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A Coupled Analysis of Heat and Moisture Transfer in Soils

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Abstract: The efficiency of energy piles depends on their dimensions and the heat and moisture transfer characteristics of soils and pile materials. Conductive heat transfer in soil deposits is based on the solution of the Fourier equation with relevant initial and boundary conditions. The equation contains two parameters representing the thermal properties of material: the coefficient of thermal conductivity and the volumetric heat capacity. In this paper, the results of an experimental study are presented first. Tests were conducted earlier to determine the heat and moisture transfer characteristics of a silty soil from the Mackenzie River Valley. COMSOL is used to simulate the heat and moisture transfer in two soil columns and the computational and experimental results are compared. Subsequently, the finite element analysis is extended to the analysis of an energy pile.

Keywords: coupled analysis, heat and moisture transfer, silty soil, energy pile.

1. Introduction

Due to the growing global energy demand, depleting natural resources and the adverse effects of greenhouse gas emissions from oil/gas consumption, there is a rapidly developing trend around the world to explore alternative energy sources. The geothermal energy is an alternative resource for the 21st century. For example, geothermal energy can be used for heating and cooling buildings by using their foundations (e.g. piles, footings). Although, Energy Piles (EP) are a relatively new innovative renewable energy technology (Brandl, 1998), they are gaining popularity with an annual increase of 10% in applications around the world in the past 10 years (Curtis et al., 2005). In this new technology, the foundation piles serve not only as load bearing structures but also as energy exchangers. The piles contain circulation tubes and act as heat exchangers as thermal energy from the superstructure is circulated through the tubes with water or antifreeze. The thermal energy is fed into and withdrawn from the ground for cooling in the summer and heating in the winter, respectively. The fluid circulation can be performed via a heat pump, similar to that used in residential and commercial facilities.

The mechanisms of heat transfer between the EP and the ground are mainly described as follows:

1) Heat conduction within the pile (H1),
2) Heat conduction within the soil (H2), and
3) Heat convection via subsurface flow (H3).

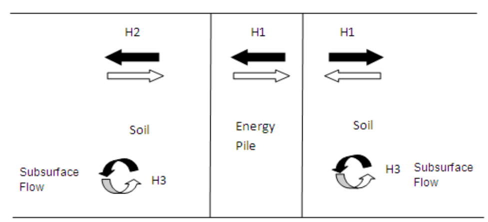

Figure 1. Heat transfer mechanisms between the EP and the ground (from Abdelaziz et al., 2011)

As schematically shown in Fig. 1, heat transfer occurs in two directions reflecting the heat injection into the ground during cooling operations (dark arrows) and heat extraction from the ground during heating operations (white arrows).

The simulation of heat and moisture transfer in geomaterials is important in the analysis and design of energy piles. Conductive heat transfer in soil deposits is based on the solution of the Fourier equation of heat conduction with relevant initial and boundary conditions. The equation (1) contains two parameters representing the thermal properties of material: the coefficient of thermal conductivity and the volumetric heat capacity. The ratio of these two parameters is called the thermal diffusivity (α). The greater the value of thermal diffusivity, the faster the heat transfer.

$$\alpha = \frac{k}{\rho c_p} \qquad (1)$$

where:

k : thermal conductivity (SI units: W/(m·K))
ρ : density (kg/m³)
c_p : specific heat capacity (J/(kg·K))
ρc_p : can be identified as the volumetric heat capacity (J/(m³·K)).

2. Laboratory tests of heat and moisture transfer in silt samples

The moisture content has a strong influence on the thermal properties of soils. The pores of dry soils are filled with air which has low heat conductivity and heat is transferred through the contact areas of soil particles. With an increase in moisture content the rate of heat transfer in the soil is also increased. A laboratory investigation was carried out to explore the physics of heat and moisture transfer in compacted Mackenzie Silt samples (Evgin and Svec, 1988). The coefficients of soil-water diffusivity under isothermal conditions and under temperature gradients were obtained.

3. Numerical analysis of heat and moisture transfer

There are two parts in the numerical study. First, a numerical model is set up to simulate the heat and moisture transfer in the soil column of the experimental investigation using COMSOL. Then a parametric study is carried out to explore the behavior of soil in the hydro-thermal coupling process around the energy piles.

3.1 Part 1 – Simulation of Evgin and Svec's Lab Tests Using COMSOL

3.1.1 Geometry of the specimen in the isothermal tests

The isothermal test is an evaporation experiment. A soil specimen with a rectangular cross section was placed horizontally to allow evaporation from its open end. The changes of density and moisture content along the soil sample were measured as a function of time.

In 2-D numerical analysis, the domain for the soil specimen has a rectangular shape with dimensions of 30 x 2.5 centimeters as shown in Fig. 2. As shown in the figure, one end of the sample was closed and the other end was open to air. Boundary conditions used in the analysis are as follows: no flow condition is imposed on boundaries labeled as AB, BC, and CD. The boundary labeled as AD is open to air. A high negative pressure head is specified at the boundary AD to simulate the effect of evaporation. The initial moisture content in the sample is 0.17 before the beginning of the evaporation test. With the progress of evaporation the water content of the soil at the open end decreases and the suction increases.

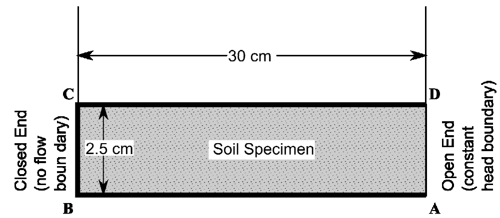

Figure 2. Schematics of solution region for an isothermal test

3.1.2 Parameters used in the numerical model

The parameters for Richards' equation are listed in Table1.

Table 1. Parameters for Richards' Equation

Hydraulic conductivity (m/s)	K_s	5.74e-7
Saturated liquid volume fraction	θ_s	0.174
Residual liquid volume fraction	θ_r	0.031
Shape coefficient for retention	α	0.423
Shape coefficient for retention	η	2.06

The water content profile due to evaporation from the open end has been computed at times: 0, 60, 300, 600, 900, 1800, 3600, 20000, and 36000 seconds.

3.1.3 Numerical results of the moisture distribution due to a pressure gradient

Moisture content distribution along soil specimen at a given time is shown in Figure 3. It can be seen that the moisture content along the soil sample from the open end to the closed end is decreasing. After 6 hours of evaporation, the calculated moisture content is 0.085 at the open end. This number is close to the measured value of 0.08 in Test-5.

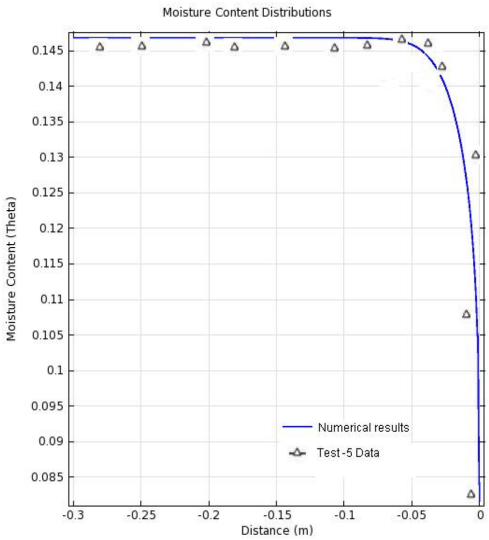

Figure 3. Moisture content distribution along the soil specimen after 6 hours

The initial degree of saturation of the soil is about 0.15. After 6 hours of evaporation, the zones that are affected by drying in the soil sample are shown in Fig. 4. The degree of saturation decreases in the whole domain, however, a large drop in the degree of saturation is observed near the open end. At the open end, the final degree of saturation is 1/5 of the initial value.

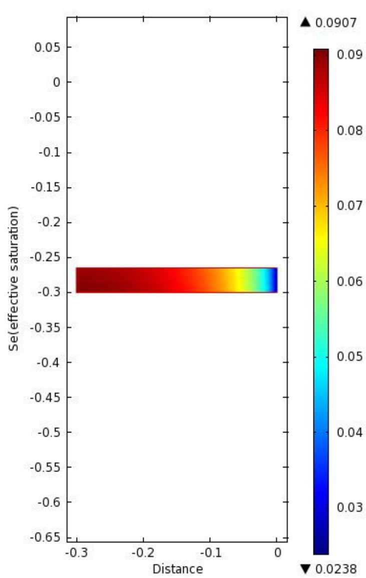

Figure 4. The effect of evaporation on the degree of saturation along the soil sample after 6 hours

3.1.4 Geometry of the thermal gradient test

A temperature gradient test was set up as shown in Fig. 5. In the numerical simulation, the geometry and soil parameters are the same as those of the isothermal test. The temperatures at each end of the soil specimen are 8.2°C and 41.2°C, respectively. The thermal parameters for the heat transfer in porous media model are listed in Table 2.

Table 2. Thermal parameters for heat transfer in porous media model

Fluid density (kg/m^3)`	ρ	1000
Fluid thermal conductivity [W/(m*K)]	k	1.5
Fluid heat capacity at constant pressure[J/(kg*K)]	C_p	3500
Fluid volumetric thermal expansion [1/K]	β	1e-6
Porosity	ε	0.396

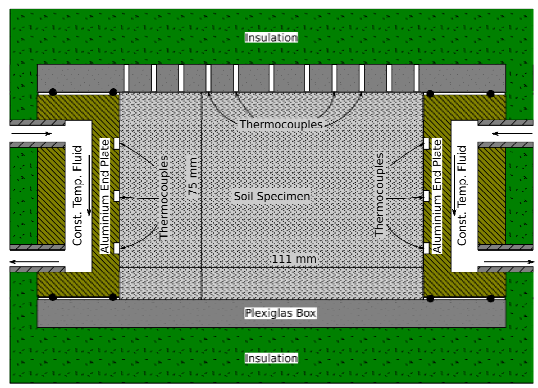

Figure 5. Schematics of the thermal gradient test apparatus

3.1.5 Numerical results of moisture distribution due to a thermal gradient

Moisture contents distribution along the soil specimens increased at the thermal equilibrium as shown in Fig. 6. It can be seen that the moisture content near the high temperature end dropped down from the initial value of 0.17 to 0.06; however, the moisture content at the low temperature end increased to 0.21. The numerical results are close to the experiment data.

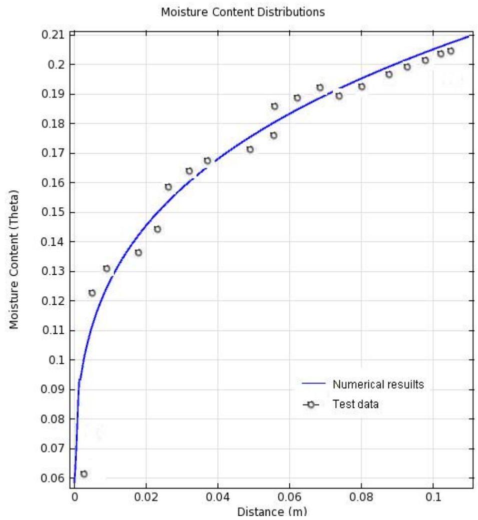

Figure 6. Calculated and measured moisture content distribution at thermal equilibrium along the soil specimen (Test data is from Evgin and Svec, 1988)

The temperature distribution along the soil specimen at different times is shown in Fig. 7. Initially, the temperature distribution in the soil is nonlinear. When the thermal equilibrium is reached, the distribution becomes linear. The trends from the numerical results match the measured temperatures in the soil.

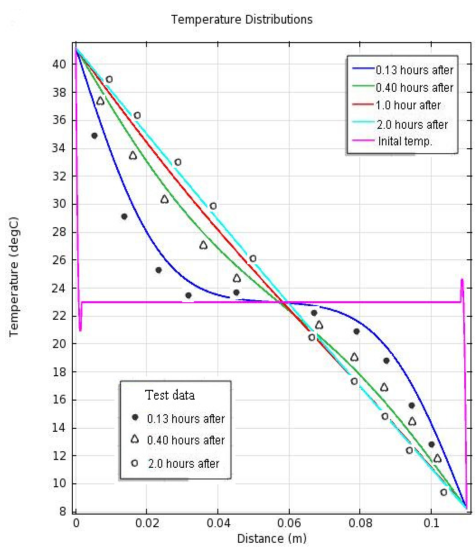

Figure 7. Calculated and measured temperature distributions along the soil specimen (Test data is from Evgin and Svec, 1988)

3.2 Part 2- Numerical analysis of soil behavior during hydro-thermal processes around an energy pile

In order to explore the influence of hydro-thermal coupling (HT) on the behavior of soil around an energy pile, a parametric study has been conducted. The results of this study are presented in this section. The moisture content distribution and temperature distribution in soil under hydro-thermal coupling processes are plotted. The heat transferred in the soil is discussed. The effect of the temperature on the other soil parameters such as permeability, pressure head, and moisture content is explored.

3.2.1 Geometry of an energy pile and analysis domain

In this study, an energy pile with 10 meters length is assumed to be installed in the Mackenzie River Silt deposits. The diameter of the pile is 0.5 meters. For the thermal boundary conditions, it is assumed that the pile is at a constant temperature of 30^{o}C. The soil is 10 ^{o}C at its initial state. The analysis is performed for hydro-thermal coupling conditions. Axi-symmetry is assumed.

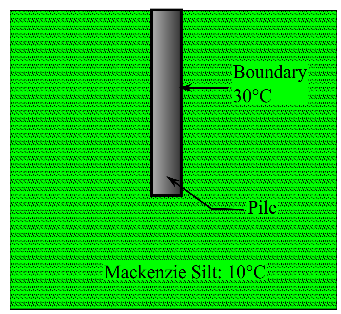

Figure 8. Schematics of solution region for an energy pile

3.2.2 Numerical results

Fig. 9 presents the moisture content distributions in the soil with time. The moisture content of the soil near the energy pile decreased with time. For example, the moisture content is 0.36 after 1 day and 0.31 after 14 days. Meanwhile, the moisture contents increased from the high temperature areas towards the low temperature areas along the soil in the horizontal direction at each time period. It can be seen that a change in the moisture contents takes place within an area of 1.5 meters from the energy pile as shown in the moisture content distribution curve at a time step of 2 days. However, the zone subjected to a change of moisture content reaches a distance of 2.2 meters away from the pile as indicated by the curve at 6 days. In other words, the moisture content is changing as a function of time during the hydro-thermal processes.

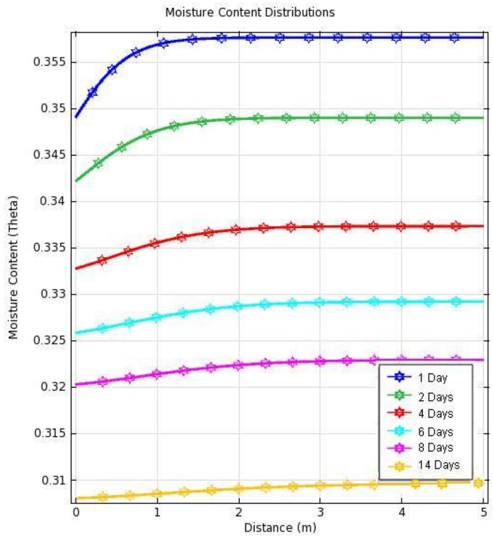

Figure 9. Moisture content distribution along soil under thermal-hydro coupling processes

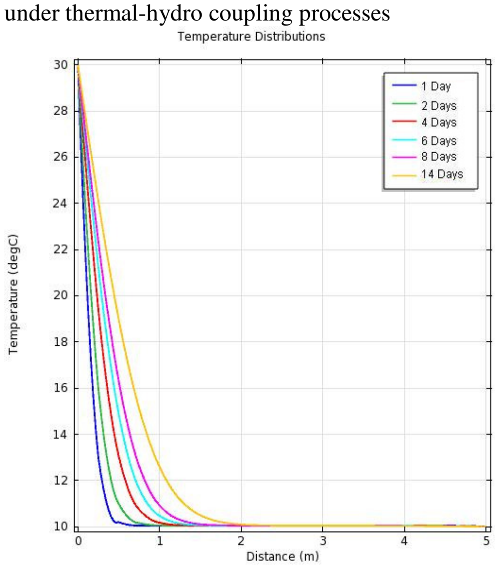

Figure 10. Temperature distributions in soil under hydro-thermal coupling processes

Figure 10 shows the temperature distributions in the soil with time. It can be seen that the temperature in the soil is increasing with time. For example, at a point 1 meter away from the pile, the temperature is 10.5^{o}C after 6 days and 13^{o}C after 14 days.

In order to explore the energy transferred to the soil, total energy fluxes are calculated during the hydro-thermal processes. Figure 11 shows the total energy flux in the horizontal direction with time along the bottom boundary. It can be seen that the energy transferred into the soil mainly takes place within a zone extending 2 meters away from the energy pile during a period of 14 days of heating. The rate of energy transferred into the soil is approximately 0.8 W/m^2/day in this study. Figure 12 shows the distributions of total energy fluxes in the soil after 14 days.

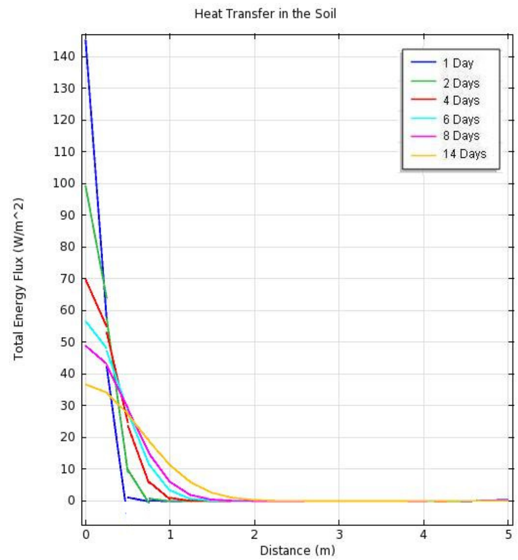

Figure 11. Total energy flux distributions in the horizontal direction with the time along the bottom boundary

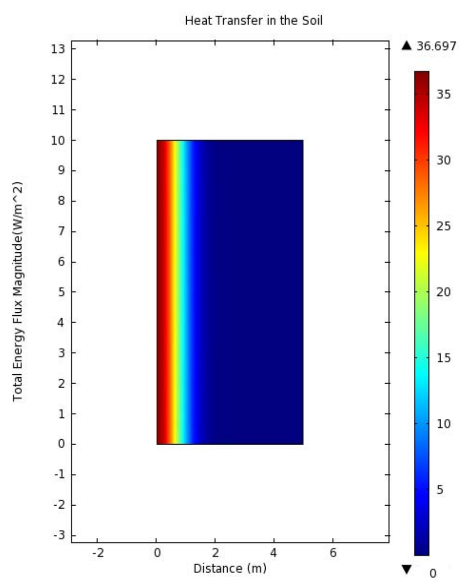

Figure 12. Total energy flux distributions in the soil at 14 days

This study also explores the effect of the temperature on other soil parameters such as permeability (K_s), pressure head (H_0), and moisture content (θ_s) in the numerical modeling of HT processes. In order to achieve the above objectives, four numerical tests are carried out: a permeability test, a pressure head test, a moisture content test and shape coefficient for retention (α) test. Each test has the same parameters except that those parameters are defined as a function of the temperature. These functions are obtained from the literature. In the moisture content test, the θ_s is expressed by the equation: θ_s= -52.47(2 + γ_d)$^{-3}T^{0.85}$ (Wang, and Su, L., 2010 and Zhao et al., 2008). Based on comparisons of numerical results, Table 3 shows the effect of the temperature on these parameters.

The effect of the temperature on the water retention curve is based on the premise that the temperature will have an effect on the surface tension at the air-water boundary. The height of the capillary rise can be expressed as (after Roberson and Crowe 1993):

$$h = \frac{4\,\sigma \cos\theta}{\gamma\, d} \qquad (2)$$

where h is the capillary rise, σ is the surface tension at the water-air boundary, θ is the contact angle, γ is the unit weight of water, and d is the tube diameter. In any given soil, the diameter of the "capillary tube" will be highly varied based on the pore size distribution within the soil mass, but is not expected to change sensibly due to a change of temperature only. The contact angle is dependent on the mineralogy of the solid, as well as the gas and liquid involved. Even for a given solid/liquid/gas combination, however, the specific geometry will be dependent on the toughness of the interface, and whether the angle is on the advancing or retreating from of the water column. Therefore, this parameter will be assumed a constant for the purpose of the current study. Within the range of temperature of liquid water at normal atmospheric pressure of 0°C to 100°C, its unit weight varies from 9.8087 kN/m^3 to 9.4017 kN/m^3 (a variation of about 4%) (CRC handbook of chemistry and physics, 2011) while the surface tension varies from 75.6 dyne/cm to 58.9 dyne/cm (a variation of about 22%). Both the density of water and the surface tension of the water-air boundary are widely published values and interpolation functions can readily be established from published data.

The van Genuchten water retention curve can be expressed as:

$$\frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} = \frac{1}{\left[1 + (\alpha h)^n\right]^{(1-1/n)}} \qquad (3)$$

where h is the pressure head, α is a fitting parameter corresponding to the air entry value, measured as a head of water, n is a fitting parameter corresponding to the steepness of the curve, θ is the volumetric water content of the soil, θ_s is the volumetric water content of the soil when saturated, and θ_r is the residual volumetric water content of the soil at high suction values. Since the shape of water retention curve, the residual water content, and saturated water content are dependent on the void ratio and the pore size distribution, only the parameter α is assumed to be affected by the variation of temperature. Since α corresponds to a pressure head, it can be equated to a capillary rise as a function of temperature in the following manner:

$$\alpha_T = K \times \frac{\sigma(T)}{\gamma(T)} \qquad (4)$$

where the value K is a fitting parameter representing the non directly measurable contributions of the grain-size distribution to the parameter α while $\sigma(T)$ and $\gamma(T)$ are the temperature, T, dependent surface tension and unit weight respectively. The value of K can be computed from the back-calculated value of α, at the temperature at which the evaporation experiment was conducted.

Table 3. Effect of the temperature on other parameters

Parameter	Temperature Effect	
	Yes	No
Permeability (K_s)	x	--
Pressure head (H_0)	--	x
Moisture content(θ_s)	x	--
shape coefficient for retention (α)	x	--

4. Conclusions

1) The computed values of the moisture content and temperature distributions in the soil are reasonably close to the experimental data. This comparison validates the procedures used in this study.
2) The coupled hydro-thermal analysis shows that the moisture content has a strong influence on the behavior of soil around an energy pile.
3) Numerical analysis provides the rate of the energy transferred into the soil from an energy pile. This rate can be used to estimate the efficiency of an energy pile.
4) The temperature has an important effect on most other soil parameters such as permeability and moisture content in HT processes as shown in the numerical analysis.

5. Acknowledgements

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6. References

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