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Role of considering non-constant soil thermal parameters in the simulation of geothermal heat storage systems in the vadose zone

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ABSTRACT: This study focuses on understanding the role of thermal properties of soils (thermal conductivity and specific heat capacity) in the performance of geothermal heat exchanger arrays used to store heat in the vadose zone. Although the impacts of degree of saturation and temperature on the apparent thermal conductivity of soils has been widely studied, the same is not true for the volumetric heat capacity of soils. To investigate the role of the heat capacity, a three-dimensional (3D), transient finite element model was built in COMSOL to consider the representative field conditions as well as coupled heat transfer and water flow processes in the unsaturated soil within a soil-borehole thermal energy storage (SBTES) system. The numerical analyses were performed considering two cases: using constant thermal properties and using thermal properties that vary with changing degree of saturation. Two models were considered to predict volumetric heat capacity of different soils with changing degree of saturation and were compared with laboratory measurements. Results indicate that using constant thermal properties leads a difference in temperature distribution in the heat exchanger arrays. The proposed prediction equation in this study for volumetric heat capacity was more successful than the common prediction equation.

Keywords: SBTES systems, Thermal properties, Numerical analysis

1 INTRODUCTION

Soil-Borehole Thermal Energy Storage (SBTES) systems are used to store heat collected from renewable sources so that it can be used later for heating of buildings (Sibbitt et al. 2012; Zhang et al. 2012, Başer & McCartney 2015). They function in a similar way to conventional geothermal heat exchange (GHE) systems, where heat is transferred from a source to a sink via circulation of fluid through a series of closed-loop heat exchangers. However, they differ from GHE systems in that the heat is injected or extracted continuously over the course of a season into the borehole heat exchanger array. Further, the borehole array in a SBTES system is overlain by a hydraulic barrier to retain pore water within the subsurface and a thermal insulation layer to minimize heat losses to the atmosphere (Başer et al. 2015, 2016).

The more the SBTES systems become popular, the greater effort has been given to determine the thermal properties of soils to model the heat storage and transfer through soils. Because the heat transfer and storage in a soil is governed by its thermal characteristics, thermal properties are necessary for modeling the heat transfer in soils (Abu-Hamdeh 2003).

The main goal of this paper is to understand the impact of the specific heat capacity on spatial temperature distributions in heat exchanger arrays installed in different types of soils in unsaturated conditions, considering coupled heat flow and thermally induced water flow. Thus numerical analysis were performed on unsaturated soils to present the importance of the thermal properties in heat transfer modeling in heat exchanger arrays. The second phase of study focused on the prediction of volumetric heat capacity of different soils with volumetric water content. Some prediction equations were used and the results were compared with the laboratory measurements.

2 BACKGROUND

Several field and numerical studies have established that SBTES are proven to be efficient at storing heat in the subsurface (Sibbitt et al. 2012, Zhang et al. 2012, Başer et al. 2015). However, a better understanding of the heat transfer processes in these systems is required as the heat transfer and the heat storage in the SBTES arrays are governed by the thermal properties; thermal conductivity and the specific heat capacity. It has been proven by various researchers that thermal properties of soils change with degree of saturation (Duarte et al. 2006, Smits et al 2012).

A recent study by Lu and Dong (2015) evaluated a new equation based on the soil-water retention curve (SWRC) that can consider the impact of changes in degree of saturation on the thermal conductivity. Although other thermal conductivity models have been developed in the past, this new equation employs the parameters from the widely-used van Genuchten (1980) SWRC model. Although they focused on the thermal conductivity, they also found that the specific heat capacity varied with degree of saturation. They evaluated several soils and found a good match between their predictive model and the measured thermal conductivity values as a function of the degree of saturation.

The volumetric heat capacity (C or VHC) describes the amount of heat (thermal energy) required to increase the temperature of a certain volume of material by 1°C, but without undergoing a phase transition. In this sense, it can be used to reflect the heat storage in a volume of material at a certain temperature. It is different from the specific heat capacity (C_p) in that the VHC is a ’per unit volume’ measure of the relationship between thermal energy and temperature of a material, while the specific heat is a ‘per unit mass; measure. VHC can converted to specific heat capacity by multiplying it by the total density of the soil (ρ). The total heat (Q) content of a system possessing the volumetric heat capacity, and being at an absolute temperature (T), is expressed by as follows:

$$Q = \int C dT \tag{1}$$

Once the heat is transferred into the ground, the ability of the soil to retain heat under the typical subsurface boundary conditions is dependent on both its heat capacity and thermal conductivity. A conceptual evaluation of heat storage in soils is given in Figure 1. From point *a* to *b* is the heating period corresponding to heat energy being absorbed in the soil at the point being monitored. The time for the heating period is denoted ΔT1. The time period ΔT2 corresponds to the period where external heat is no longer being put in the ground but energy is still being received from point *d* to *e* at the same depth. The thermal storage capacity of the soil is then can be defined by the area under the curve. During ΔT3 the dissipation stage of the heat happening. From a practical point of view, the ideal soil for use in thermal storage applications will have a small ΔT1 and a large ΔT2.

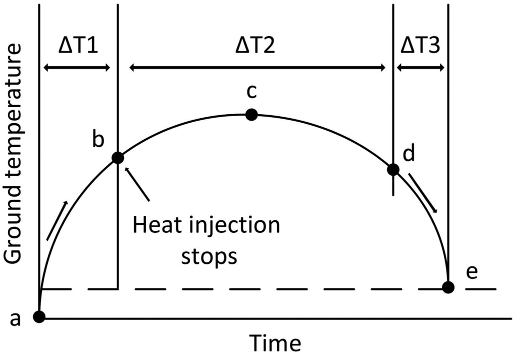


Figure 1. Conceptual heat storage capacity of soils (Adapted from Fang and Chaney 1983).

3 NUMERICAL MODEL

3.1 *Model formulation*

A transient three-dimensional finite element model was built in COMSOL to predict temperature distributions inside and outside of the thermal heat exchanger arrays. The model was developed considering both heat transfer and water flow since when the unsaturated soils is heated water flows due to the decrease in density. The other driving mechanism for water flow is the alteration of surface tension with temperature. Thermally-induced vapor flow is not considered in this study.

Water flow in unsaturated soils, assuming that air pressure in the pores equal to atmospheric pressure, is governed by Richards’ equation. Using this equation, mass balance in unsaturated soils can be expressed as follows (Bear 1972):

$$n\frac{dS_w}{dP_c}\frac{\partial \rho_w P_c}{\partial t} + \nabla \cdot \left(\frac{-\rho_w k_{rw} k_{\text{int}}}{\mu_w} (\nabla P_w + \rho_w g) \right) = -Q_m \tag{2}$$

where n = porosity of the soil; S_w = wetting (water) degree of saturation (dim.); ρ_w = density of water (kg/m^3); μ_w = dynamic viscosity of water (Pa·s); P_c = capillary pressure ($P_c = P_{nw} - P_w$) (kPa); t = time (s); k_{int} = intrinsic permeability of soil (m^2); k_{rw} = relative permeability of water (dim.); g = gravitational acceleration (m^2/s); and Q_m = mass storage (kg/m^3) which is assumed to be zero in this study.

Heat transfer in unsaturated soils is governed by the combination of Fourier’s law for heat conduction and Newton’s law for heat convection. For these two

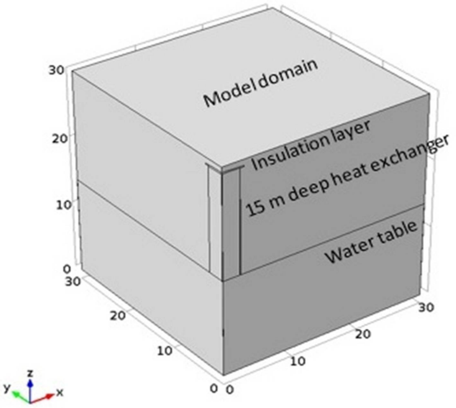


Figure 2. Model geometry.

modes of heat transfer, the governing equation for heat transfer is porous media can be expressed as follows:

$$(\rho C_p)\frac{\partial T}{\partial t} + \nabla \cdot (\rho C_p u_w T) = \nabla \cdot (\lambda \nabla T) + Q \tag{3}$$

where ρ = total density of the soil (kg/m^3); C_p = specific heat capacity of the soil at constant pressure (J/(kgK)); u_w = Darcy velocity; T = absolute temperature (K); λ = apparent thermal conductivity of the soil (W/(mK)); and Q = heat source.

3.2 *Model geometry and boundary conditions*

The model geometry consists of an SBTES array of 15 m-deep vertical borehole geothermal heat exchangers installed in a deep homogeneous soil layer in an array having a width of 30 m and a depth of 30 m. A 0.1 m-thick insulation layer was placed on top of the heat exchangers, which was covered by a layer of site soil. The details of the model geometry is given in Figure 2. Symmetry was used in configuring the model geometry, with one of the geothermal heat exchangers at the corner of the array, and the other two are spaced at a distance of 2.5 m from the center in orthogonal directions.

3.3 *Material properties*

The entire domain is assumed to be a uniform and isotropic soil layer. The properties of Hopi silt were considered for the soil layer. To perform coupled heat transfer and water flow analysis the thermal and hydraulic properties are needed. These properties differ for the different type of soils as they are dependent on the grain size, pore size distribution, and degree of saturation of the soil. Dong et al. (2014) used a transient water release and imbibition method (TRIM) which was modified to include measurement of the thermal conductivity function (TCF) and volumetric heat capacity function (VHCF) in conjunction with concurrent measurement of the soil water retention curve (SWRC) and hydraulic conductivity function (HCF). The modified TRIM test works in a way that two pairs of dielectric and thermal needle sensors embedded in the soil specimen monitor continuously spatial and temporal variation of degree of saturation, thermal conductivity, thermal diffusivity, and volumetric heat capacity during drying and wetting processes. For SWRC van Genuchten (1980) fitting model was used. The soil hydraulic and thermal properties are given in Figures (3a) to 3(b). The saturated hydraulic conductivity of Hopi silt is 5.3×10^{-7} (m/s).

Lu and Dong (2015) proposed a closed form equation for the thermal conductivity function (TCF) based on soil water retention regimes to predict the thermal conductivity. This equation allows prediction of thermal conductivity as a function of degree of saturation incorporating van Genuchten (1980) parameters. TCF is expressed as follows:

$$\frac{\lambda - \lambda_{\mathrm{dry}}}{\lambda_{\mathrm{sat}} - \lambda_{\mathrm{dry}}} = 1 - \left[1 + \left(\frac{S}{S_{\mathrm{f}}}\right)^m\right]^{1/m-1} \tag{4}$$

where λ_{dry} and λ_{sat} are the dry and saturated thermal conductivities, respectively, S is the actual degree of saturation, S_f is the degree of saturation at which the funicular regime is onset, m = defined as the pore fluid network connectivity parameter for thermal conductivity that also could be related to the pore-size parameter n in the van Genuchten (1980) SWRC model. Volumetric heat capacity can be assumed to varying a similar way with the degree of saturation as the thermal conductivity. In this case, the saturated and dry thermal conductivities can be replaced with the volumetric heat capacities for soil in saturated and dry conditions. Accordingly, the Lu and Dong (2015) TCF can be converted to a VHCF:

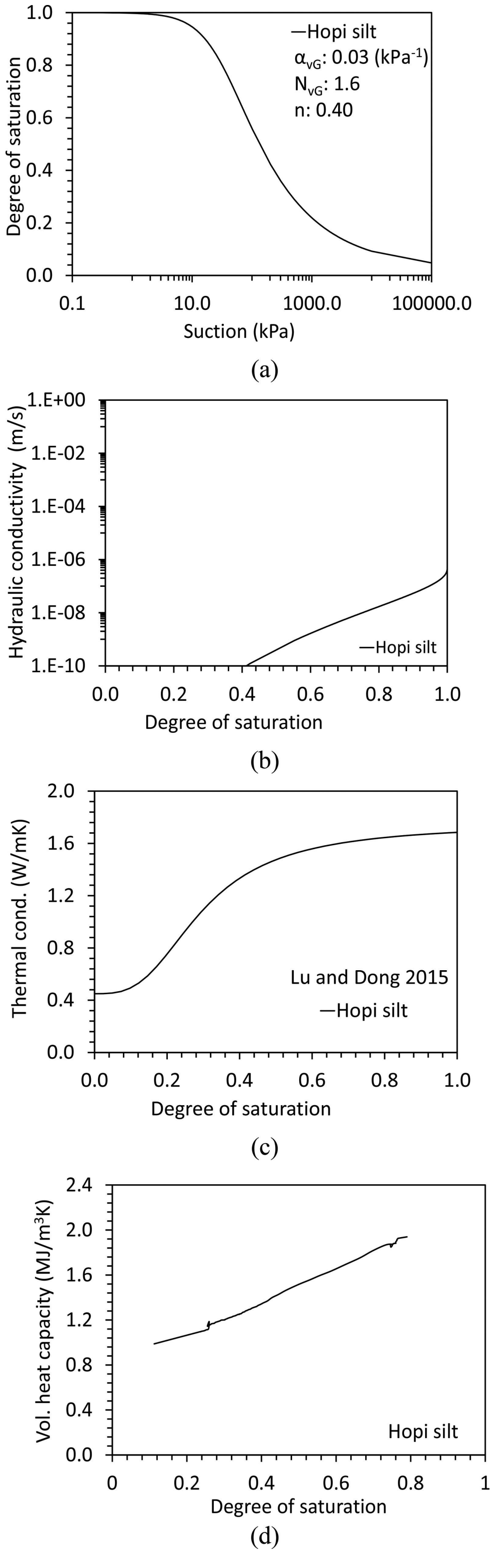
$$\frac{C_p - C_{p\,\mathrm{dry}}}{C_{p\,\mathrm{sat}} - C_{p\,\mathrm{dry}}} = 1 - \left[1 + \left(\frac{S}{S_{\mathrm{f}}}\right)^m\right]^{1/m-1} \tag{5}$$

There are another prediction methods exist in the literature. One of the most common prediction method for volumetric heat capacity is expressed by the following equation (Abu-Hamdeh 2003):

$$C_v = \rho_d \left(c_s + Snc_w\right) \tag{6}$$

where ρ_d = the dry density of the soil, n = porosity, and c_s and c_w are the specific heats in J/kg/^{o}C of dry soil particles and soil water. Usually, the contribution of air can be neglected because of negligible mass of gaseous phase. Volumetric heat capacity of Hopi silt was predicted both VCHF and Abu-Hamdeh (2003) and the results were compared with the laboratory measurements in Figure 4.

Although the fit is not perfect, the newly proposed VHCF provides a better prediction of the VHC better than Abu-Hamdeh (2003) equation. Overall Abu-Hamdeh (2003) equation gives a relationship between



(a)

(b)

(c)

(d)

Figure 3. Hydraulic and thermal properties of Hopi silt used in the analyses (a) SWRC; (b) HCF; (c) TCF; (d) C_v vs degree of saturation.

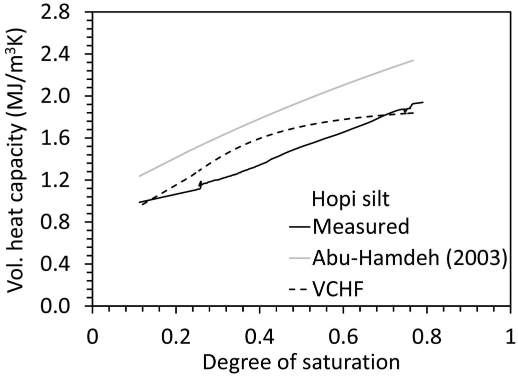


Figure 4. Comparison of predicted and measured heat capacities.

degree of saturation and VHC. It is not always the case, in fact, thermal properties are proven to follow the trend of the water retention regimes (Lu and Dong 2015).

3.4 *Initial and boundary conditions*

For heat transfer, a constant heat flux of 30 W/m was applied at the borehole boundaries for a period of 90 days. A sinusoidal temperature function was applied at the top assuming that maximum and minimum daily air temperatures are 25°C and 10°C. The bottom temperature was fixed to 12°C because of the groundwater. For water flow, zero flux was assumed for all boundaries except the bottom boundary, where a constant total head of 14 m was applied.

The initial temperature of the domain was assumed to be uniform and equal to 12°C. This is equal to the mean annual air temperature in San Diego, CA, and represents the transition profile between the hot and cold seasons of the year. The water table was assumed to be at a depth of 16 m, coinciding with the bottom of the heat exchangers. The initial conditions for the profiles of degree of saturation and suction with depth correspond to hydrostatic conditions.

After the implementation of the initial and boundary conditions, the system of partial differential equations (1) and (2) in three-dimensional domain was simultaneously solved using the COMSOL Multiphysics software to understand the effect of non-constant thermal properties on the heat transfer in unsaturated soils. The simulated domain has a volume about 10 times that of the heat exchanger domain in order to minimize boundary effects. Also initial simulations verified that there was no boundary effects.

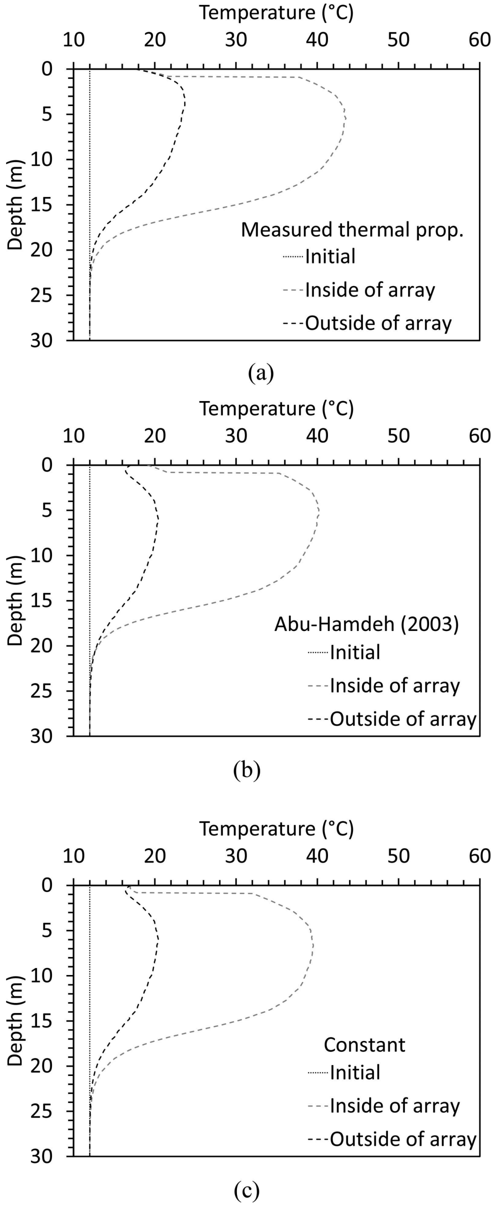
4 ANALYSIS

In heat transfer modeling efforts specific capacity is one of the governing parameters. In most of the heat transfer modeling studies it is assumed to be a constant parameter. This assumption is valid when the soil is either nearly dry or saturated. On the other hand when the soil in the heat exchanger array is unsaturated thermal properties change with depth due to the degree of saturation. To understand the effect of specific heat capacity spatial and temporal distributions of the temperatures inside (x = y = 1.25 m) and outside (x = y = 3.75 m) of the heat exchanger array were determined considering three cases. First simulation was run considering the actual laboratory measurements while the second case considered the Abu-Hamdeh (2003) prediction values. Lastly, in the third case analysis was performed assuming that soil is having a uniform degree of saturation of 0.6 along the heat exchangers and the associated thermal properties with this particular degree of saturation were used in the model. The temperature distributions were plotted in Figures 5(a) to 5(c).

It was observed that although not significant, there are differences in the temperature distributions in the soil after 90 days of heating period when the actual values and the predictions from the model of Abu-Hamdeh (2003) were compared. The maximum temperature in the array was observed to be 44°C when the actual thermal properties were used while this value was 40°C in the case of the model of Abu-Hamdeh (2003). This is because the model of Abu-Hamdeh (2003) over-predicting the VHC led to a decrease in the temperature inside and outside of the heat exchanger array. On the other hand in the case of constant thermal properties there was only 1°C difference between the model of Abu-Hamdeh (2003) and the constant parameters in the maximum temperatures of inside and outside of the array. The reason might be the selecting the constant thermal parameters associated with the degree of saturation of 0.6. Although not given, because the newly proposed VHCF predicted the measured volumetric heat capacity better than the Abu-Hamdeh (2003) model, the temperature distribution in the array was quite similar. These results concluded that the usage of representative thermal properties will result in proper heat transfer modeling.

5 CONCLUSIONS

The effect of non-constant thermal properties on volumetric heat capacity in heat transfer modeling and the prediction approaches of volumetric heat capacity were investigated in this study. A 3D transient finite element model was built to understand the effect of specific heat capacity in unsaturated soil profiles. A particular soil properties those of Hopi silt was used in the coupled heat transfer and water transfer numerical modeling. Two prediction equations for volumetric heat capacity were investigated and compared with the actual laboratory measurements. These predictions then were employed in the numerical model. Initial numerical results concluded that using constant thermal properties in heat transfer modeling in the vertical heat exchanger arrays may result in different temperature distribution than the actual when the SBTES systems are designed. The temperature distributions in the SBTES array using the newly proposed VHCF were in good agreement than the results obtained using the common prediction equation.



(a)

(b)

(c)

Figure 5. Temperature profiles inside (x, y = 1.25 m) and outside (x, y = 3.75 m) of the array (a) using the newly-proposed VHCF; (b) with Abu-Hamdeh (2003); (c) Constant thermal properties.

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