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Effect of soil type and moisture content on ground heat pump performance

W. H. Leong[a], V. R. Tarnawski[b] and A. Aittomäki[c]
[a]Hatch Associates Ltd, Non-Ferrous Business Unit, Energy and Fluid Mechanics Group, 2800 Speakman Drive, Mississauga, Ontario L5K 2R7, Canada
[b]Division of Engineering, Saint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada
[c]Institute of Energy and Process Engineering, Tampere University of Technology, Tampere, S-F 33101 Finland

Three different soils (sand, silty loam and silty clay) with five different degrees of saturation (0, 12.5, 25, 50 and 100%) were used in computer simulations. The performance of a ground heat pump system was found to depend strongly on the moisture content and the soil type (mineralogical composition). Alteration of soil moisture content from complete dryness to 12.5% of saturation strongly influences the ground heat pump performance, and any decrease of soil moisture in this range has a devastating effect on the coefficient of performance (COP). Therefore, it is beneficial to keep the soil moisture value as high as possible above dry soil conditions. Soil moisture content above the quarter saturation state leads to a much better heat pump performance. It was found, however, that the effect of moisture content variation above 50% of saturation on ground heat pump performance is relatively insignificant. © 1998 Elsevier Science Ltd and IIR. All rights reserved.

(Keywords: thermal properties; ground heat pumps; heat exchangers)

Effet du type et de l'humidité du sol sur la performance des pompes à chaleur à capteurs enterrés

On a utilisé trois types de sol différents (sable, glaise limoneuse et argile limoneuse) avec cinq degrés de saturation (0, 12,5, 25, 50 et 100%) pour des simulations par ordinateur. Les auteurs ont montré que la performance d'un système utilisant une pompe à chaleur dépendait fortement de l'humidité et du type du sol (c'est à dire sa composition minéralogique). L'augmentation de l'humidité du sol (d'un taux d'humidité de zéro à taux de 12,5%) influence fortement la performance de la pompe à chaleur et toute diminution de l'humidité du sol dans cette zone exerce des effets extrêmement néfastes sur le COP. Donc, le maintien de l'humidité du sol au niveau le plus élevé au dessus des conditions de sol sec influence favorablement la performance. Un taux d'humidité au-dessus du seuil d'un sol 25% saturé donne lieu à une performance nettement améliorée de la pompe à chaleur. Cependant, on a montré que les variations dans le taux d'humidité au dessus du seuil d'un sol 50% saturé ont exercé des effets relativement insignificants sur la performance. © 1998 Elsevier Science Ltd and IIR. All rights reserved..

(Mots clés: propriété thermique; pompes à chaleur sol; échangeur de chaleur)

Introduction

In ground heat pump applications, deposition or extraction of thermal energy from the ground is accomplished by using a ground heat exchanger (GHE), whose operation induces a simultaneous heat and moisture flow in the surrounding soil. The transfer of heat between the GHE and adjoining soil is primarily by heat conduction and to a certain degree by moisture migration. Therefore, it depends strongly on the soil type, temperature and moisture gradients. The entire process of heat extraction/deposition is a transient one,

Nomenclature

T_f	freezing temperature of circulating fluid	ρ_{db}	dry bulk density of soil
m_{qz}	mass fraction of quartz content	ρ_s	density of solids
ϕ	soil porosity ($\phi = 1 - \rho_{db}/\rho_s$)	θ_{sat}	saturated volumetric water content

due to the weather-dependent ground surface boundary conditions and heating/cooling load. The soil thermal conductivity varies greatly with the soil type (texture, mineralogical composition), moisture content, dry bulk density, temperature, and soil air humidity. The soil moisture content in close vicinity to the GHE can be influenced by numerous factors, such as: soil structure, temperature gradient, moisture gradient, irrigation, and gravity effects. In particular, the temperature gradient in the soil surrounding the GHE plays an important role in the combined heat and moisture flow. When the soil temperature near the GHE is well above 40°C, the effect of the moisture gradient is limited as compared to the temperature gradient, which may lead to a dry soil belt around the GHE behaving like an annular zone of insulation[1]. Moreover, structural and textural properties of the same soil sample can vary considerably with seasonal climatic conditions. Therefore, thorough knowledge of the intricate nature of soils and transport phenomena related to coupled heat and moisture flow in the ground is essential to both the design and the operation of ground heat pump systems. Due to the very complex character of the ground, the actual design of the GHE should be based on a detailed mathematical model of simultaneous heat and moisture flow in soils, an integrated heat pump model and reliable ground hydro-geological data. The parameters influencing the soil thermal properties are essential for testing the GHE length and carrying out a parametric analysis, which is very useful for estimating the long-term effects of GHE operation on the surrounding ground. The results of laboratory testing of soil samples (grain size, soil dry bulk density, water content, mineralogical composition) should also be available prior to the evaluation of soil thermal properties.

A few papers dealing with the influence of soil types and moisture conditions on ground heat pump performance have been published in the last decade. Hailey et al.[2] analyzed the behavior of the thermal conductivity of soils adjacent to the GHE. It was found that soil moisture content was a dominant factor responsible for seasonal thermal conductivity variations. High heat rejection rates to the ground (cooling mode) had a detrimental impact on the soil thermal conductivity, leading to reduction of heat transfer. Drown and Den Braven[3] monitored for several seasons the effect of soil conditions and thermal conductivity on heat transfer in ground heat storage. Augmentation of the soil thermal conductivity by 0.17 W $(\mathrm{m\ K})^{-1}$ led to reduction of heat pump operating time by 1.3%. Heat transfer in multi-layered ground (coarse sand, clay, fine sand) with a vertical GHE was examined by Deng and Fedler[4]. A two-dimensional model of unsteady heat conduction in soils was used to simulate the ground temperature profiles. The model disregarded soil moisture migration and assumed the average thermal properties of homogeneous and isotropic

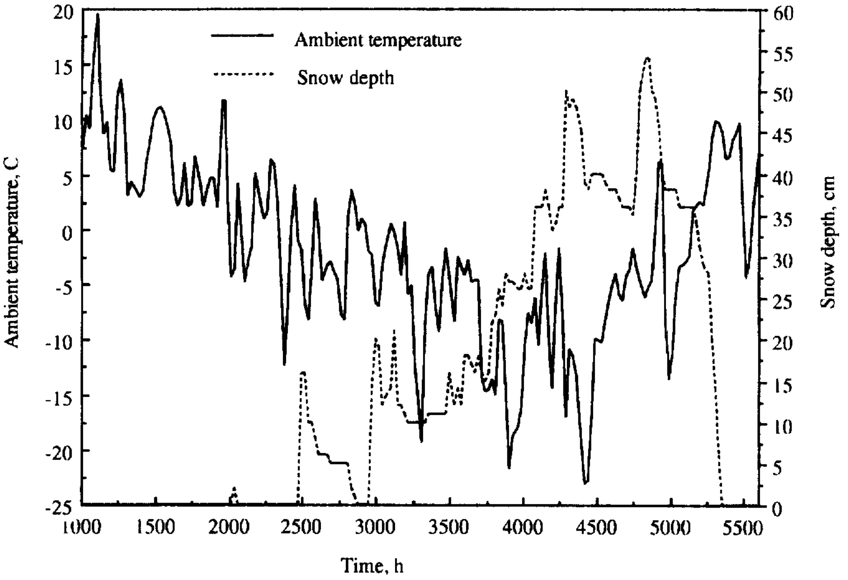

Figure 1 Ambient temperature and snow depth (Ottawa 1987–88) vs time

Figure 1 *Température ambiante et profondeur de la neige (Ottawa 1987–88) en fonction de la durée*

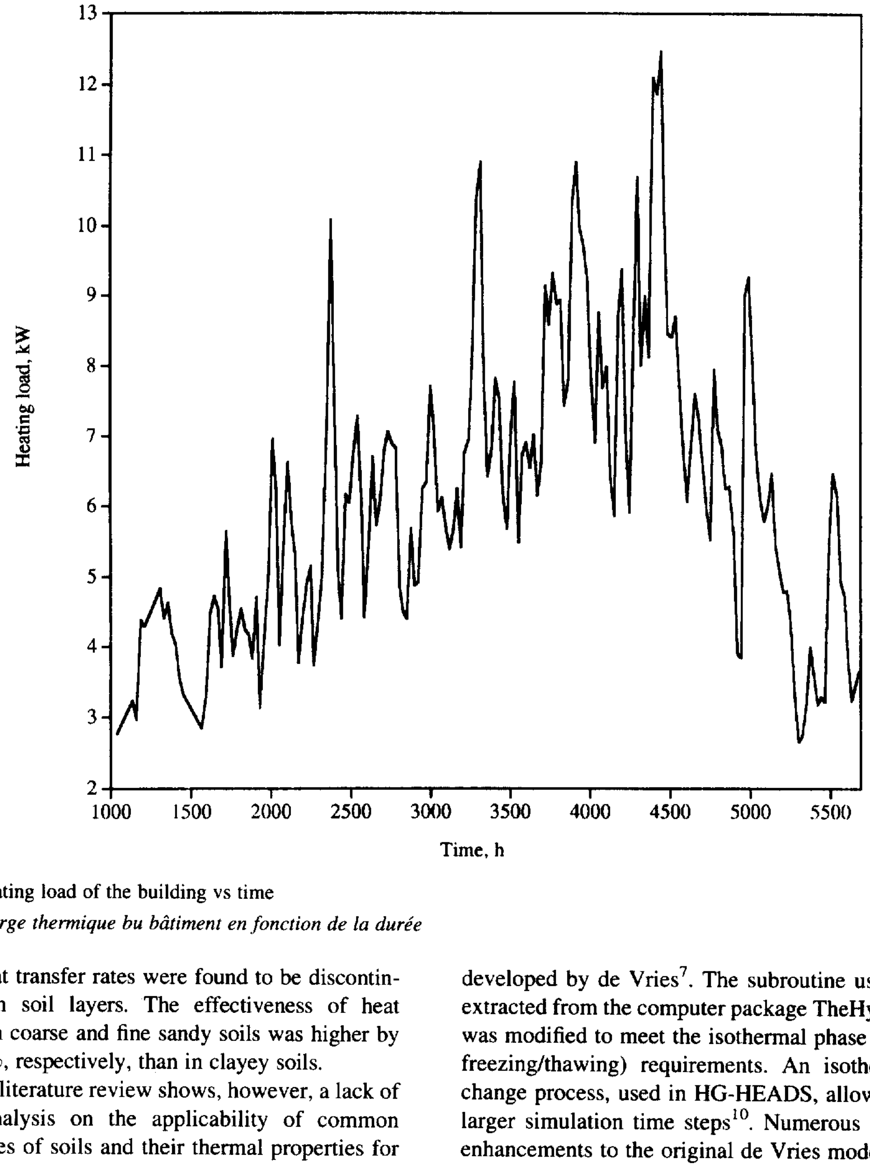

Figure 2 Heating load of the building vs time

Figure 2 *Charge thermique bu bâtiment en fonction de la durée*

soils. The heat transfer rates were found to be discontinuous between soil layers. The effectiveness of heat distribution in coarse and fine sandy soils was higher by 62% and 27%, respectively, than in clayey soils.

The above literature review shows, however, a lack of a general analysis on the applicability of common textural classes of soils and their thermal properties for use in ground heat pump systems. Experimental assessment of the above task would be very time consuming, expensive, error prone, and limited to conditions at a particular site. Therefore, a computer package for horizontal ground heat exchanger analysis, design and simulation (HG-HEADS[5,6]) has been used to examine the influence of three different standard soils on ground heat pump performance. Five different constant values of soil moisture content corresponding to 0, 12.5, 25, 50 and 100% of saturation have been used in computer simulations. The above values have been kept constant throughout the soil domain and the simulation period.

Evaluation of thermal characteristics of soils

The thermal and hydraulic properties of soils are evaluated by a special subroutine developed for use in the HG-HEADS package. Evaluation of soil thermal conductivity is based on the enhanced model originally developed by de Vries[7]. The subroutine used has been extracted from the computer package TheHyProS[8,9], and was modified to meet the isothermal phase change (soil freezing/thawing) requirements. An isothermal phase change process, used in HG-HEADS, allows the use of larger simulation time steps[10]. Numerous changes and enhancements to the original de Vries model have been made, and the most important additions are listed below.

- The soil system can be made of up to 26 mineralogical components whose individual characteristics, such as mass fraction, thermal conductivity, density, shape and specific heat, must be known. The default option considers five principal soil minerals (quartz, feldspar, calcite, clay-minerals, mica).
- A general relationship for mineralogical composition of any natural soil has been introduced.
- Soil water is assumed to be a continuous medium over a full moisture range (dryness to saturation).
- The hydraulic soil water model of Campbell[11] is used for evaluation of water vapor migration in soil air pockets.
- Unfrozen water content in freezing soils follows relations published by Williams[12] and Anderson and Tice[13].

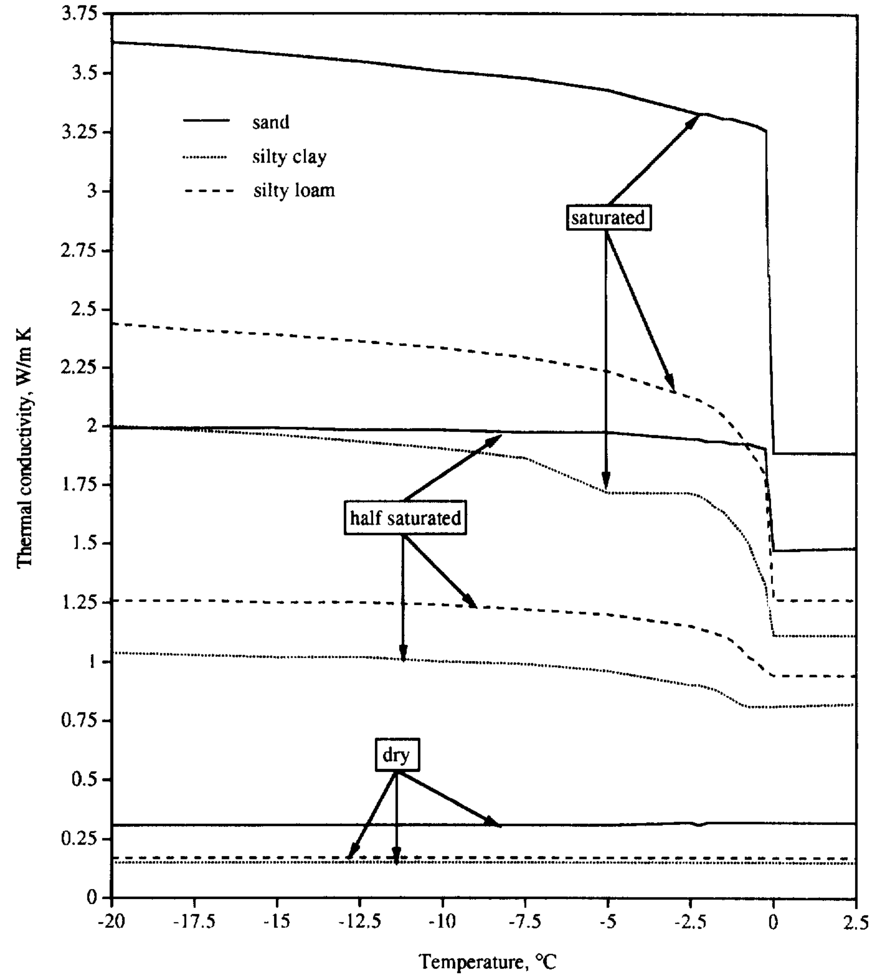

Figure 3 Thermal conductivity of sand, silty loam and silty clay vs temperature (dry, half- and fully saturated soils)

Figure 3 *Conductivité thermique de sable, glaise limoneuse et argile limoneuse selon la température (sols sec, à moitié saturé et complètement saturé)*

- The air shape factor follows a logarithmic function of soil moisture content.
- Equations by Carslaw and Jeager[14] are used for shape values of soil constituents.

The TheHyProS package evaluates the thermal conductivity, specific heat and hydraulic properties of practically any soil for a full range of moisture content (dryness to saturation) and temperatures from −30 to 95°C. The required input data is as follows:

- selection of twelve standard soils (according to USDA) or user-defined soil with known composition (i.e., a combination of clay, silt, sand and gravel);
- dry bulk density or porosity;
- temperature; and
- moisture content (in terms of volumetric or mass based).

The remaining data (e.g., mineral characteristics and shape values) are default values which may be overridden by the user. The predicted thermal conductivities of soils were compared with the experimental data by Kersten[15], using only default data. In general, agreeable results[8,9] were obtained.

Computer simulation

The influence of soil types on the performance of a ground heat pump system has been studied using the HG-HEADS program. The software has a number of built-in design features, such as:

- twelve standard soils;
- nine configurations of the GHE, namely:
- single layer in series and parallel,
- double layer: series counterflow, parallel counterflow, parallel parallelflow,
- triple layer: parallel parallelflow,
- quadruple layer: series counterflow, parallel counterflow, parallel parallelflow;
- sixteen standard pipes for GHE (inner and outer diameters, wall thermal conductivity);

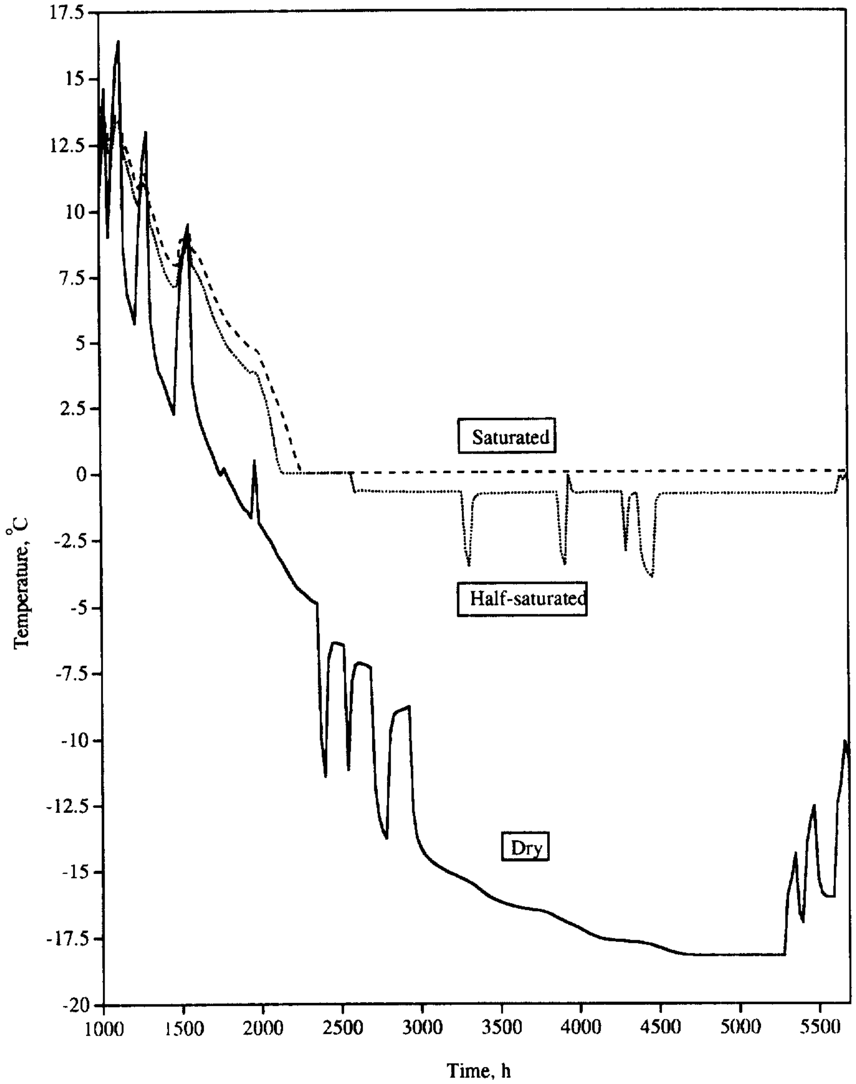

Figure 4 Variation of sand temperature at GHE inlet vs time (dry, half- and fully saturated conditions)

Figure 4 *Variation de la température du sable à l'entrée de l'échangeur de chaleur à capteurs enterrés en fonction de la durée*

- thirteen working fluids (brine and antifreeze solutions with various concentrations);
- manufacturer's data for twelve heat pump models.

The following parameters have been considered in computer simulations:

soils:	sand ($\rho_{db} = 1480$ kg m^{-3}, $\phi = 0.441$, $m_{qz} = 82.8\%$), silty loam ($\rho_{db} = 1230$ kg m^{-3}, $\phi = 0.536$, $m_{qz} = 44.4\%$), silty clay ($\rho_{db} = 1200$ kg m^{-3}, $\phi = 0.547$, $m_{qz} = 23.1\%$);
soil moisture content:	0; $0.125\theta_{sat}$, $0.25\theta_{sat}$, $0.50\theta_{sat}$, $1.0\theta_{sat}$, where $\theta_{sat} = 1 - \rho_{db}/\rho_s$;
soil domain:	depth × width = 5 m × 0.25 m; 75 triangular finite elements; 61 nodes; small finite elements are used in the upper part of the domain (2 m), the rest of domain is discretized with larger elements;
GHE data:	single layer (serpentine arrangement), depth = 1.0 m, horizontal spacing = 1.0 m, length = 500 m, polyethylene PE 3408 (31.75 mm nominal pipe diameter);
heat pump data:	WX041 by WaterFurnace International Inc., 12 kW nominal heating capacity, summer entering air temperature 24°C, winter entering air temperature 16°C;

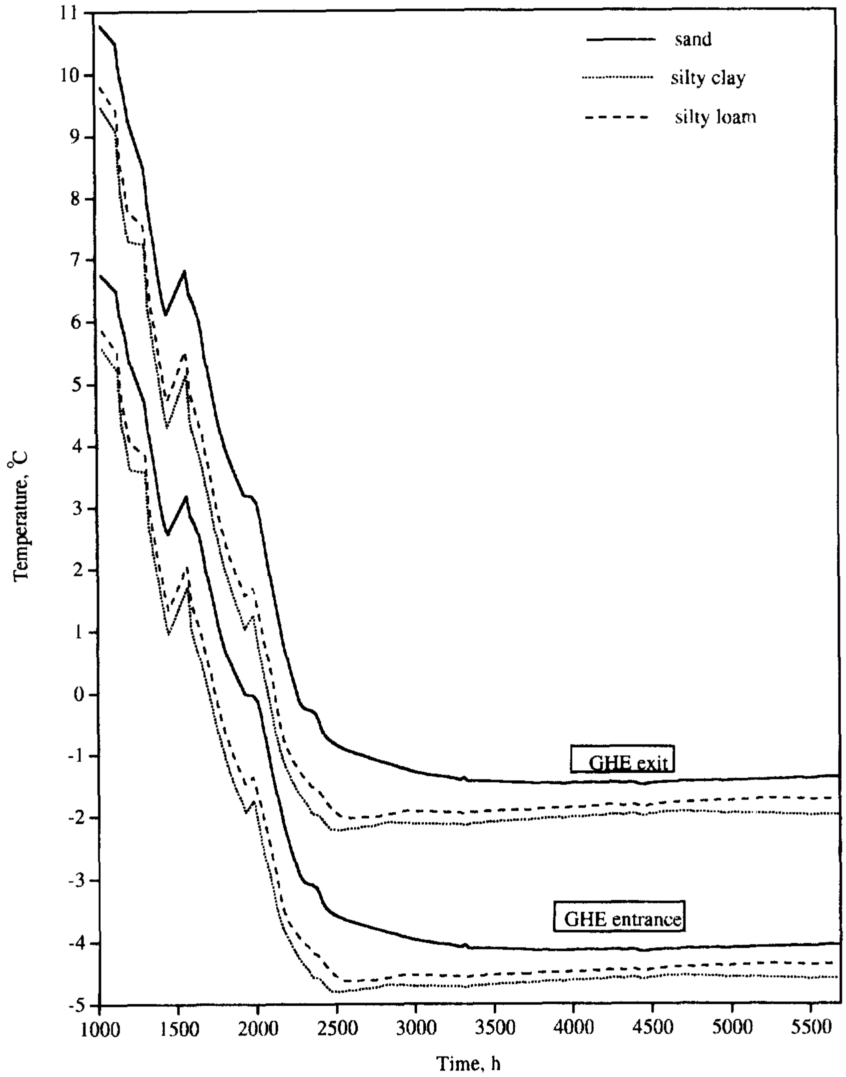

Figure 5 Variation of the brine temperature (GHE entrance/exit) vs time, for saturated sand, silty clay and silty loam

Figure 5 *Variation de la température de la saumure (entrée/sortie de l'échangeur de chaleur à capteurs enterrés) en fonction de la durée*

circulating fluid:	sodium chloride in water (20% by weight), freezing point $-17°C$ (when the temperature of the circulating fluid falls below the fluid freezing point, the program issues a warning and the fluid properties are evaluated using $T_f + 1°C$), flow rate = 11 gpm;
meteorological data:	Ottawa (1987–88);
simulation period:	15 August 1987 (0 h)–14 August 1988 (8760 h);
heating season:	26 September (1008 h)–8 April (5688 h).

The ambient temperature, the snow depth at the ground surface and the heating load for the heating season corresponding to the winter of 1987–88 are displayed in *Figures 1* and *2*.

Results and discussion

Dry soils generally do not exhibit thermal conductivity variation with temperature (*Figure 3*). The thermal conductivity evaluation is based on the mineralogical composition, dry bulk density and air content which is equal to soil porosity. The value of thermal conductivity for moist soils is considerably higher than for dry soils. This is a strong argument for maintaining the soil water content as high as possible above the dry state. Saturated and half-saturated soils display a noticeable change in the thermal conductivity, particularly below the freezing point (0°C). The superior thermal conductivity of sand is mainly due to its high quartz content.

In the first 1000 hours of the heating season, sand temperature at the GHE inlet (*Figure 4*) drops rapidly. This is because the sensible heat is a main mode of heat transfer and the rates of temperature decrease depend on

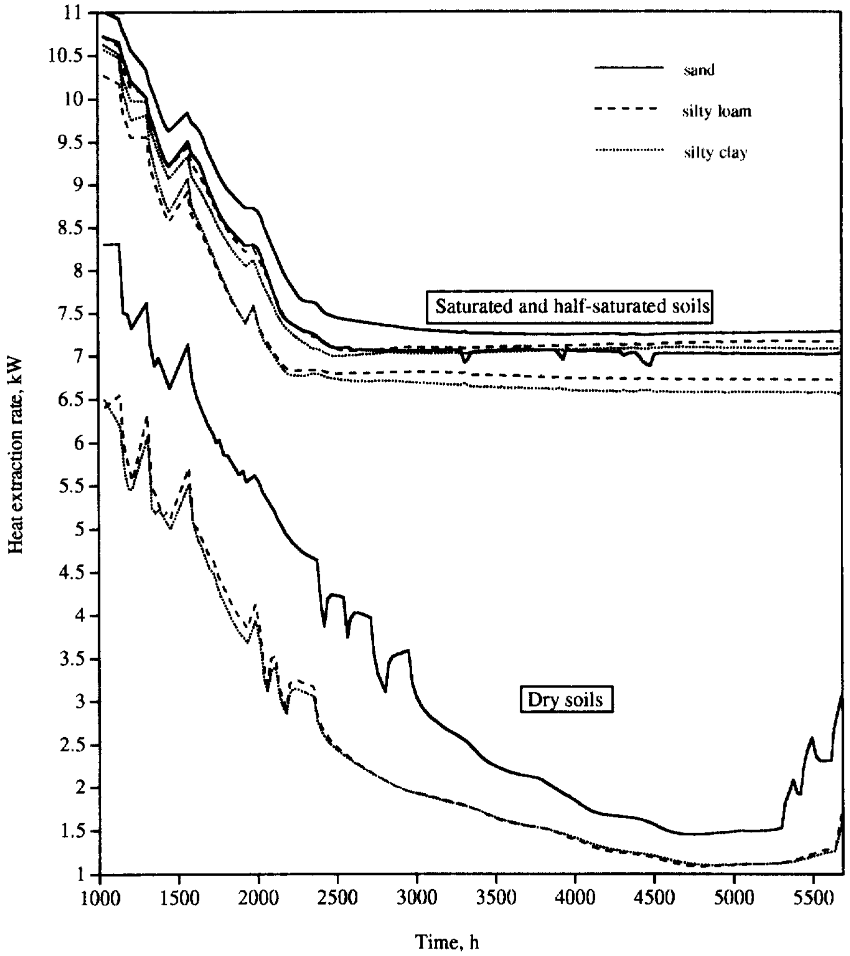

Figure 6 Heat extraction at the GHE vs time (dry, half- and fully saturated sand, silty loam and silty clay)

Figure 6 *Extraction de la chaleur de l'échangeur de chaleur à capteurs enterrés en fonction de la durée pour des sols (sable, glaise limoneuse et argile limoneuse) saturés en fonction de la durée*

the sand moisture content. An erratic temperature variation and a high rate of temperature change are observed for completely dry sand. During a heat pump off-operation period, dry sand around the GHE recovers heat from a peripheral zone of the ground; hence, its temperature rises rapidly due to a very low specific heat as compared with moist sand. Once the freezing point of water is reached, a release of latent heat from the moist sand is utilized by the GHE until the freezing process is over. Therefore, there is no sign of a temperature drop below the freezing point until the total amount of latent heat is removed from the sand undergoing freezing. For dry sand, there is obviously no latent heat to be removed, and its temperature continues to decline sharply down to about −17.5°C, which nearly corresponds to the end of the heating season. A similar trend has also been observed for two other soils, except that the rates of temperature decrease for the two soils are slightly higher and the lowest temperature of the soils is about −19°C.

Figure 5 displays variation of the brine temperature at the entrance and exit of the GHE for the saturated soils under investigation. The soil moisture content in the immediate vicinity of the GHE has a strong effect on the brine temperature. In the first 1500 hours of the heating season, brine temperature drops rapidly at a similar rate for all saturated soils, and then remains constant (e.g., at the GHE exit: −1.5, −1.8 and −2.0°C for sand, silty loam and silty clay, respectively). During this time, extraction of sensible heat from the moist soil causes a high soil temperature drop. In the remaining part of the heating season all moist soils in the vicinity of the GHE experience freezing and their temperature remains constant. Moreover, the brine temperatures at the entrance and exit of the GHE buried in sand are always higher than those for silty loam and silty clay. This is due to a larger amount of heat being extracted from the sand.

As far as the amount of heat extraction is concerned (*Figure 6*), its largest value is observed for saturated sand, particularly in the initial part of the heating season, followed by silty loam and silty clay. A rapid decrease of heat extraction in the first 1500 hours of the heating season followed by an almost steady heat removal is then

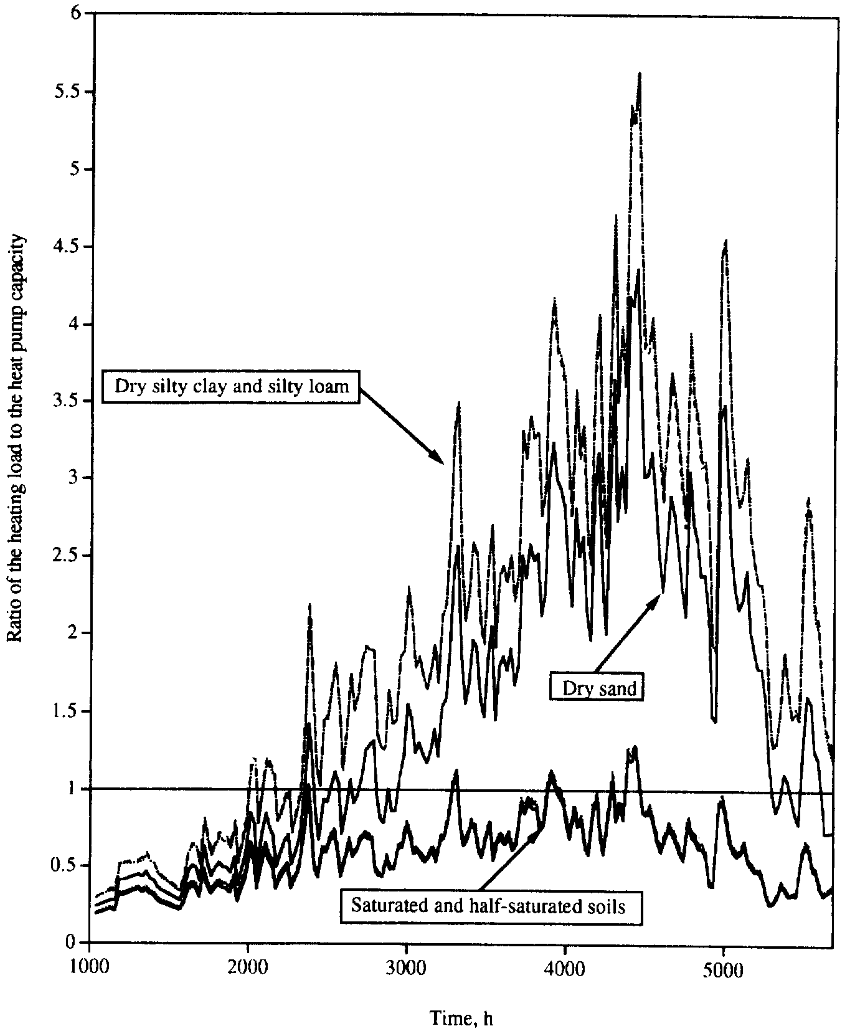

Figure 7 Ratio of heating load to heat pump capacity vs time, for sand, silty loam and silty clay at dry, half- and fully saturated conditions

Figure 7 *Relation entre la charge thermique et le rendement de lma pompe à chaleur en fonction de la durée pour des types de sol différents (sable, glaise limoneuse et argile limoneuse) avec des degrés de saturation différentes (moitié ou complètement saturé)*

observed. This behavior is due to the freezing of soils, as previously described. Half-saturated soils show a very similar change of heat extraction with time to that observed for saturated soils. For the steady state period, the heat extraction for the half-saturated sand is about 2% lower than for the saturated sand. Dry soils experience a much more rapid decrease of heat extraction than moist soils. This is caused by a very low heat capacity of the soil and an absence of the freezing process.

For moist soils at 50 and 100% of saturation, the ratios of heating load demand to heat pump capacity are approximately the same, with only a few days when supplemental heating is required (*Figure 7*), i.e., when the ratio is greater than one. Any decrease of soil moisture content below half saturation leads to an increase in the number of days required for supplemental heating. For example, dry soils exhibit a sharp increase in that ratio up to a value of about 5.5. This indicates that dry soils must not be used for ground heat pump applications. Furthermore, soil moisture content is indeed one of the most controlling factors influencing ground heat pump performance. Its value should be between full saturation and half saturation.

Moist sand at half and full saturation shows a slightly better heat pump COP than moist silty loam or silty clay (*Figure 8*); the COPs for the last two soils are almost identical. The relative difference in the COP for sand moisture contents corresponding to the saturated and the half-saturated state is about 1.5%. Further decrease of soil moisture content (i.e. $0.25\theta_{sat}$ and $0.125\theta_{sat}$) results in more significant drops in the COP. For dry sand a sharp decline of the heat pump COP is observed; it drops as much as 35% with respect to the COP for saturated sand. Dry silty loam and silty clay show a much lower COP with respect to dry sand. The more valuable results

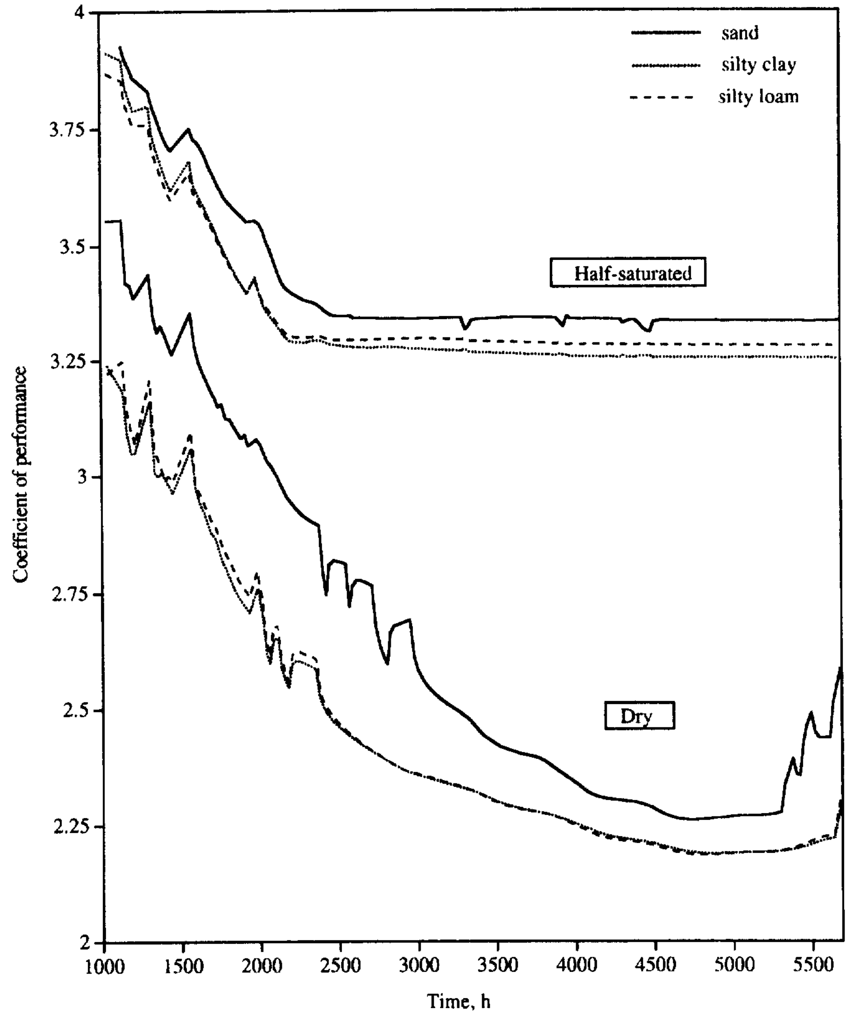

Figure 8 Variation of the coefficient of performance vs time, for dry and half-saturated soils

of sand are due to its much higher quartz content and its superior thermal conductivity even in the completely dry state. These results prove again that dry soils must not be used for ground heat pump applications as their use leads to a sharp decrease and low values of the COP.

Almost steady values of brine temperature, heat extraction rate and COP for all soils at half and full saturation were observed (*Figures 5*, *6* and *8*) in the last two-thirds of the heating season from 2616 to 5688 h. Therefore, the average values of the above quantities over that duration were compared against the five different degrees of soil saturation. *Figure 9* displays the variation of the average heat extraction rate from the ground vs soil degree of saturation. A very sharp increase of the heat extraction rate was obtained for all soils between 0 and 12.5% of saturation, followed by a moderate increase between 12.5 and 25% of saturation. The heat extraction rate between 50 and 100% of saturation shows much better results and a relatively small variation. In all cases sand shows the best performance, followed by silty loam and silty clay. The variation of the average COP vs the degree of soil saturation (*Figure 10*) shows a very similar trend.

The average brine temperature at the exit of the GHE also rises with an increase of the degree of saturation (*Figure 11*). The highest brine return temperatures are obtained for sand at all degrees of saturation, which can be explained in terms of the largest amount of heat extracted by the ground heat exchanger.

For all soils under investigation, the average heat extraction, the COP and the brine temperatures are similar at fully saturated soil conditions. These results may imply that at fully saturated conditions these soils are equally suitable for ground heat pump applications. It is worth knowing, however, that the use of silty loam and silty clay is limited due to their high sensitivity to frost heave.

Conclusions

(1) The performance of a ground heat pump system was found to depend strongly on the moisture content

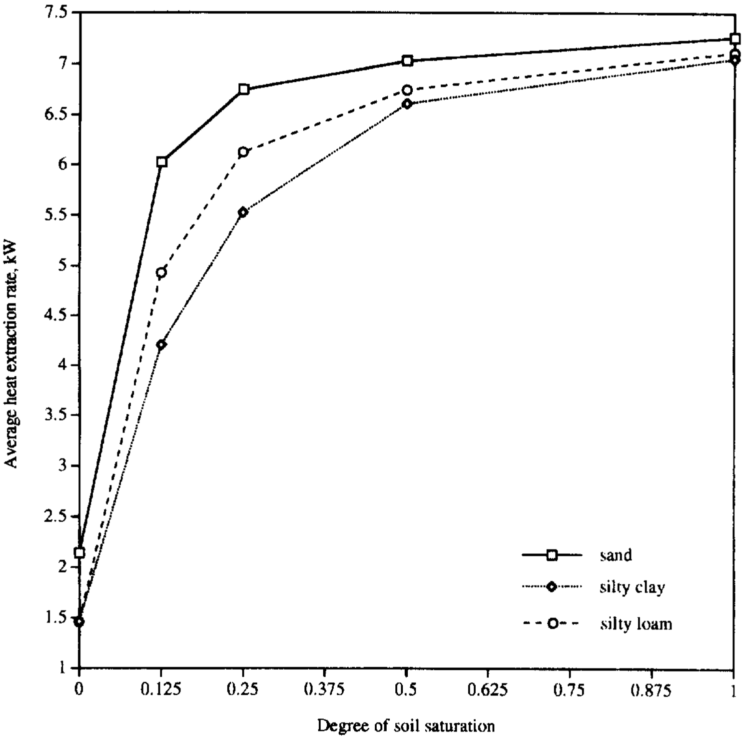

Figure 9 Variation of the average heat extraction rate (2616–5688 h) from the ground vs soil degree of saturation

Figure 9 *Variation de l'extraction de chaleur moyenne (2616–5688 h) du sol en fonction du degré de saturation du sol*

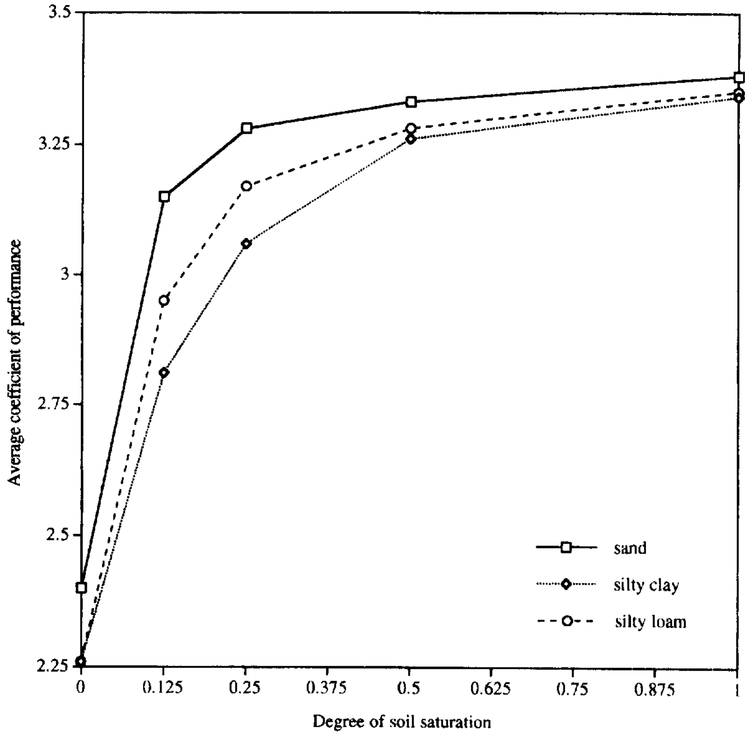

Figure 10 Variation of the average COP (2616–5688 h) vs soil degree of saturation

Figure 10 *Variation du COP moyen (2616–5688 h) en fonction de la saturation du sol*

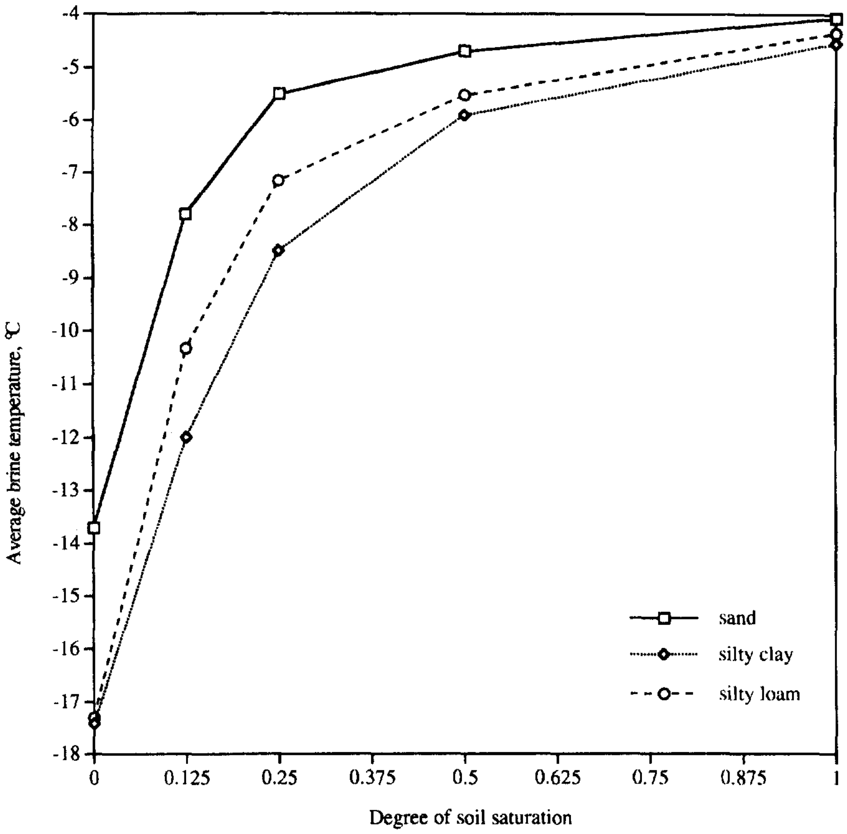

Figure 11 Variation of the average brine temperature (2616–5688 h) at the GHE inlet vs soil degree of saturation

Figure 11 *Variation de la température moyenne de la saumure (2616–5688 h) à l'entrée de la pompe à chaleur à capteurs enterrés en fonction du degré de saturation du sol*

and the soil type (mineralogical composition). Dry soils show a very sharp decline of the COP—it is lower by up to 35% with respect to saturated conditions. Alteration of soil moisture content from 12.5% of saturation to complete dryness strongly decreases the ground heat pump performance, and any reduction of soil moisture within this range has a devastating effect on the COP. Therefore, it is beneficial to keep the soil moisture value as high as possible above dry soil conditions. The best performance of the ground heat pump was obtained for sand at all degrees of saturation, as compared to silty loam and silty clay.

(2) Soil moisture content above 25% of saturation leads to generally better heat pump performance. It was found, however, that the effect of moisture content variation above the half-saturated state on ground heat pump performance is relatively insignificant. The difference in the COP for sand moisture contents corresponding to 50 and 100% of saturation is only about 1.5%.

(3) The freezing process of saturated soils releases such a large amount of latent heat that, for the heat pump system considered, it was not fully completed during the heating season. The freezing of soil around the ground heat exchanger produces almost constant values of the brine temperature, heat extraction, and the COP.

(4) The amount of heat extracted from the ground is highest for sand, followed by silty loam and silty clay which both exhibit very similar results. As the saturation approaches 100%, however, the amount of heat extracted from different soils is approximately the same.

(5) For saturated and half-saturated soils, the ratio of the heating load to the heat pump capacity is below unity for nearly all of the heating season. Therefore there is almost no need for supplemental heating. Reduction of the soil moisture content from half saturation to dryness leads to an increasing demand for supplemental heating.

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