A numerical study of the influence of groundwater flow on heat loss from residential foundations

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

Beaulieu Dominique & Côté Jean
Department of Civil Engineering – Université Laval, Québec, QC, CA

ABSTRACT
This paper aims at determining the relative effects of groundwater flow (heat convection) on the total heat loss towards surrounding soils using a finite elements method to solve coupled heat and mass transfer in porous media. Three different soils were studied: clay, silt and sand. The results show that the flow of groundwater under the foundation has a significant influence on the total foundation heat loss if the surrounding soil is made of coarse grained soil such as pervious sands. As expected, the high water conductivity of sand has a strong influence on total heat loss due to varying pore-water velocities (hydraulic gradient). However, in low permeability soils such as silts and clays, groundwater flow has negligible influence on the total heat loss. Very low pore-water velocity does not allow for noticeable heat extraction under any water table or hydraulic gradients conditions.

RÉSUMÉ
L'objectif de cet article est de déterminer l'importance relative de l'écoulement de l'eau dans un sol de fondation résidentielle sur le total des pertes de chaleurs par cette fondation en utilisant un modèle par éléments fini pour résoudre le transfert couplé de chaleur et de masse dans un milieu poreux. Trois différents types sols ont été utilisés : le sable, le silt et l'argile. Les résultats montrent que l'écoulement de l'eau sous la semelle d'une fondation a de l'importance lorsque cette fondation est construite sur un sol pulvérulent dont la conductivité hydraulique est élevée. Dans le cas des sols à faible perméabilité comme le silt et l'argile, l'écoulement dans la nappe n'a pas d'influence sur la déperdition thermique totale par la fondation. Une faible vitesse d'écoulement ne permet pas d'extraction de chaleur significative, peu importe la hauteur de la nappe ou le gradient hydraulique.

1 INTRODUCTION

The insulation of above ground shell in residential building has been considerably improved is the past two decades resulting in a larger share of the whole building heat loss through the ground. A numerical and experimental study was initiated by IREQ (Hydro-Quebec research institute) and Université Laval to explore the effect of the different heat transfer mechanisms on energy efficiency of foundations, including buried walls and basement slab.

The aim of this paper is to evaluate the influence of ground water flowing in the vicinity of residential foundation on the heat loss through buried walls and floor slab. A recently developed numerical model (*Maghoul et al.* [2012]) was used to analyse the heat flow through a residential foundation built in three different soil types: sand, silt and clay. Numerical calculi were performed with a finite element model builder (FlexPDE 6).

The results show the influence of soil type, hydraulic gradients and depth of water table. The modelling results are also compared with in situ data from full scale experimental houses.

2 MODEL

2.1 Equations

This section briefly present the equations used in this paper.

For pure conduction, the equation for energy conservation can be expressed as:

$$\frac{\partial\left(\varphi_T T\right)}{\partial t} - \nabla\cdot\left(\lambda_T \nabla T\right) = 0 \qquad [1]$$

C_T is the volumetric heat capacity of unsaturated soil neglecting the insignificant heat capacity of air: $C_T = \theta_s \cdot C_s + \theta_w \cdot C_w$ where C_s is the volumetric heat capacity of solid (2.16 MJ/m^{3}K), θ_s is the volumetric solid content and θ_w the volumetric water content. λ_T is the thermal conductivity of the soil which is explained in section 2.3. T represents the temperature variable and t is time.

Coupling conduction and convection, eq. [1] becomes:.

$$\nabla\left(C_w U\left(T - T_0\right)\right) + \frac{\partial \varphi_T}{\partial t} + \nabla(-\lambda_T \nabla T) = 0 \qquad [2]$$

Where U is the pore-water velocity, C_w is the volumetric heat capacity of water (4.17 MJ/m^{3}K) and φ_T is the volumetric heat content formulated:

$$\varphi_T = C_T\left(T - T_0\right) \qquad [3]$$

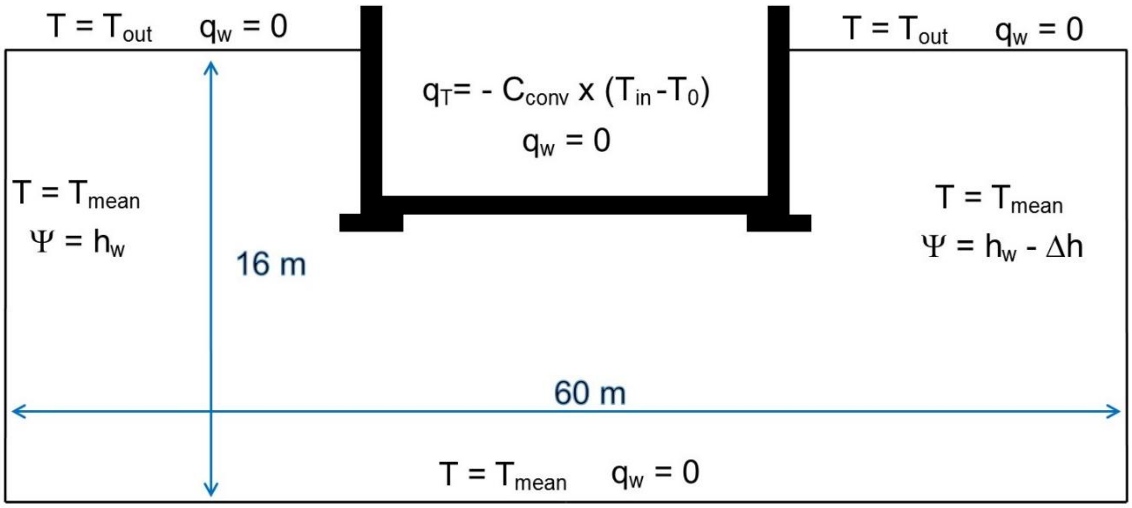


Figure 1 : Model boundaries

T_0 is the temperature of reference inside the building (20ºC). The volumetric water content, θ_w can be modeled using *Van Genuchten* [1980] equation:

$$\theta_w = \theta_r + (\theta_{sat} - \theta_r) \cdot \left(1 + \left(-\alpha\left(\Psi\right)\right)^n\right)^{-\left(1-\frac{1}{n}\right)} \qquad [4]$$

θ_{sat} is the water content for the saturated soil and θ_r is the residual water content of the soil. "α", "n" are constant.

Pore-water velocity (U) in this paper is determined by using generalised Darcy's law :

$$U = -K_h \nabla\left(\Psi + z\right) \qquad [5]$$

K_h is the hydraulic conductivity of the soil, "z" is the position in reference to a datum and Ψ is the water suction. To solve coupled heat and mass transfers, the water conservation equation is required:

$$\frac{\partial\left(\theta_w\right)}{\partial t} + \nabla U = 0 \qquad [6]$$

2.2 Boundaries

Figure 1 shows the modeled foundation and the boundary conditions of the model. There is two category of boundary in the model: temperature and water suction.
Water suction boundaries at the top and bottom of the model are of Neumann type and correspond to zero flux. The same boundaries apply between the foundation and the soil. The left boundary is of Dirichlet type and is equal to the water suction at water table h_w. The right boundary is equal to the water suction at $h_w - \Delta h$, where Δh is a difference of water suction. Values of h_w and Δh were varied to study the influence of water table level and of hydraulic gradient (pore-water velocity) on heat loss through the foundation.

The temperature boundaries at the bottom, at the left and at the right of the model are of Dirichlet type and equal to the mean annual air temperature (T_{mean}) of 6.52ºC. Theses boundaries are placed far enough from the foundation so that they do not influence the total flux calculated. The boundaries at the interface between the air and the soil are given by a sinusoidal function that represents an approximation of the annual variation of the outdoor temperature in Montreal, QC (Eq. 7).

$$T_{out} = T_{mean} + T_{amp} \cdot \cos\left(1.992 \cdot 10^{-7} \cdot t - 0.3112\right) \qquad [7]$$

The inner building boundaries ate the air-foundation interface are of the Neumann type and correspond to Eq. 8 where C_{conv} is a convection coefficient and is equal to 8.3 W/m^2°C for the wall and 6 W/m^2°C for the slab [*ASHRAE*, 2013]. T_{in} is the indoor temperature and is equal to 20ºC.

$$q_t = -C_{conv} \cdot (T_{in} - T_0) \qquad [8]$$

2.3 Parameters

Figure 2 shows the water retention curves for the clay, the silt and the sand that will be used in this paper. Van Genuchten parameter 'α' equals to 0.21 m^{-1}, 1.5 m^{-1} and 0.9 m^{-1} in clay, sand and silt respectively while 'n' is equal to 1.2, 3.19 and 1.5 and θ_r is equal to 0.102, 0.058 and 0.09.

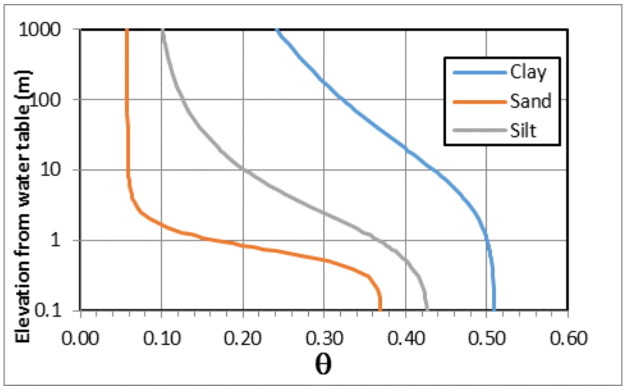


Figure 2 : Water retention curves for clay, silt and sand

Hydraulic conductivity (k) is determined with *Van Genuchten* [1980] equation (Eq. 9) where k_{sat} is set equal to 1e-4 m/s in sand, 1e-7 m/s in silt and 1e-9 m/s in clay.

$$k = k_{sat} S_r^{0.5}\left(1-\left(1-S_r^{\frac{1}{\left(1-\frac{1}{n}\right)}}\right)^{\left(1-\frac{1}{n}\right)}\right)^2 \qquad [9]$$

$$\lambda = \left(\lambda_{sat} - \lambda_{dry}\right)\cdot\lambda_r + \lambda_{dry} \qquad [10]$$

Thermal conductivity of soils (λ) are calculated according to [*Côté and Konrad*, 2005] model (Eq. 10) where λ_r is the normalized thermal conductivity of soil, λ_{sat} the thermal conductivity of saturated soil and λ_{dry} the thermal conductivity of dry soil. The readers are referred to [*Côté and Konrad*, 2005] for more details on this thermal conductivity model. Typical values of thermal conductivities for a saturated clay is 1.32 W/(m·^{0}C), while it is about 1.00 W/(m·^{0}C) for nearly dry sand.

Foundations are made of concrete for which thermal conductivity is 1.5 W/(m·ºC) and mass heat capacity is 2.4e6 J/(kg·K). 50mm of insulation is lying on the exterior side of the wall which thermal conductivity is 0.0284 W/(m·ºC) and mass heat capacity is 4.48e3 J/(kg·K).

2.4 Initial conditions

Presented results are for the last year of an at least 5 years simulation, to allow the impact of initial conditions to fade out.

3 RESULTS

This section presents the simulation results for the foundation in sand, silt and clay. It shows the temperature profile of the foundation in hydrostatic condition and with hydraulic gradient. In this paper, 3 different values of hydraulic gradient were used : i = 0, which represents hydrostatic conditions, i = 0.0043, represents a typical gradient used in hydrogeology [*Sudicky*, 1986] and i = 0.02, which represent a strong gradient equivalent to a residential foundation near a river. Water table levels were also varied at depths of 2.5 m, 5 m, 10 m, and 15 m.

3.1 Sand

Figure 3 shows the temperature profile in December with and without hydraulic gradient in sand. Figure 3a) shows the isocontours of temperature without hydraulic gradient at water table 15m. In Figure 3b), water table is set at 2.5 m depth and isocontours are symmetric on both side of the foundation and very similar to Figure 3a). With the hydraulic gradient of 0.02, on Figure 3c), temperature isocontours are dragged to the right of the model as water is flowing from left to right. In both case, maximum temperature of 19.4 ˚C is observed near the bottom of the foundation but is offset to the right wall when a hydraulic gradient is applied. The coldest temperature is at the surface of the soil which is expected for temperature profiles in December. At the edges of the soil's surface, the values of temperature follow a smooth transition to avoid discontinuities between the surface boundary and both left and right boundaries.

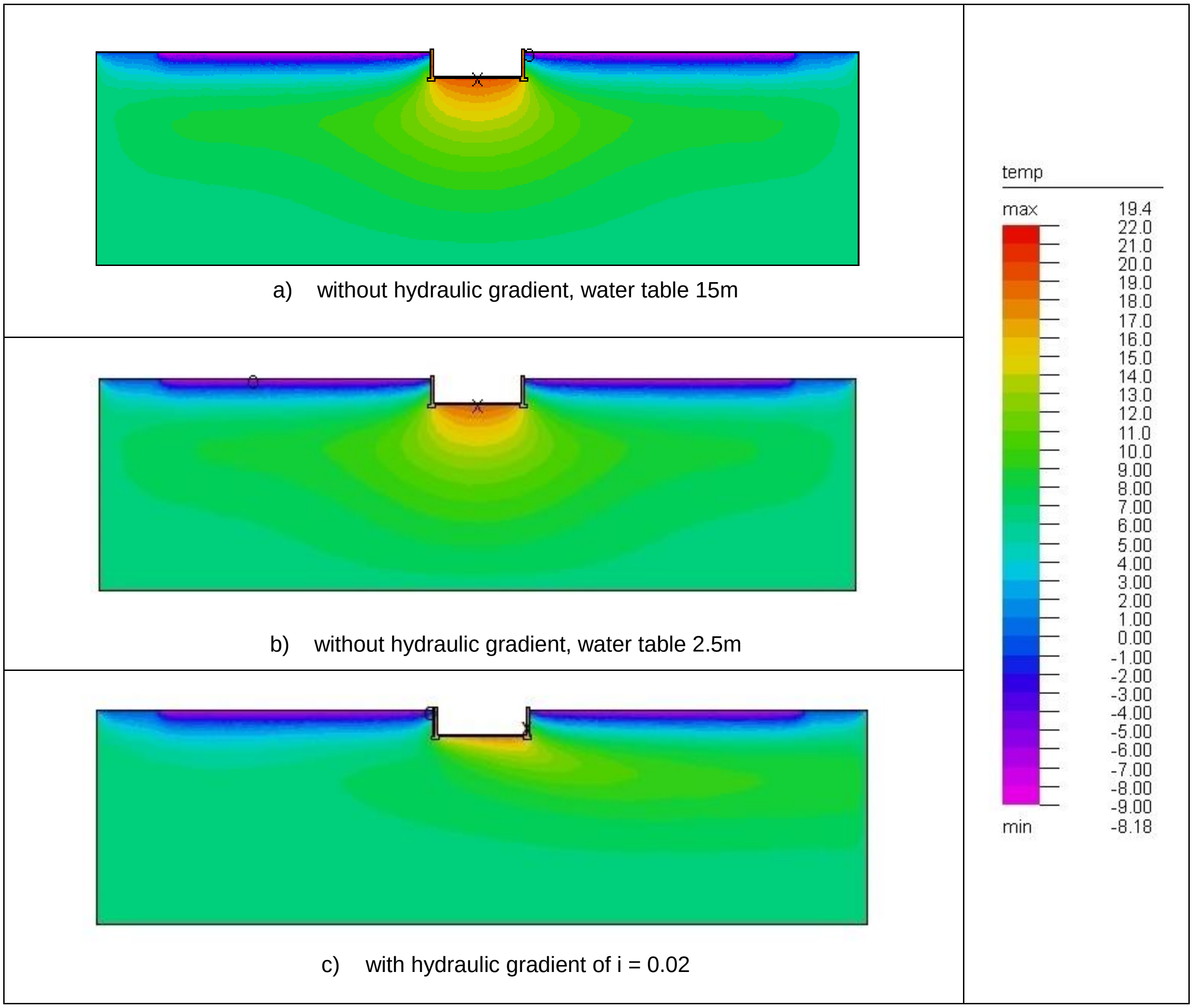
3.2 Silt and Clay

Figure 4 shows the temperature profile for silt in December without hydraulic gradient at 15 m depth water table, without hydraulic gradient at 2.5 m depth water table and with hydraulic gradient of 0.02 at 2.5 m water table level. As in sand, temperature profiles in both Figure 4a) and Figure 4b) are very similar. When including a hydraulic gradient (Figure 4c), isocontours stays similar as opposed to Figure 3c). It can be explained by the very low hydraulic conductivity of the silt used in the model (1e-7 m/s). The water flows very slowly from left to right and heat transfer is not significantly influenced as shown from the undisturbed temperature isocontours if compared to no flow isocontours. Further analysis (not shown here) demonstrated that an even stronger hydraulic gradient (0.067) would have no more influence on the heat loss from the foundation.

The results were the same in the case of the clay since its hydraulic conductivity is even lower (1e-9 m/s). These results are not shown in this paper.

4 DISCUSSION

In this section, simulation results are analysed for different water table depths in sand, silt and clay. The overall influence of the hydraulic gradients on the heat loss from the foundation is also discussed.



a) without hydraulic gradient, water table 15m

b) without hydraulic gradient, water table 2.5m

c) with hydraulic gradient of i = 0.02

Figure 3 : Temperature isocontours in sand with water table depth at 2.5 m

4.1 Heat loss in sand

Figure 5 shows the heat loss distribution from the total foundation at different water table depths without water flow under the foundation. At 2.5 m, the water table is located directly under the foundation slab. At this level, a maximum heat loss of -83 W/m is reached in January while the minimum of -39 W/m is reached in July. The heat loss is the highest when the water table is the closest to the surface. High water table results in higher water content, which in turn results in higher thermal conductivities. In the sand, the total heat loss is increased by about 25% during wintertime when the water table reaches the slab level, even without a hydraulic gradient. Below 10 m, there is no significant influence of the water table on the total heat loss. This is mostly due to the fact that the highly conductive saturated sands are too far from the foundation to exert any thermal influence.

Figure 6 and 7 show the heat loss for the same depths of water table but with a hydraulic gradient under the foundation of 0.0043 and 0.02 respectively. In those cases, the heat loss from the foundation is more important. When the water table is directly under the slab of the foundation (2.5 m depth), heat loss is increased very significantly. For example, the maximum monthly heat loss is equal to 99 W/m for a hydraulic gradient of 0.0043, while for a gradient of 0.02, the maximum heat loss is 125 W/m. These correspond to about 20% and 50% increase compared to hydrostatic conditions of Figure 5. However, the increase of heat loss is a lot less significant at water table depth 5 m from the surface: 5% for hydraulic gradient of 0.0043 and 10% for a gradient of 0.02. At further depth (10 meter and below), the hydraulic gradient has no influence on the heat loss from the foundation. Figure 7 also shows heat loss at water table 2.5 m when hydraulic gradient is zero and 0.0043.

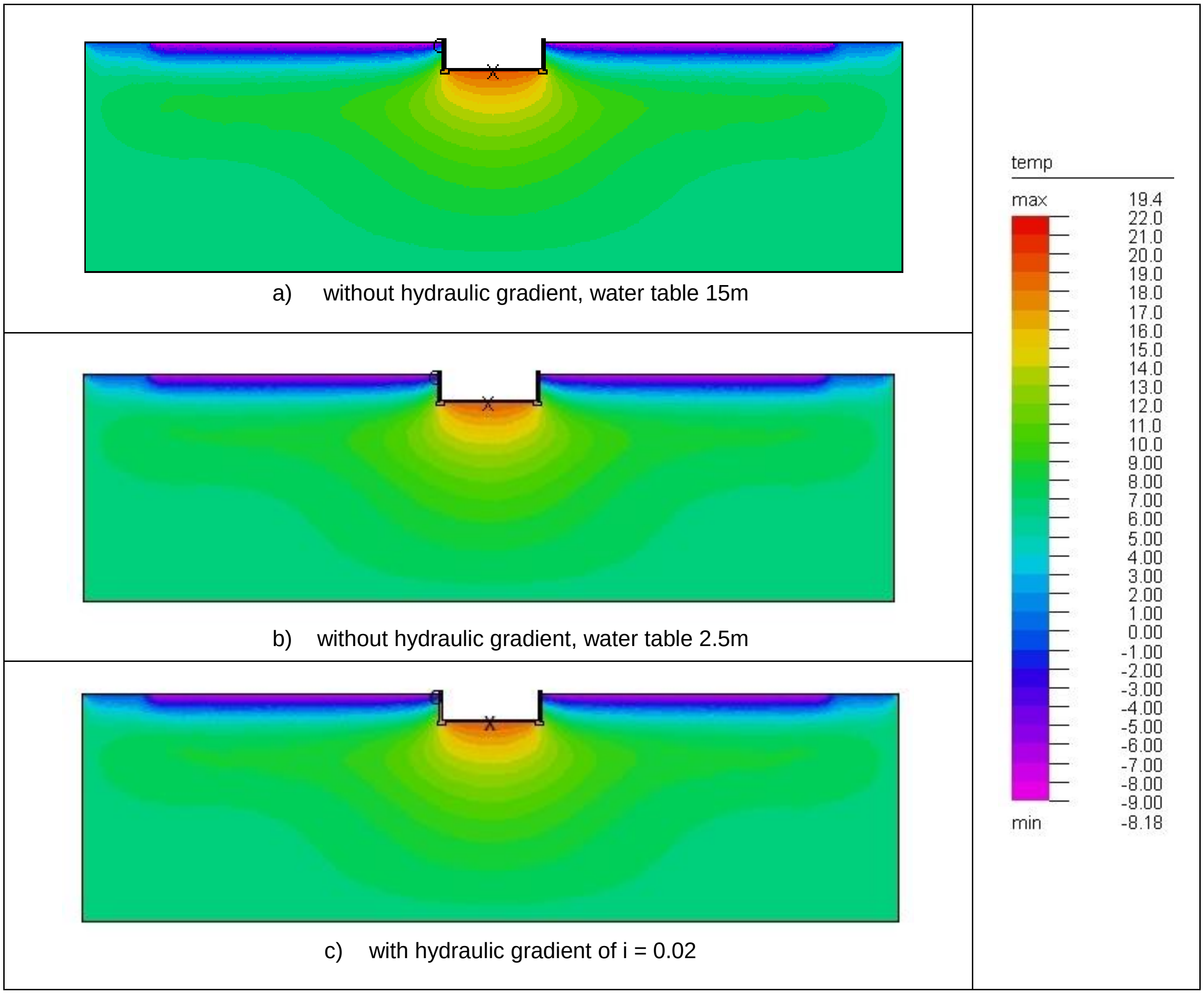


Figure 4 : Temperature isocontours in silt with water table depth at 2.5 m

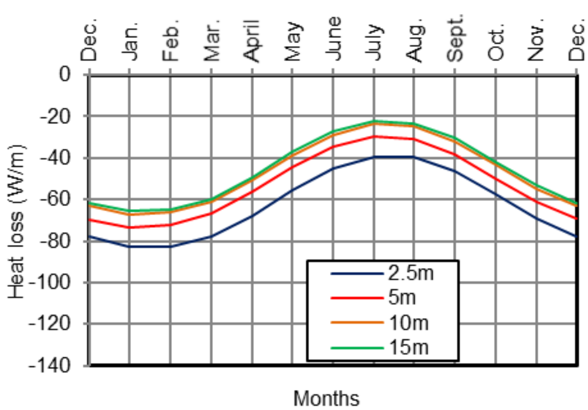


Figure 5 : Heat loss from total foundation in sand for different depth of water table. Hydraulic gradient is 0.

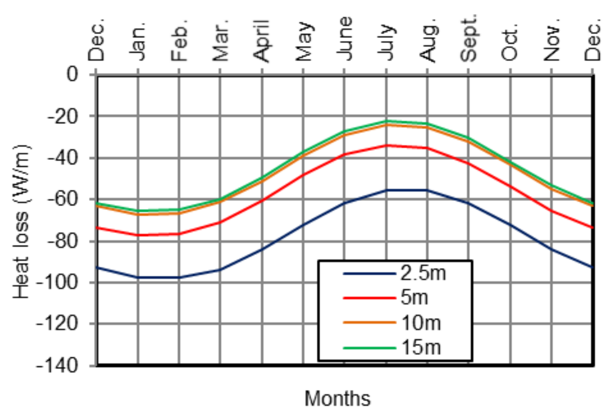


Figure 6 : Heat loss from total foundation in sand for different depth of water table with hydraulic gradient of i = 0.0043.

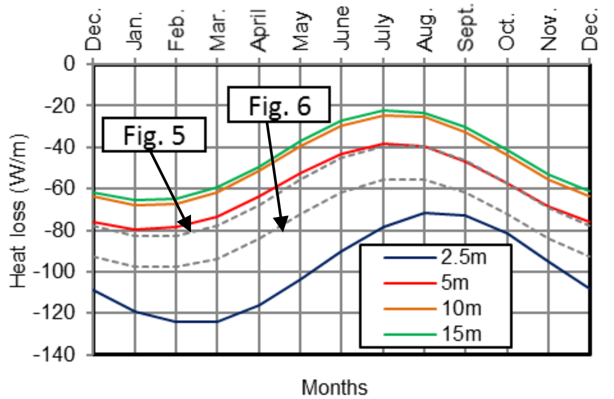


Figure 7 : Heat loss from total foundation in <u>sand</u> for different depth of water table with hydraulic gradient of i = 0.02. In dotted gray lines: heat loss at water table 2.5 m from Fig. 5 and 6.

To further explain the effect of the hydraulic gradient and the water table level on the heat loss, Figure 8 shows the total yearly energy loss in heat from the foundation built in sand. The 3 different hydraulic gradients are represented.

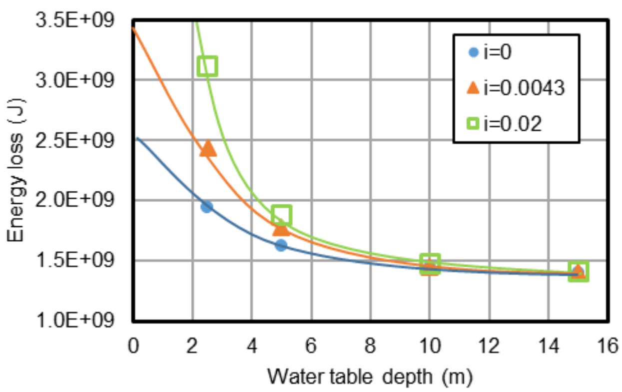


Figure 8 : Total energy loss from foundation built in sand during one year

As expected, the results show that there is an important difference of energy loss between the different hydraulic gradient when water table is the nearest to the surface. At 10 m and more, no difference is observed.

4.2 Heat loss in silt

Figure 9 shows the heat loss from a foundation built in silt soil for the 4 water table depth without hydraulic gradient., The variation of the heat loss at different water table level is less important, since the water content at suctions corresponding to elevations between 2.5 m and 15 m varies a lot less in the silt than in the sand. Figure 10 and 11 shows the heat loss for the same depth of water table but with a hydraulic gradient under the foundation of 0.0043 and 0.02 respectively. As expected, the very low flow conditions result in almost the same heat losses than for hydrostatic condition (Figure 9).

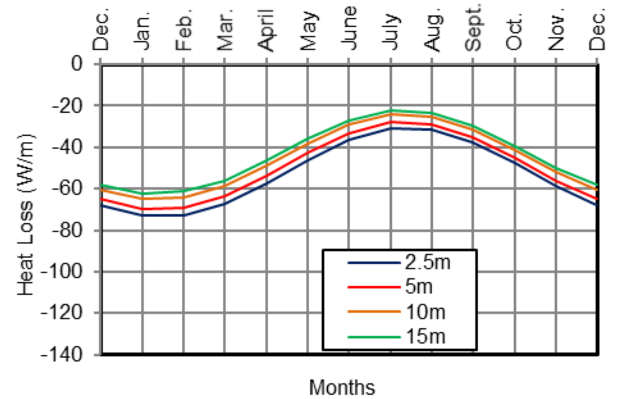


Figure 9 : Heat loss from total foundation in <u>silt</u> for different depth of water table with hydraulic gradient of <u>i = 0</u>.

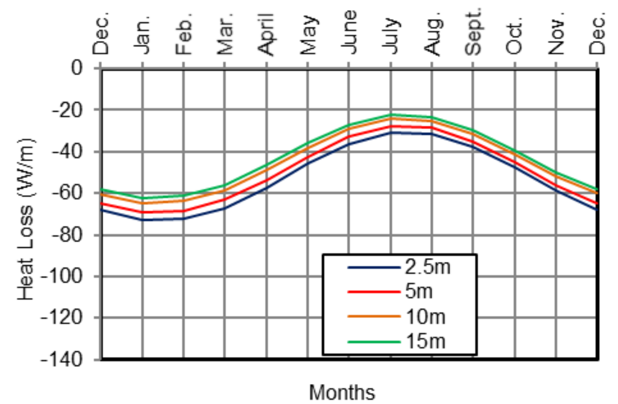


Figure 10 : Heat loss from total foundation in <u>silt</u> for different depth of water table with hydraulic gradient of <u>i = 0.0043</u>.

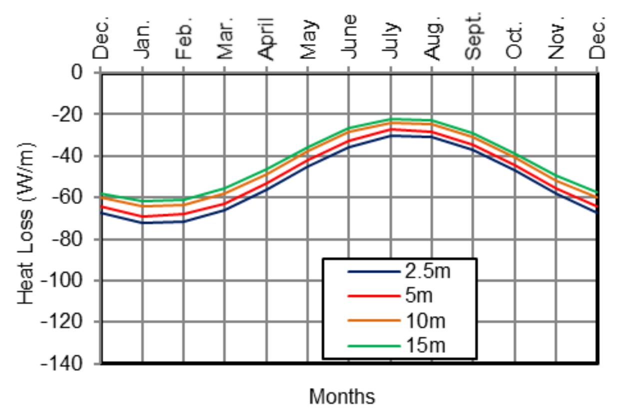


Figure 11 : Heat loss from total foundation in <u>silt</u> for different depth of water table with hydraulic gradient of <u>i = 0.02</u>.

This can be summarized as shown in Figure 12, where the total yearly energy loss from the foundation built in silt is similar for the maximum and minimum simulated hydraulic gradient.

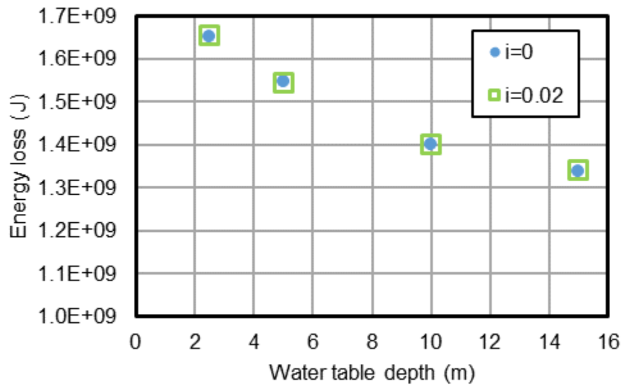


Figure 12 : Total energy loss from foundation built in silt during one year.

4.3 Heat loss in clay

Figure 13 shows the heat loss from a foundation built in clay for grad = 0 and different water table depth. Since the hydraulic conductivity of clay is about 100 times lower than the hydraulic conductivity of silt, the variation of the heat loss will be even smaller. Even when applying different values of hydraulic gradients, the results have shown that there is no significant influence on the total heat loss from the foundation.

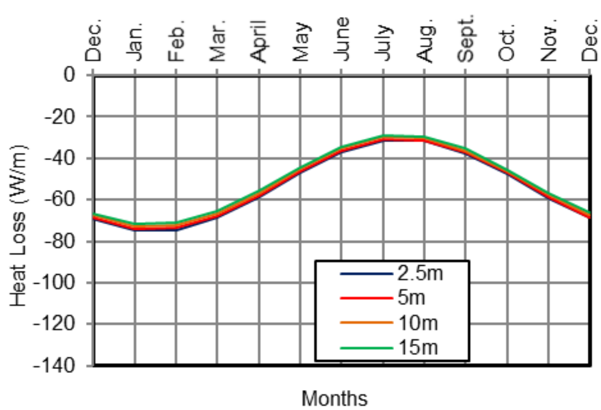


Figure 13 : Heat loss from total foundation in clay for different depth of water table.

4.4 Comparison with experimental results

The computed values of heat loss were compared with experimental data measured on a test site built by Hydro-Québec research institute (IREQ) and where two houses were fully instrumented. Instrumentation included temperature and water content probes that were installed in foundation soil, slab and walls. These data were collected on a high frequency basis all year round and allowed calculating heat loss through walls and slab using the measured cement concrete thermal conductivity.

According to the experimental data, average yearly values of heat flux registered for a foundation built in clay ranges from 3.73 to 4.20 W/m^2. In this paper, the average yearly flux calculated for similar soil type is about 4.85 W/m^2, which is fairly close to experimental data. The slightly higher computed heat flux value can mostly be attributed to the surface temperature function used in the model. This boundary condition did not consider the insulating effect of snow cover during winter that tends to reduce cooling from the surface, hence the slightly higher average yearly heat flux computed herein. Comparison of in situ results with the numerical approach will be further discussed in details in future publications.

5 CONCLUSION

This paper showed the relative effects of groundwater flow (heat convection) on the total heat loss towards surrounding soils using a finite elements method to solve coupled heat and mass transfer in porous media.

Analyses were performed for 3 types of soils: sand, silt and clay. The results showed that the heat loss from the foundation increases with increasing level of water table. This can be attributed to the fact that saturated soils have higher thermal conductivities than unsaturated ones. Results also showed that ground water flow, under various hydraulic gradients had a significant influence on the heat loss only when two conditions are met: a) foundation built in coarse and permeable materials such as sands and b) shallow water table depths close to the foundation slab. However, these conditions are unlikely to be found in typical hydrogeological conditions in residential developments of the province of Quebec since the water table levels in sandy soil deposits are generally low. This results in an insignificant water convection effects as outlined in this paper. In general, it is therefore reasonable to conclude that convection heat transfer has an insignificant influence on heat loss through residential foundations.

Future work will study the effect of other heat transfer mechanisms such as pore vapour heat transfer and surface heat balance including evaporation and precipitation as well as snow cover effect.

ACKNOWLEDGEMENTS

This work was funded through the Cooperative Reseach and Development grants program (CRD). Contributions of NSERC and Institut de recherche d'Hydro-Québec (IREQ) are highly appreciated

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