through the below-grade building envelope.

One of the most significant factors that affect the thermal properties of soils is the amount of water content in voids because water has relatively higher heat capacity and conductivity than soil particles. In fact, the effective thermal conductivity of soil can increase by a factor of ten when voids are filled with water Deru, 2003. In addition, thermal conductivity of soils in frozen and unfrozen states have been studied by Johansen, 1977 and O. T. Farouki, 1981, among others. They attempted to formulate the thermal conductivity of soil as a combination of the thermal conductivities of all components (soil particles, water, air, and ice).

Temperature changes generated in surrounding soils by heat losses from the foundation to the ground may result in strongly-coupled, nonlinear moisture and energy flow (heat and mass transfer). Cold climates may lead to freezing of pore-water in soil near the ground surface. Freezing involves temperature gradients and moisture migration due to cryo-suction. This phenomenon, with or without frost heave, has significant consequences in foundation engineering in areas of both seasonal frost and permafrost. Finding solutions is often complicated by unknown physical properties of the soil and complex physical processes.

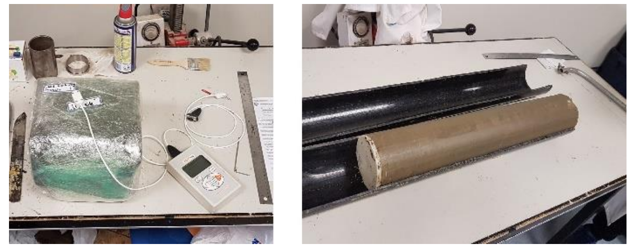
This paper aims to study the energy efficiency of the below-grade envelope of the new Stanley-Pauley Engineering Building in the Fort-Gary campus in Winnipeg. During the excavation in August 2017, a total of eighteen soil samples were collected at different locations and depths based on the geological profile of the ground. Thermal properties (thermal conductivity and volumetric heat capacity) of the collected soil samples were obtained in the Geotechnical Engineering Lab using a K2-Pro device by Decagon. Other laboratory tests were performed to determine the physical properties of soil samples such as the bulk density, water content, dry density and porosity. The thermal and physical properties of the foundation soil obtained in the lab, as well as the construction materials used in the basement structure have been used to estimate heat loss of the foundation of Stanley Pauley building. For this purpose, two approaches have been used. The first approach treats soil as a solid material with constant thermal properties in unfrozen state while the second approach takes into account the effects of redistribution of partially unfrozen water and ice content during freezing-thawing cycles in the soil by considering the phase change mechanism. The simulation has been performed for one year. Values of obtained heat fluxes and overall energy loss were then compared. Finally, different alternatives for insulation are suggested and compared.

2 SITE INVESTIGATION AND SOIL PROPERTIES

Winnipeg soil is represented mainly by fine-grained deposits of Lake Agassiz overlying the Precambrian bedrock. Since frost penetration reaches about 1.8m in Winnipeg area, the top glaciolacustrine clays and tills would be mostly affected by this seasonal changes (Ferguson & Woodbury, 2004).

The construction site has topsoil cover and asphalt followed by gravel pack of approximately 250mm. The geological profile of the site is represented by three stratigraphic layers. They consist of clays of different consistency and depth of formation. The first two meters of clay were black in colour later turning into brown clays of higher moisture content. Clays encountered to depths 16.7m are classified as very soft to very stiff in consistency. Moisture content varied from 27% to 61% along the whole profile (Essex et al., 2017).

To obtain thermal properties of the soil, many samples were taken from elevations mentioned above. Overall, 18 intact and disturbed samples were retrieved and tested to obtain soil thermal properties. Thermal conductivity and heat capacity, as well as their relation to the value of water content, were of the primary interest. During the current study, twelve grab samples were taken from elevation 1-1.5m and 2.0m from different locations of the construction site. Cubical cohesive specimens 20x20 cm were properly preserved and sealed prior to tests to avoid moisture loss as this significantly affects it's thermal conductivity and heat capacity. Another six intact samples were taken from the bottom of the excavation according to ASTM D1587-15 using Shelby tubes which provided better quality of samples.



a) b)

Figure 1. a) Testing grab sample b) Preparation of intact specimen for tests

This survey was conducted with KD-2 Pro by Decagon device providing ±10% accuracy. Measurements of TR-1 single probe were accompanied by additional SH-1 dual needle probe measurement for better statistical analysis. Table 1 provides summary of the measured parameters.

Table 1. Characteristics of tested soils

Depth (Thickness of layer) (m)	Thermal conductivity (W/m·C^0)	Heat capacity (J/kg·C^0)	Density (kg/m^3)	Water content (%)
1.5 (~1.5)	1.252	1,338	1,802	39.4 – 47.1
2.0 (~3.0)	1.124	1,513	1,862	45.8 – 51
4.0 (~12)	1.062	2,205	1,744	35.9 – 42.4

Groundwater table was observed at depth -8m which explains unsaturated conditions of the profile.

2 MODEL DESCRIPTION

In order to study heat losses through the basement wall and floor to the ground as well as heat transfer in surrounding soils, conduction is considered as the primary heat transfer mechanism. This implies several assumptions: (1) soil domain is incompressible, meaning that no stress occurs due to temperature change, (2) soil is homogeneous and isotropic to provide a smooth solution for heat transfer, and (3) phase change is considered when temperature goes beyond freezing point, so energy of enthalpy is required to overcome unfrozen-frozen transition.

Conductive heat transfer in soils can be expressed by the following equation:

$$\rho C_p \frac{\partial T}{\partial t} - \nabla \cdot q_c = 0 \quad [1]$$

where, C_p [J/kg·K] is the specific heat capacity of soil, ρ [kg/m^3] is the density, T [C^0] is the temperature, q_c [W/m^2]

is net energy conductive flux through the volume defined by generalized form of Fourier's law as follows:

$$q_c = k\nabla T \quad [2]$$

where, k is thermal conductivity.

2.1 First approach: Constant Thermal Properties

In this simplified approach, it is assumed that the thermal parameters in Equations 1 and 2, k and C_p, are constant and correspond to the values observed during laboratory measurements. Soil properties are represented in Table 1. Energy of enthalpy required to overcome unfrozen-frozen transition is not considered.

2.2 Second approach: Variable Thermal Properties

In the second approach, the thermal parameters in Equations 1 and 2, k and C_p, vary for frozen and unfrozen states. Main assumption of the second approach is that model has fully saturated condition.

The transient heat transfer by considering phase change can be written as:

$$\rho C_p \frac{\partial T}{\partial t} - \rho_i L_f \frac{\partial \theta_i}{\partial t} - \nabla \cdot q_c = 0, \quad [3]$$

where L_f is latent heat of fusion (333.5 kJ/kg), θ_i [-] is ice content. Index 'i' refers to ice.

Since the second approach studies soil with varying proportion of water and ice content it's density will be expressed as:

$$\rho = \rho_s(1-\theta_s) + \rho_w\theta_w + \rho_i\theta_i, \quad [4]$$

where subscripts s, w, i denote solid particles, water and ice, respectively. θ_s stands for the porosity.

However, it is important to mention that density of water and ice is considered equal to 1000 kg/m^3 to maintain volumetric balance.

In this study, the thermal conductivity of soil is expressed as the geometric mean of the thermal conductivity of each component (water, ice, solid particles) multiplied by their volumetric contribution.

$$k = k_s(1-\theta_s) + k_w\theta_w + k_i\theta_i \quad [5]$$

Similarly to Eq. 5, the apparent heat capacity may be expressed as follows:

$$C_{app} = \rho_s C_s(1-\theta_s) + \rho_w C_w\theta_w + \rho_i C_i\theta_i - \rho_i L_f \frac{\partial \theta_i}{\partial T} \quad [6]$$

Since the problem is considered as fully saturated, meaning that all voids are filled with water, the ice content may be expressed as difference between the porosity and unfrozen water content.

Unfrozen water content is expressed by the following equation (Zhu & Michalowski, 2005):

$$\theta_{w1} = \theta_r + (\theta_w - \theta_r)e^{a(T-T_0)} \quad [7]$$

where, $\theta_r = 0.05$ [-] is residual unfrozen water content, $a = 0.16$ is curvature coefficient, $\theta_w = \theta_s = 0.32$ [-] is unfrozen water content at the freezing temperature T_0. This assumption is made based on the measurements on the soil samples collected from the construction site. Additionally, it conforms with fully saturated condition when temperature remains positive.

2.3 Heat Loss Simulation

Heat losses through the basement structure of the new Stanley-Pauley Engineering Building is studied by implementing the above-mentioned models in COMSOL Multiphysics® Software. The soil medium is modelled by Heat Transfer in Solids physics.

An axisymmetric condition is considered. The model built in COMSOL is based on the structural drawings of the new building provided by the Faculty of Engineering.

The concrete basement walls are 300mm thick and are covered with 125mm of hard insulation. The floor slab is 200mm thick and is laid on 230mm of void foams which are assumed to be of the same material as insulation. General view of the model is shown in Figure 2.

Material properties of structural elements have been assigned according to Table 2.

Table 2. Material properties

Material	Thermal conductivity k (W/m·C^0)	Heat capacity C_p (J/kg·C^0)	Bulk Density ρ (kg/m^3)
Concrete	1.8	880	2300
Insulation	0.041	1450	34
Soil particles (skeleton)	2.5	867.92	2650
Water	0.6	4188	1000
Ice	2.2	2117	1000

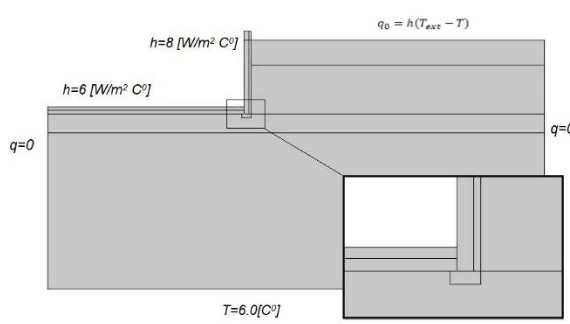


Figure 2. General view and boundary conditions

2.4 Boundary and Initial Conditions

The initial temperature of the structural material is set to 15 C^0, while soil domain is assumed to be 6 C^0. Bottom boundary of the domain was assigned with fixed temperature T=6.0 C^0. This explains infinite thermal capacity of ground potential (Ferguson & Woodbury, 2004).

Weather data from 2005 to 2016 were taken from ASRHE 2013 database for central Winnipeg area. Considering the ambient temperature and wind velocity taken from this weather station, the convective heat flux q_0 [W/m^2] has been defined on the upper boundary at the ground surface as follows,

$$q_0 = h(T_{ext} - T) \quad [7]$$

where, T_{ext} and T [C^0] are ambient and surface temperatures, h [W/m^2 C^0] is fitting parameter related to wind velocity.

The process of heat transfer through the basement structure can be assumed stationary. This allows using a thermal transmittance for the foundation structure without modelling it explicitly. The temperature inside the basement is fixed at $T_{amb} = 20\,°\mathrm{C}$. Considering the convective heat transfer coefficient h equals to 8 and 6 W/m^2 °C for the basement wall and floor slab (M. P. Deru & Kirkpatrick, 2002), respectively, the heat flow through the basement structure will be (Maghoul, 2017).

$$q_{conv} = h(T_{amb} - T_s) \quad [8]$$

where T_s is the temperature of soil surronding the basement.

The left and the right sides of the model have adiabatic boundaries. The domain was refined with fine mesh near the basement structure, as shown in Figure 3.

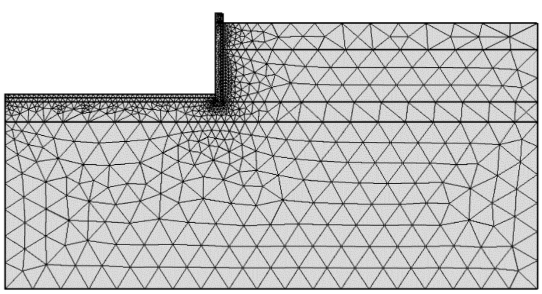


Figure 3. Mesh refinement of principal section.

3 RESULTS

To ensure that the results are not affected by the initial temperatures imposed on parts of the field, only the 11th year of simulation was analyzed in detail. For example, in both models, it has been observed that within the first ten years, heat flux through the floor is continuously decreasing until it levelled to slightly fluctuating sinusoidal curve due to seasonal temperature variations as shown in Figure 4.

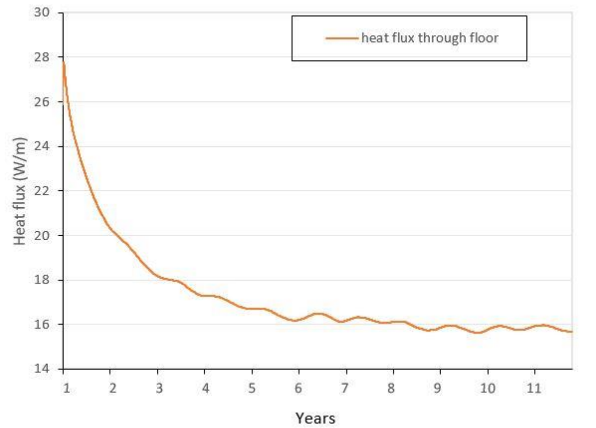


Figure 4. Stabilization of heat flux through floor slab after 10 years of service

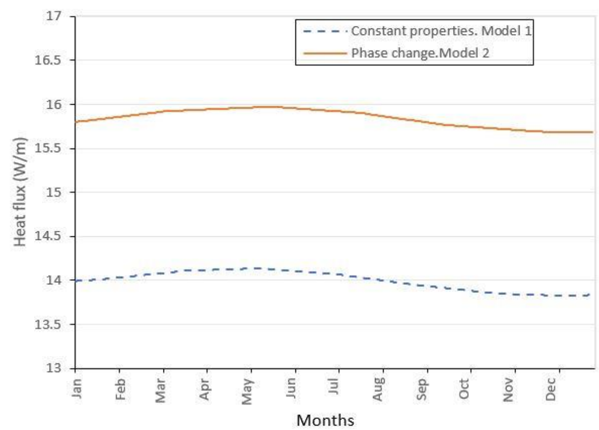


Figure 5. Variation of total floor heat flux during the 11th year of service.

It can be seen from Figure 5 that considering the latent heat in the heat transfer mechanism increases the heat flux through the floor by 2 W/m. Also, the difference in energy dissipation between Model 1 and Model 2 at winter time through the wall is much more severe and demonstrate 25 and 34 W/m, respectively (Figure 6). The difference in heat loss through the basement wall is almost 10 W/m during winter time between the two models. Since there is no phase change during summer period, no heat loss difference has been observed between the two models.

Overall, the two heat transfer models applied to study the heat loss through the basement structure show an approximate difference of 16.7% in the results. Model 2 which considers the effect of phase change and redistribution of ice and water content, demonstrates a higher heat loss compared to Model 1 with constant thermal properties.

Annual heat losses are shown in Table 3.

Figure 6. Heat flux through wall during the 11th year of simulation.

Table 3. Summary of heat loss during the 11th year of simulation

Parameter	Constant soil's Properties Model 1	Phase change Model 2
Heat loss through wall (W/m)	6060	7632
Heat loss through floor (W/m)	5120	5800
Total (W/m)	11 180	13 432

4 ALTERNATIVE INSULATION SOLUTION

An alternative solution to reduce the heat loss through the basement structure consists of additionally insulated pavement along the perimeter of the building (O. Farouki, 1992). Also, a 100mm thick and 1m wide layer of insulation is placed at a depth of 0.6m as shown in Figure 7.

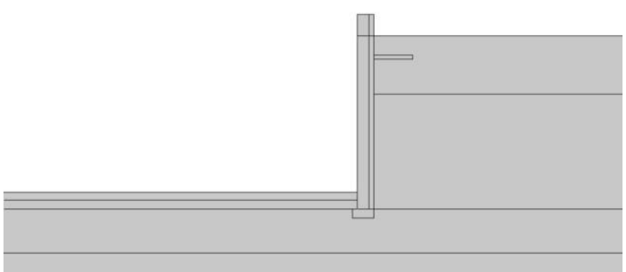


Figure 7. Insulated pavement.

To study the efficiency of the proposed insulation configuration, Model 2 (considering phase change) is applied by considering the same initial and boundary conditions explained in section 2.4. The simulation is run for the same period of time.

In this case, the resulting heat loss through the wall is 6220 W/m, which is 18.4% less than the initial result (Table 3). Heat loss through the floor has been estimated 5,850 W/m which is almost the same as the initial model result. Overall, a heat loss of 12,070 (W/m) has been estimated with a new configuration of insulation. This allowed reducing overall energy dissipation by almost 10%. As can be seen from Figure 8, horizontal insulation reduces the rate of frost penetration into the ground and temperature gradient along the wall below horizontal insulation. This in turn significantly reduces heat loss (Figures 9 and 10).

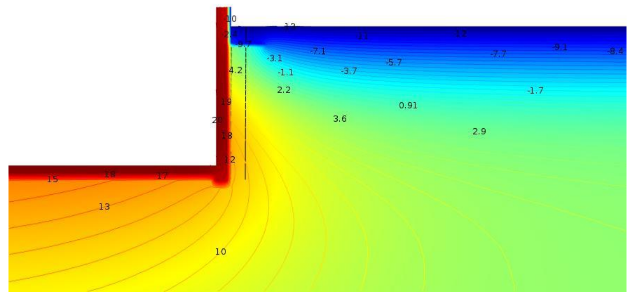


Figure 8. Distribution of temperature isotherms in February.

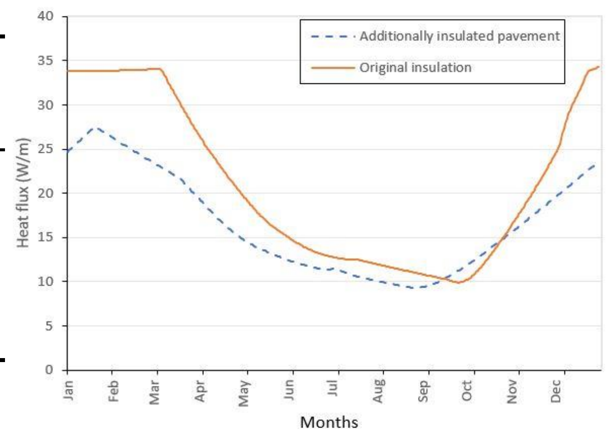


Figure 9. Variation of wall heat flux over design period.

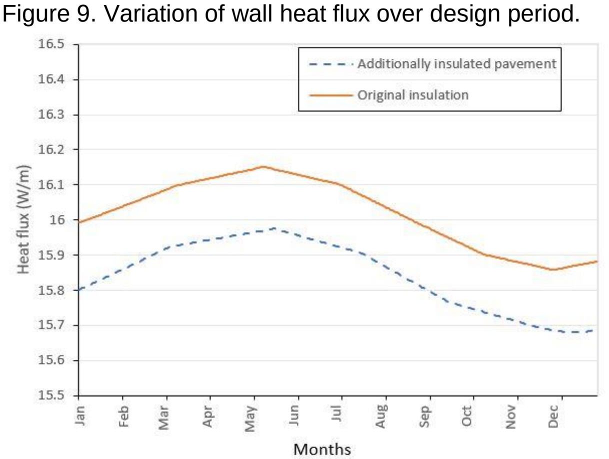


Figure 10. Variation of total floor heat flux over design period.

5 CONCLUSION

Two approaches were used to calculate the heat loss through the basement structure. The first approach assumed the constant soil's thermal properties while the second approach considered changes in thermal properties of the soil undergoing seasonal freezing.

It is concluded that the heat loss through the basement calculated by using the second approach is 16.7% greater than one obtained by using the first approach. This means that variable moisture content together with latent heat of fusion can no longer be disregarded in calculations of heat loss.

Additionally, an alternative solution with insulated pavement demonstrated an 18% decrease in heat dissipation through the basement wall which resulted in valuable 10% of overall energy savings. Horizontal insulation of the pavement placed along perimeter of the building shows better energy performance of the foundation.

It was also observed the heat loss along the vertical surface (basement wall) appears to be more severe than the heat loss through the floor. Heat loss through the slab-ground interface makes approximately one-third of overall energy loss. Closer to the ground surface frost action increases temperature gradient between interior and exterior part of the foundation creating more intensive heat transport. That is why it is important to provide sufficient insulation along the depth of frost penetration.

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