Shallow Horizontal GCHP Effectiveness

in Arid Climate Soils

by

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ABSTRACT

Ground coupled heat pumps (GCHPs) have been used successfully in many environments to improve the heating and cooling efficiency of both small and large scale buildings. In arid climate regions, such as the Phoenix, Arizona metropolitan area, where the air conditioning load is dominated by cooling in the summer, GCHPs are difficult to install and operate. This is because the nature of soils in arid climate regions, in that they are both dry and hot, renders them particularly ineffective at dissipating heat.

The first part of this thesis addresses applying the SVHeat finite element modeling software to create a model of a GCHP system. Using real-world data from a prototype solar-water heating system coupled with a ground-source heat exchanger installed in Menlo Park, California, a relatively accurate model was created to represent a novel GCHP panel system installed in a shallow vertical trench. A sensitivity analysis was performed to evaluate the accuracy of the calibrated model.

The second part of the thesis involved adapting the calibrated model to represent an approximation of soil conditions in arid climate regions, using a range of thermal properties for dry soils. The effectiveness of the GCHP in the arid climate region model was then evaluated by comparing the thermal flux from the panel into the subsurface profile to that of the prototype GCHP. It was shown that soils in arid climate regions are particularly inefficient at heat dissipation, but that it is highly dependent on the thermal conductivity inputted into the model. This demonstrates the importance of proper site characterization in arid climate regions. Finally, several soil improvement methods were researched to evaluate their potential for use in improving the effectiveness of shallow horizontal GCHP systems in arid climate regions.

ACKNOWLEDGMENTS

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TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

1 INTRODUCTION

Overview of Ground-Coupled Heat Pump Systems

Ground-coupled heat pump (GCHP) systems have received considerable attention in the past during times of petrochemical energy scarcity. In all cases up until now, the interest has waned after the alarm over the price or availability of petrochemical resources has been reduced. At the moment, however, there appears to be a growing and long-term interest in alternative energy resources and conservation. A ground-coupled heat pump is in essence a geothermal energy system that exchanges thermal energy with the earth in order to allow the heat pump system to operate more efficiently. The gained efficiency of the heat pump system comes from the relatively constant free-field earth temperature and depends on the mode in which the pump is working: Heating or cooling. The primary focus of this thesis in on the cooling applications of GCHPs in hot, arid climates, where cooling demand governs the load, and therefore there will be no in-depth discussion or analysis regarding heating applications.

The general functioning of a GCHP cooling system is not much different from a conventional air conditioning (AC) cooling system, aside from the use of the earth instead of air as the heat sink. Heat is collected from the load-side of the cooling system, concentrated, and rejected into the sink medium at a higher temperature. In most cases, and all cases considered in this study, GCHPs are closed-loop systems, in that water or another liquid medium is cycled within the system to transfer the rejected heat from the heat pump to the earth sink. This is accomplished through a piping system buried in the earth, generally in either vertically or horizontally oriented excavations.

Vertical ground-coupled heat pump systems. Vertical ground-coupled heat pump systems are systems in which the piping system is installed vertically in the earth, typically in a drilled borehole. The piping is a simple loop that extends down to the bottom of the borehole in one pipe and returns to the top in another, while the borehole is backfilled with a material that will prevent damage to the pipe and not inhibit (and may facilitate) heat transfer with the earth. Figure 1 shows the configuration of a typical large-scale ground source heat pump system with vertical heat exchange elements.

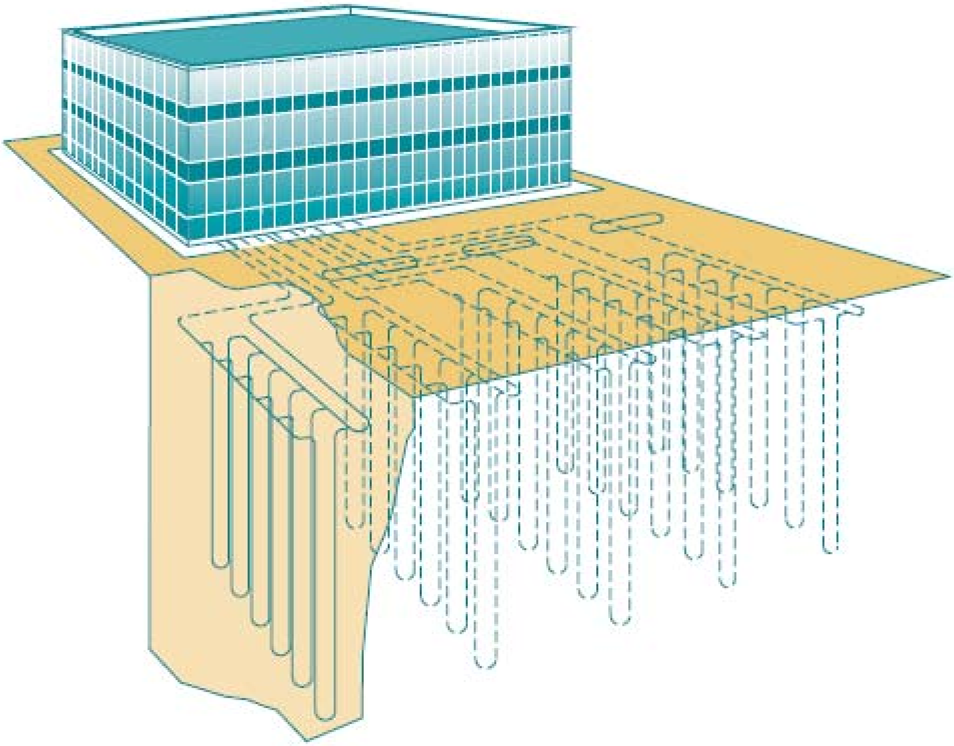


Figure 1. Large-scale vertical GCHP system (NRC, 2005).

The two main advantages of a vertical GCHP system are: 1) a limited footprint for sites where space is at a premium, and 2) the ability to transfer the heat load further down into the earth often resulting in greater efficiencies, due to a minimized effect from surface conditions, such as air temperature and climate, and the ability to extend the heat sink into soils or bedrock with more favorable heat transfer properties. Disadvantages include the relative complexity of the required subsurface characterization compared to that of a horizontal system, high installation costs and the potential for thermal interaction between boreholes if not spaced adequately due to the same space constraints which may have proscribed the use of a vertically-oriented system in the first place.

Horizontal ground-coupled heat pump systems. Horizontal ground-coupled heat pump systems differ from vertical systems in that the piping system is installed horizontally, in near-surface trenches. The piping is often either comprised of parallel horizontal lines or concentric “slinky” loops that are stretched out along a trench, which can be backfilled with soils or an engineered backfill that promotes heat-dissipation. Figure 2 shows the configuration of a typical large-scale ground source heat pump system with shallow horizontal heat exchange elements.

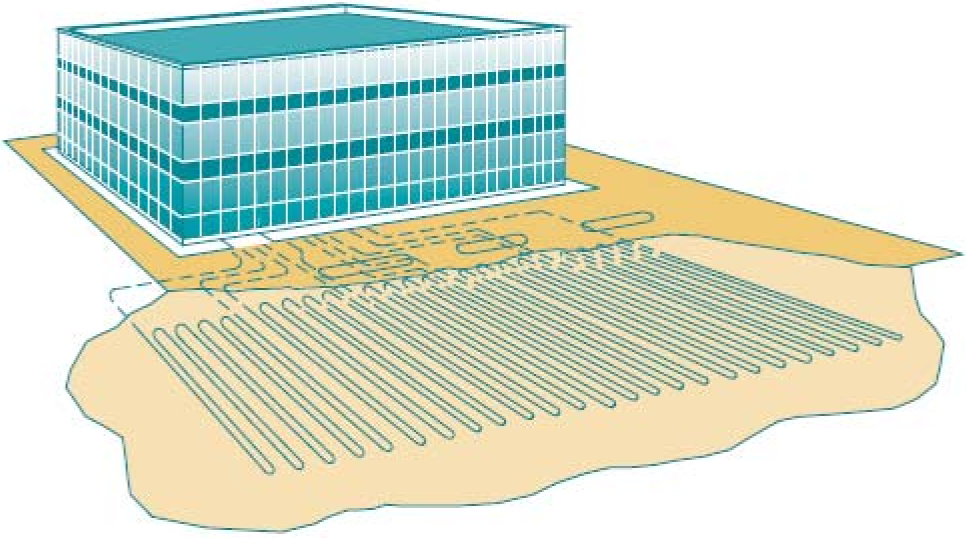


Figure 2. Large-scale horizontal GCHP system (NRC, 2005).

The main advantages of a horizontal GCHP system are the shallow depth of the trenching in which the system is installed, typically allowing for more cost-effective site investigations and faster and less costly construction, which can subsequently allow for more conservative designs when uncertainty exists regarding the ability of the subsurface soils to dissipate heat. Disadvantages include the relatively large installation footprint, and the potential for greater interaction from surface conditions, such as temperature and climate.

Measuring GCHP Efficiency

The efficiency of a heat pump system can be defined by the unit-less Coefficient of Performance (COP), which is defined as the ratio of the thermal output at the condenser to the energy (usually in the form of electricity) input:

$$COP = \frac{Thermal\ Output}{Energy\ Input} \tag{1}$$

The typical COP for an existing conventional air-source heat pump is on the order of about 2, with modern high-efficiency air-source systems exhibiting COPs of up to 4. Typical COPs for GCHPs operating in heating mode range on the order of 3 to 6 (Lund, Sanner, Rybach, Curtis, and Hellström, 2004).

In the cooling mode, the top term of the COP equation is represented by cooling energy output at the condenser. Typically, in the United States, the Seasonal Energy Efficiency Ratio (SEER) is used to rate the efficiency of cooling units. The SEER is the COP of a cooling unit expressed in BTU/W·hr, and is equivalent to approximately 3.41 times the COP. SEER offers a more useful method of quantifying the efficiency of a cooling unit, in that it employs units that are more commonly encountered in the HVAC industry and it evaluates the overall performance for a typical year of operation under seasonal weather conditions. In the United States, new HVAC systems are required to have a minimum SEER of 13. Extremely efficient small air-source air-conditioners have been known to achieve SEERs of more than 25, while specialized installations of GCHP systems in have achieved SEERs of greater than 70. Typically however, GCHPs operating in the cooling mode in environments where the soils are conducive to GCHP operation (ie, soils are saturated, high groundwater table, etc.) have shown SEER improvements on the range of 4% to almost 40%, depending on variables of the system being measured.

As mentioned above, efficiency calculations are performed using the input energy and output energy of the entire system. The study discussed in this thesis was limited to the subsurface components of the GCHP system and more specifically to the efficiency of the surrounding soils in dissipating the heat from the buried pipes. Consequently, without the energy input into the system, COP and SEER calculations could not and were not performed. Instead, the comparative heat dissipation effectiveness of the buried heat exchanger portion of the system subjected to various subsurface conditions was analyzed. Further discussion regarding the assessment and selection of soil properties and boundary conditions and their relative effects on heat dissipation efficiency are discussed later in this text.

GCHPs in Arid Climate Regions

Arid climates such as the Phoenix, Arizona metropolitan area, where soil moisture contents are low and ambient surface temperatures are high, have proven a challenging environment for the operation of GCHPs in the cooling mode. This is an unfortunate circumstance, as the cooling load easily dominates household energy demand during the hot summer months in arid climate regions. The reasons for these challenges are related to the physical properties of dry soils.

The thermal properties of dry soils are unfavorable for dissipating thermal energy for many reasons, all of which stem from the hot, dry environment to which they are exposed. For reasons that will be discussed later in this text, the lack of any moisture in the matrix of the soils as a result of evaporation at the ground surface and coupled heat and moisture flows within the soil matrix caused by high ambient air temperatures results in particularly poor thermal conductivity.

Horizontal GCHP systems may be especially inefficient in these conditions, as the near-surface soils are the most affected by the harsh surface conditions, and furthermore the even higher temperatures resulting from the heat dissipation from the system can further degrade the quality of the surrounding soils. The lack of thermal stability in the soils can lead to desiccation cracking and shrinkage, which can reduce the contact area between the buried pipes and the soils.

Vertical GCHP systems can function better in arid climate regions by either extending deeper beyond the effects of climate, penetrating the groundwater table where thermal conductivity is drastically improved, and/or embedding the lower reaches of the system into dense thermally-conductive bedrock. The use of vertical GCHPs for residential and small-scale commercial systems is almost always precluded however, by the costs of drilling through the dense, cemented soils typically encountered in arid climate regions.

Given these challenges, the development of soil improvement alternatives (for more favorable thermal properties and better stability) and other methods of the improving the effectiveness of shallow horizontal GCHP systems in arid climate regions is deemed necessary for such systems to become economically feasible, and thus gain acceptance, as a method of improving cooling efficiency in such environments. More importantly, the increased efficiency must be significant enough to justify the likely higher initial installation costs when compared to the currently employed conventional air-source heat pump cooling systems.

Thesis Objective and Scope

This research and study is intended to provide a preliminary assessment of the viability of horizontal shallow ground-coupled heat pump systems with stable or enhanced backfill for cooling in arid climate regions, where efficient geothermal cooling could prove most useful, but the soil properties are not favorable to heat dissipation.

The objectives of this thesis are to:

a) apply the SVHeat computer model to represent an installed prototype shallow horizontal GCHP heat exchanger and calibrate the modeled representation by comparing the results to those obtained during a monitored trial run of the prototype system;

b) adapt the calibrated computer modeled prototype GCHP system to an arid climate region by selecting appropriate soil properties and environmental effects to reflect arid climate conditions and compare the effectiveness of the GCHP heat exchanger to dissipate heat in the adapted system to that of the calibrated prototype GCHP system; and

c) employing the adapted arid climate region model, evaluate the effects on the GCHP effectiveness of stabilizing and otherwise enhancing the thermal properties of the backfill around the heat exchanger.

2 MODELING APPROACH AND PARAMETER SELECTION

Heat Transfer in Soils

There exist three primary ways for heat transfer in soil to occur: radiation, convection and conduction. Heat transfer by radiation and convection, both known to be involved in the analysis of heat flow in soils, generally is considered to be small in comparison to that by conduction (Fredlund, Rahardjo, and Fredlund, 2012). Conductive heat transfer deals with the transfer of heat through a material, particularly in this case through direct contact between soil particles or through the pore materials of air or water. For the purposes of this study, only conductive heat transfer will be considered unless otherwise noted.

Thermal properties of soils. Conductive heat transfer in soils is modeled similarly to other flows in soil, such as that of water, in that it is gradient-driven and generally controlled by two soil properties. In the case of water flow, it is modeled according to Darcy's Law, while in the case of thermal conduction, Fourier's Law can be treated as the analogue of Darcy's Law, which are both forms of Fick's Law of Diffusivity. The two soil properties integral to conductive heat transfer are: 1) thermal conductivity, which represents the rate of heat flow through the soil medium, and 2) volumetric heat capacity which represents the capacity of the soil medium to store heat.

Thermal conductivity. Thermal conductivity is represented by the greek letter λ in the differential form of Fourier's law, shown below for the x-direction, but which holds true in all three dimensions. The units used to represent thermal conductivity are in the form of watts per meter kelvin, W/m/K (SI), and British Thermal Units per foot hour degrees Farenheit, BTU/ft/hr/°F (Imperial).

$$q_{hx} = -\lambda \frac{dT}{dx} \tag{2}$$

Where q_{hx} = heat flow in across unit area of soil in the x-direction

$\lambda =$ Soil thermal conductivity

The dependent state variable T, temperature, drives the conductive heat flow. Conductive heat flow can occur through the solid soil particles as well as through pore materials of water or air. Unlike hydraulic conductivity, which can vary over several orders of magnitude, thermal conductivity typically does not vary more than one order of magnitude for all types of solids. In this respect, estimates of soil properties involved in heat flow are often acceptable in most applications. The thermal conductivity of a solid material often varies with temperature. Some average values for various solids and other relatively homogeneous materials are provided in Table 1.

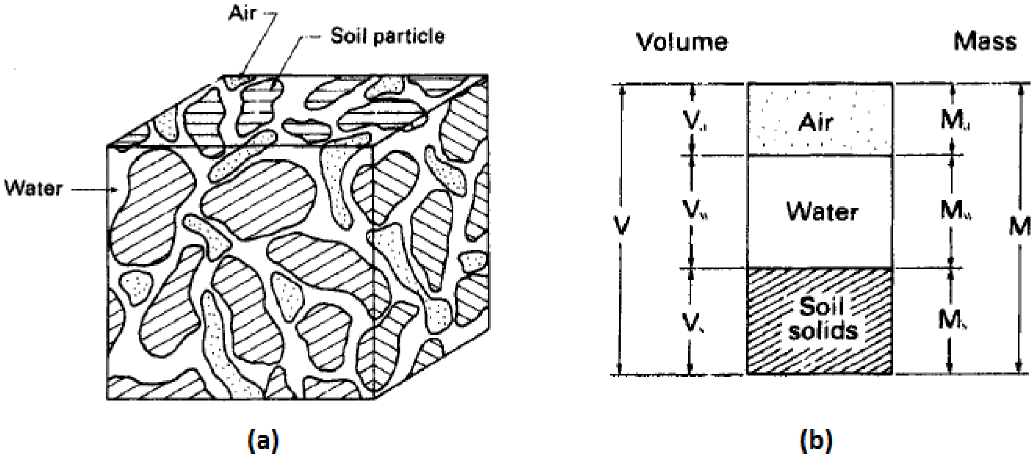
Table 1

Thermal Conductivities of Various Materials

Material or Substance	Thermal Conductivity, λ (W/m/K)
Air (20°C)	0.025
Air (20°C)	0.58
Quartz	8.8
Clay Minerals	2.9

Source: DeVries (1963)

Since soil exists as a multiphase material, and there exists a relatively large difference in thermal conductivity between air and water (0.025 versus 0.58 W/m/K), thermal conductivity can be significantly affected by varying porosity and/or water content of the soil. Among the solid particles of a soil, the thermal conductivity is directly related to the area of contact between the soil particles and the simplified resulting phase diagram of the soil, as shown in Figures 3 (a) and (b). While the thermal conductivity of solid quartz is relatively high at 8.8 W/m/K, the low contact area of the angular particles in a quartz sand result in a significantly lower conductivity (around 0.3 W/m/K for a dry sand). While finer grained materials, such as silts and clays, have greater contact areas than granular soils, the thermal conductivities of their constitutive particles is typically lower and results in lower aggregate thermal conductivities.



Figures 3. (a) Unit soil mass diagram and, (b) simplified soil phase diagram (Fredlund et al., 2012).

While the thermal conductivity of water is relatively low compared to that of the solid materials listed above, it plays a large part in influencing the overall thermal conductivity of a soil. Due to the fluid nature of water and forces such as capillary action and adhesion, water in a soil can exist as a relatively continuous element in a sufficiently saturated soil. In such cases, the water phase of the soil can account for more than 90 percent of the thermal conductivity observed. De Vries (1963) developed an equation to account for the determination of the thermal conductivity of a multi-phase material consisting of solids, water and air.

$$\lambda = \frac{f_p\theta_p\lambda_p+f_w\theta_w\lambda_w+f_a\theta_a\lambda_a}{f_p\theta_p+f_w\theta_w+f_a\theta_a} \tag{3}$$

where $f_p,\ f_a,\ f_w =$ weighing factors solids, air and water, respectively

$\theta_p,\ \theta_a,\ \theta_w =$ percentage of total soil volume comprising solids, air and water,

$\lambda_p,\ \lambda_p,\ \lambda_p =$ respective thermal conductivities of solids, air and water phases,

A summary of thermal conductivities for various soils at listed moisture contents and densities are provided in Table 2.

Table 2

Thermal Conductivities of Various Soils at Varying Moisture Contents

Soil	Source	Thermal Conductivity, λ (W/m/K)	
		Dry	Saturated
Sand	Kavazanjian, 1983	1.04	2.94
	Abu-Hamdeh & Reeder, 2000	0.29	0.76
	Van Wijk, 1963	0.3	2.25
	Wilson, 1990	0.45	2.10
	ASHRAE, 1997 (as cited in McQuay, 2002)	0.87	3.40
Clay / Clay Loam	Kavazanjian, 1983	0.52	1.73
	Abu-Hamdeh & Reeder, 2000	0.36	0.69
	ASHRAE, 1997 (as cited in McQuay, 2002)	0.52	1.90
Silt / Silt Loam	Riha, McInnes, Childs, & Campbell, 1980	0.10	1.00

Heat capacity. Volumetric heat capacity, represented by the greek letter ξ (xi), is the soil property related to the ability of a material to absorb or release heat. As with the thermal conductivity of a soil, the volumetric heat capacity is a function of the constituent materials, porosity and water content. The units used to represent volumetric heat capacity are in the form of joules per cubic meter kelvin, $J/m^3/K$ (SI), and British Thermal Units per cubic foot degrees Farenheit, $BTU/ft^3/°F$ (Imperial). As with thermal conductivity properties, in a multiphase soil consisting of solids, air and water, the volumetric heat capacity can be calculated as the aggregate of the volumetric contents of each phase, as presented below (de Vries, 1963).

$$\xi = \xi_p\theta_p + \xi_w\theta_w + \xi_a\theta_a \tag{4}$$

Where θ_p, θ_a, θ_w = percentage of total soil volume comprising solids, air and water, respectively

Volumetric heat capacities for constituent material and select soils at listed moisture contents and densities are provided in Table 3.

Table 3.

Volumetric Heat Capacity of Various Soils at Varying Moisture Contents

Soil	Source	Volumetric Heat Capacity, $\boldsymbol{\xi}$ (J/m^3/K)	
		Dry	Saturated
Sand	Kavazanjian (1982)	1.47×10^6	2.48×10^6
	Van Wijk & DeVries (1963)	1.26×10^6	2.93×10^6
Clay / Clay Loam	Kavazanjian (1982)	1.34×10^6	2.14×10^6
	Van Wijk & DeVries (1963)	1.26×10^6	2.93×10^6
Peat	Van Wijk & DeVries (1963)	0.51×10^6	3.85×10^6

Determination/estimation of soil thermal properties. As shown above, the assessment of soil properties for heat flow analyses can result in properties that vary significantly for very similar material. This can be due to the fact that the thermal properties of a soil are dependent on many variables, such as density, degree of saturation, void ratio and mineral composition. Another reason for the large variation in results is the various methods, both direct and indirect, of soil thermal properties. As with any laboratory soil testing methods, the results can vary significantly with the skill of the tester and the quality of the testing equipment.

Given the above-mentioned limitations in determining the soil thermal properties, along with the fact that both the thermal conductivity and heat capacity values for various soils do not vary over more than a single order of magnitude, the estimation of soil properties based on previously obtained values and easier to ascertain properties (water content, density, etc.), is generally considered acceptable in most geotechnical engineering problems.

Numerical Modeling

Heat flow in soils, similar to water flow in soils, is modeled by finding the solution to a conservation equation. In the case of water flow, it must meet the laws of conservation of mass, in that the water in must equal the water out, and in the case of heat, or thermal energy, it must similarly meet the law of conservation of energy. To model flow of any kind in and out of a mass of soil it is useful to model the mass as a unitless representative elemental mass (REV). This involves imagining an infinitesimally small element of soil with equal sides where the soil properties are assumed to be homogenous and isotropic. Partial differential equations can then be formulated to model the heat flow through an REV, in one-, two- or three-dimensions. A visual representation of a REV for one-dimensional vertical heat flow is shown in Figure 4.

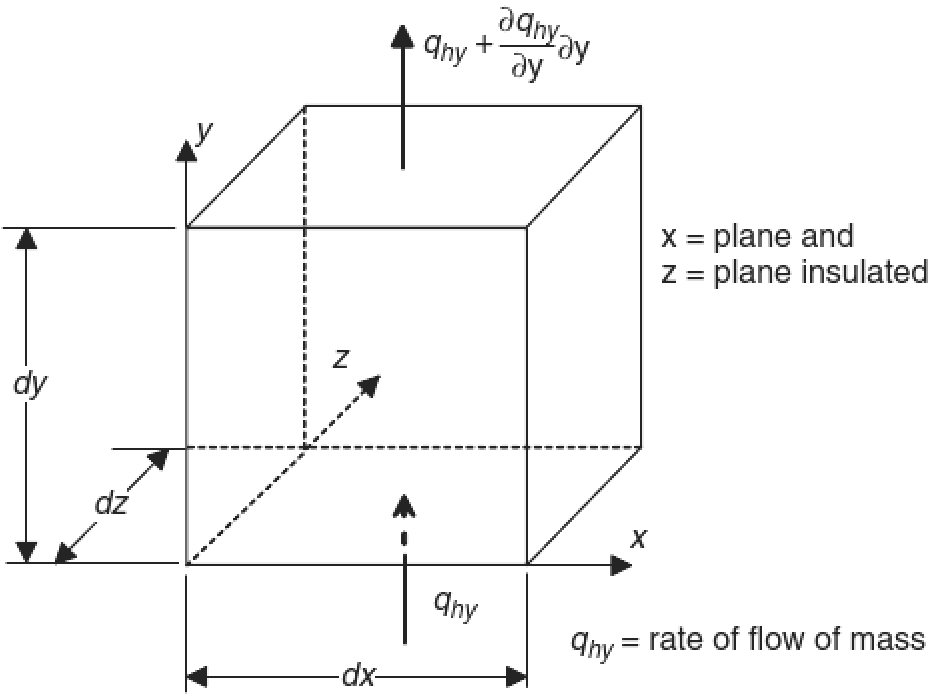


Figure 4. Relative Elemental Volume (REV) for one-dimensional vertical heat flow (Fredlund et al., 2012)

Partial differential equations for heat flow. As mentioned above, heat flow is governed by the law of conservation of energy. In its one-dimensional simplified form, for an unfrozen, normally saturated soil with no groundwater flow, this can be represented by the following equation:

$$\frac{\partial q_{hx}}{\partial x} = \xi \frac{\partial T}{\partial t} \qquad (5)$$

When Fourier's heat flow equation, Eq. 1, is substituted into the above relationship, and the variation in thermal conductivity in the x-direction is taken into consideration, the equation can be written in the following form:

$$\lambda \frac{\partial^{2}{}_{T}}{\partial x^{2}} + \frac{d\lambda}{dx}\frac{dT}{dx} = \xi \frac{\partial T}{\partial t} \tag{6a}$$

$$\lambda \frac{\partial^{2}{}_{T}}{\partial x^{2}} + \frac{d\lambda}{dx}\frac{dT}{dx} + \lambda \frac{\partial^{2}{}_{T}}{\partial y^{2}} + \frac{d\lambda}{dy}\frac{dT}{dy} = \xi \frac{\partial T}{\partial t} \tag{6b}$$

$$\lambda \frac{\partial^{2}{}_{T}}{\partial x^{2}} + \frac{d\lambda}{dx}\frac{dT}{dx} + \lambda \frac{\partial^{2}{}_{T}}{\partial y^{2}} + \frac{d\lambda}{dy}\frac{dT}{dy} + \lambda \frac{\partial^{2}{}_{T}}{\partial z^{2}} + \frac{d\lambda}{dz}\frac{dT}{dz} = \xi \frac{\partial T}{\partial t} \tag{6c}$$

Equations 5a, 5b and 5c are the basic forms of the equations governing all heat flow in unfrozen, normally saturated soil with no groundwater flow, presented in one-, two- and three-dimensions, respectively. The two terms on the left consist of the heat flow due to the thermal conductivity of specific soil mass being examined and the heat flow due to variations in thermal conductivity in the x-direction, respectively. The term on the right side of the equation represents the heat storage of the mass being examined.

Boundary conditions. In general, there are two typically applied boundary conditions for heat flow problems. These boundary conditions can be either temperature or flux dependant, and can either remain constant (steady-state) or change over time (transient).

Temperature dependant boundaries. Temperature dependant, or Neumann-type, boundary conditions are typically used at model boundaries where the temperature is either assumed to be constant or vary according to known or estimated functions. Prime examples of temperature dependant boundary conditions are the below-ground and surface boundaries of a two-dimensional soil model.

Subsurface boundaries. In steady-state and shorter-term transient systems, the bottom of the model is typically assigned a constant temperature value dependant on the assumed ground temperature at that depth. For transient models that span longer periods, recorded average temperature data or a function representing an approximation of how the boundary condition temperature varies with time may be employed.

The following equation for earth temperature as it varies with time, t, and depth, z, has been derived from the partial differential equation for heat flow, eq. 5, assuming a constant thermal conductivity and heat capacity throughout the soil profile (Hillel, 1982).

$$T(z,t) = T_a + A_0 e^{-z/d} \sin\left[\omega(t - t_0) - \frac{z}{d}\right] \tag{7}$$

Where $T_a =$ average annual soil surface temperature,

$A_o =$ annual amplitude of soil surface temperature variation,

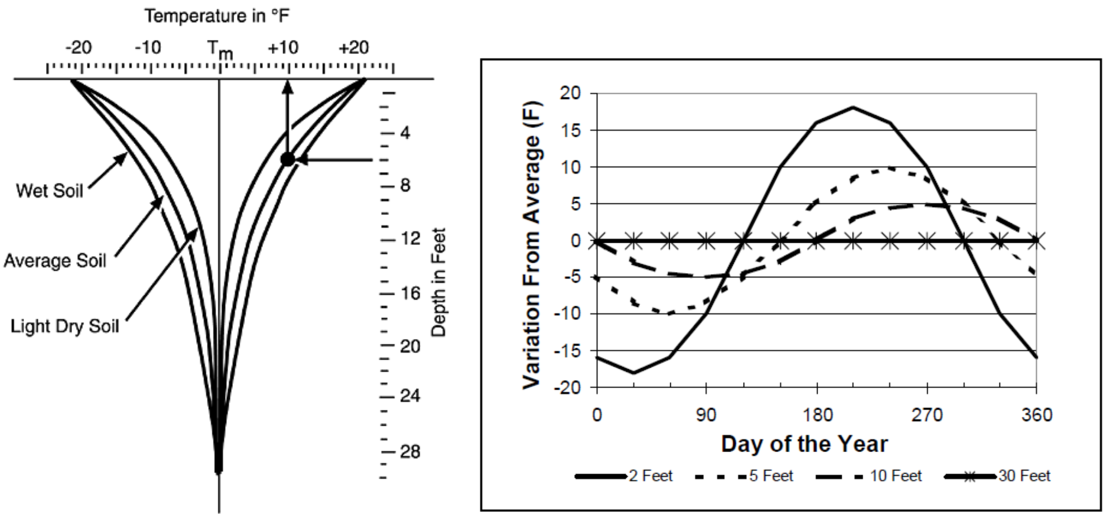
$d =$ damping depth, $= \sqrt{2D_h/\omega}$,

$D_h =$ thermal diffusivity, $D_h = \lambda / \xi$,

$\omega =$ angular frequency of the annual temperature oscillation,

$t_0 =$ initial time taken from start date.

Depth plays the most significant part in the determination of subsurface temperatures relative to ambient air temperatures at the ground surface. Seasonal variations in earth temperature are common near the surface, but these variations tend to decrease with depth, as shown in Figure 5a. Effectively, the near surface soils serve as an insulator, which allows not only for more constant temperatures, but also causes significant lags in the seasonal changes with increasing depth, an example of which is shown in Figure 5b.



(a) (b)

Figure 5 (a) Earth temperature variation with depth, and (b) shallow ground temperature variation with season (McQuay, 2002).

Surface boundaries. While subsurface temperatures are relatively static on a day-to-day basis, surface boundary temperatures are much more transient. Significant temperature changes can take place throughout a single day, due to climate factors such as solar radiation, convection, ambient air temperature, windspeed, and relative humidity. Additionally, surface thermal boundary conditions can be further complicated by including coupled heat and moisture flows representing evaporation at the surface.

The surface boundaries may also be assigned a constant average daily temperature value, which is typically available through local or national soil science databases. In the absence of such data, it may be determined using temperature data acquired at weather stations and if necessary, even further adjusted to represent the difference between air temperature and surface temperature, using equations such as that developed by Wilson (1990):

$$T_s = T_a + \frac{1}{C_f \eta f(u)} (Q_n - AE) \tag{8}$$

Where: T_s = soil temperature (in degrees Celsius)

T_a = air temperature (in degrees Celsius)

C_f = conversion factor

η = psychrometric constant (0.06733 kPa/°C)

$f(u)$ = wind speed function

Q_n = net radiation

AE = actual evaporation

Finite element analysis using SVHeat. SVHeat is a geothermal modeling software program which is a part of the SVOffice analysis suite produced by SoilVision Systems, Inc. of Saskatoon, Saskatchewan, Canada. The software is capable of one- to three-dimensional modeling of geothermal soil systems in both steady-state and transient time conditions.

As described above, the solution to heat flow problems involves the use of relatively complicated partial differential equations (PDE), which would prove very time consuming if solved by hand. Instead, with SVHeat this is accomplished using finite element analysis, which separates the problem geometry into a geometric “mesh” of discrete “finite elements”. Each finite element represents a discrete portion of the problem, for which the solution of the PDE must be solved. Specifically, the SVHeat software is capable of providing automatic mesh generation for the finite element selection, and uses a PDE equation solving software, FlexPDE, to resolve the various finite elements. The problem is then solved as a “continuum” of the finite elements, constrained by the model boundary conditions.

Limitations of the SVHeat soil model. While SVHeat is a powerful piece of software, there are limitations to what can be accomplished with any computer model. These limitations arise from both the capabilities of the software, as well as the ability of the modeler to accurately represent the real-world system upon which the model is based.

For example, some fine-grained soils have a tendency to shrink when dried, which can result in the loss of the thermal connection between the soil and the GCHP piping. The air-filled void surrounding the pipe can then act as an insulator, resulting in discontinuities in the model, which cannot be accurately represented in SVHeat.

3 MODEL CALIBRATION

While the SVHeat modeling software is over 10 years old, and has been applied to numerous heat transfer problems in the past, it is generally used for problems involving frozen soils and geothermal heating applications. While the application of the software in this study is certainly not unique, the use of the software to create models of geothermal cooling applications, and especially those with dry soils, is certainly not common. Prior to performing the analysis of the geothermal cooling system in an arid climate region, calibration of the modeled GCHP heat exchanger using measured data from a real-world application of geothermal cooling was determined to be a prudent practice. Fortunately for this researcher, such measured subsurface temperature data exists from a prototype cooling-load dominated GCHP system installed by his advisor in the past (Kavazanjian, 1982).

Prototype System

The prototype system was installed at a site adjacent to the Stanford University campus in the San Francisco Bay area in California, United States. The prototype system installed was a shallow GCHP system consisting of a relatively unique system called a panel heat exchanger, oriented vertically in a trench, as shown in Figure 6. Hot water from the heat source flows in to a vertical header pipe on one end of the panel, enters numerous parallel thin-walled pipes mounted horizontally on top of, across the another vertical header where the cooled fluid is returned to the heat source for another cycle. At the time of the test, the hybrid panel heat exchanger system was being evaluated as a novel new technology for GCHP installations. Since the time of the original prototype installation and testing, such systems have not been adopted for general use, in favor of classic vertical borehole and horizontal piping systems. In spite of this, the data obtained remains useful and the underlying principles and physics remain the same. In fact, the panel system also allows for simpler modeling; as the system can be modeled in two dimensions with symmetry along the centerline of the panel meaning that only half the soil mass must be modeled.

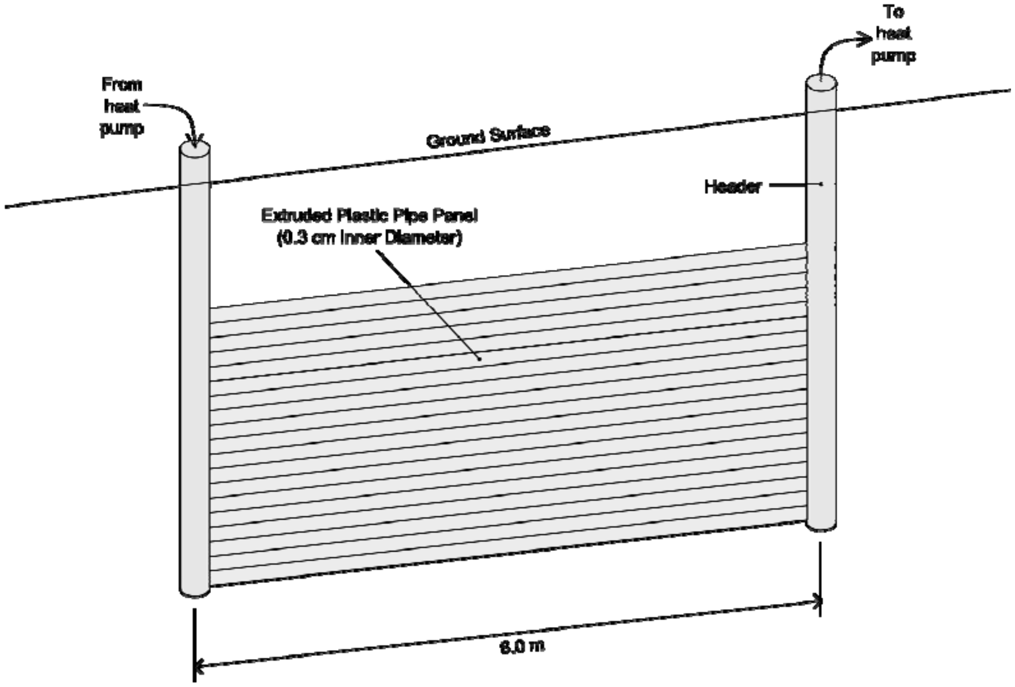


Figure 6. Prototype GCHP Panel (adapted from Kavazanjian, 1982)

The panel used in the prototype system was a 1.2 meter high by 6.1 meter long extruded plastic panel composed of longitudinally oriented thin-walled circular tubes with an inner diameter of 0.3 centimeters, as shown in Figure 6. The heat exchange fluid used in the panel consisted of water which flowed through the panel tubed by way vertical headers. Theoretically, the panel exhibits greater efficiency than conventional pipe heat exchangers due to the greater surface area through which heat can be exchanged with the ground. The panel was installed in a 2.1 meter deep backhoe trench excavated in stiff saturated silty clay (Bay Mud) typical of the test area. A generalized diagram of the installed prototype system is shown in Figure 7.

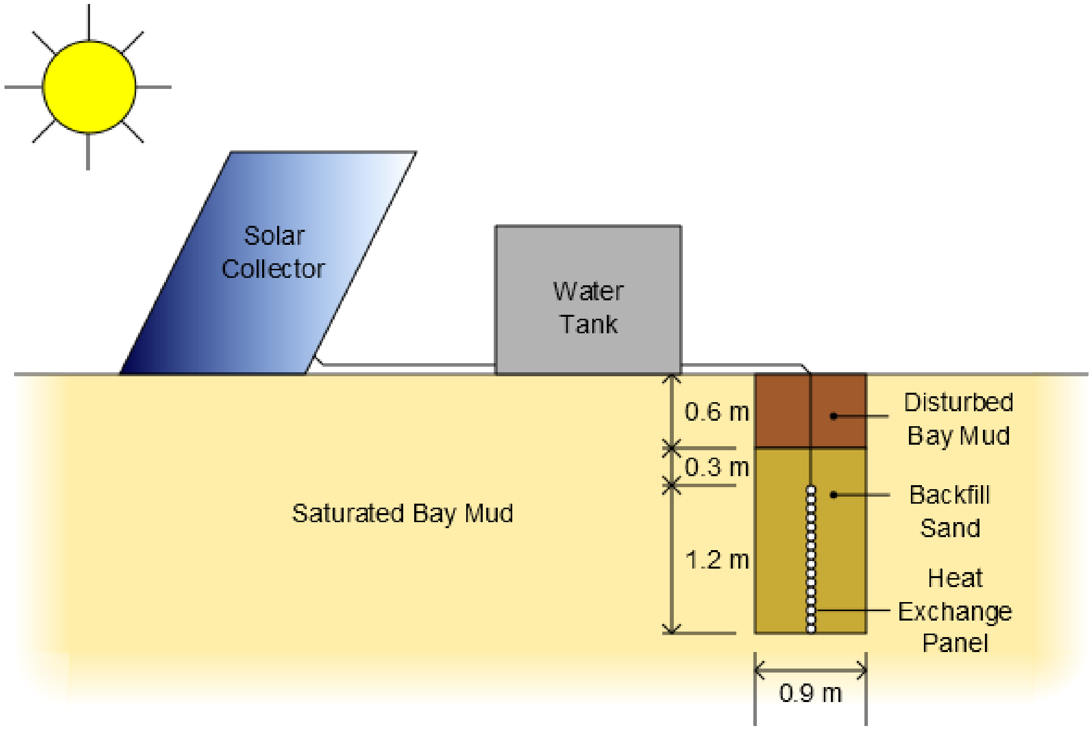


Figure 7. Generalized diagram of the installed prototype system (adapated from Kavazanjian, 1982)

Heat input into the prototype system was provided from a connected solar heated hot water tank in order to simulate the input from a central air conditioning heat pump. The system was run over four days, with the heat rejection cycle operating for seven hours each day. Temperature measurements continued for an additional three day "cool down" period. Based on measurements of heat flow during the test, the heat rejection rate was determined to be 4.33 x 10^2 kcal/hr/m of collector panel into the ground during the heat rejection cycle. The entire system was monitored with a system of thermocouples and flow monitors placed during construction. The temperature response of the soils immediately adjacent to the center of the panel and 0.3 meters away from the center of panel, as measured by the thermocouples and extracted from the figures contained in the unpublished paper, is shown in Figure 8.

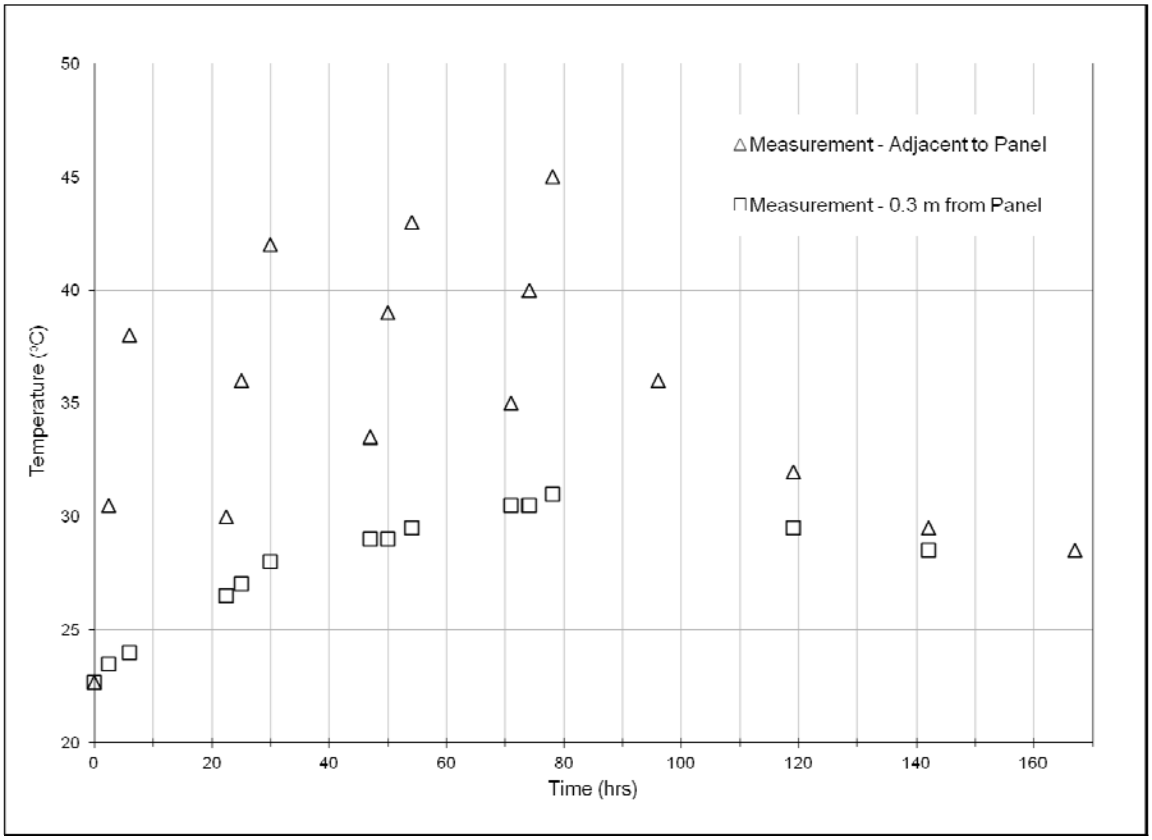


Figure 8. Measured data from prototype system (adapted from Kavazanjian, 1982).

Applying the SVHeat Software to Represent the Prototype System

For the purpose of constructing the SVHeat computer model, the thermal properties of the soils used in the prototype were assumed based on visual classification of the soils, which were correlated to typical thermal properties for Bay Mud and clean backfill sand. The source of these originally assumed soil properties has not been provided by the original researchers, and therefore for the purpose of this study, a later sensitivity analysis of the effects of the variation of the two properties will be used to evaluate the measured results of the prototype system. A summary of the originally assumed soil properties for the soil conditions at the location of the prototype test are summarized in Table 4.

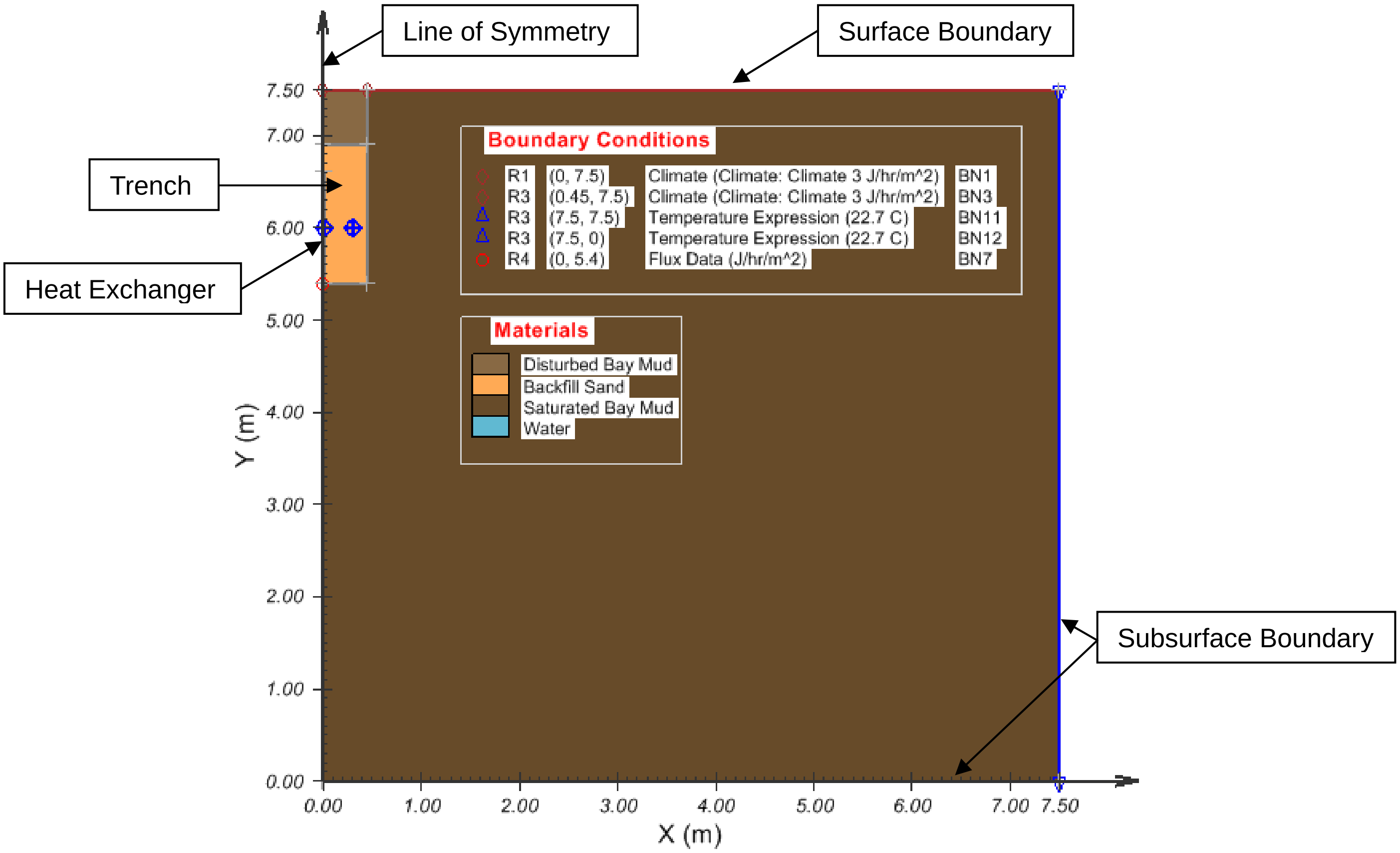
Table 4.

Soil Properties for Prototype System GCHP Heat ExchangerModel (Kavazanjian, 1982).

Material	Thermal Conductivity, λ (W/m/K)	Volumetric Heat Capacity, λ (J/m^3/K)
Backfill Sand	2.25	2.48 x 10^6
Saturated Bay Mud	1.56	2.14 x 10^6
Water	0.58	4.18 x 10^6

The boundaries of the model were selected based on assumptions regarding the conditions of the soil surrounding the system and the climate conditions above the soil surface. Because of symmetry, the boundary along the centerline of the panel system was designated a "no flux" boundary, through which no loss or gain of soil thermal flux can pass. The bottom and outer boundaries were designated as constant thermal boundaries with a temperature of 22.7°C, the approximate measured constant soil temperature at the time of the beginning of the test (Kavazanjian, 1982). The initial temperature of the interior nodes of the mesh were also assigned a temperature of 22.7°C. The top (surface) boundary was designated a climate boundary using the methods integrated into the SVHeat software, with convection properties equivalent to an ambient air temperature of 22.7°C and a constant wind velocity of 8 kilometers per hour, which is understood to have been representative of the conditions at the time of the prototype test sequence. No special boundaries were applied at the internal soil geometry contacts.

The panel system was represented in the model as a thin layer of water, equivalent to half the diameter of the panel tubing (0.015m), and assigned the thermal properties of water shown in Table 4. The heating load was treated as a flux boundary condition along the centerline of the panel (left boundary of the model) that varied over the period of the test according to the heating schedule described above. To account for symmetry across the centerline, only half the presumed heat flux was applied at the boundary. During the 7-hour "on" time, the halved load of the heat exchanger was applied as a thermal flux, while during the "off" time, the flux was reduced to zero. A graphic representation of the SV Heat model is shown in Figure 9.



◇	R1	(0, 7.5)	Climate (Climate: Climate 3 J/hr/m^2)	BN1
◇	R3	(0.45, 7.5)	Climate (Climate: Climate 3 J/hr/m^2)	BN3
△	R3	(7.5, 7.5)	Temperature Expression (22.7 C)	BN11
△	R3	(7.5, 0)	Temperature Expression (22.7 C)	BN12
○	R4	(0, 5.4)	Flux Data (J/hr/m^2)	BN7

Figure 9. Graphic representation of prototype system in SVHeat.

Initial Model Results

The results of the geothermal computer modeling of the prototype system using SVHeat are presented in Figure 10.

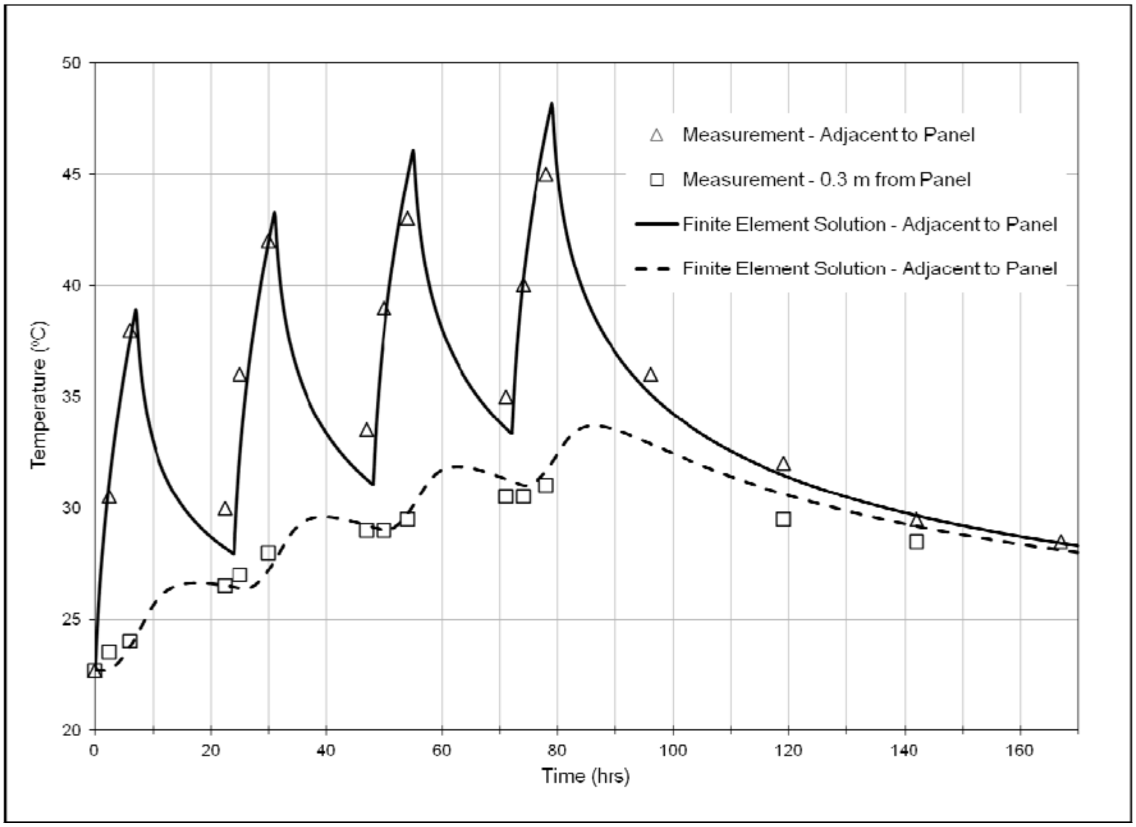


Figure 10. Initial finite element model results for the prototype system.

In general, the results of the prototype analysis appear to agree relatively closely with the measured temperature data recorded during the actual prototype test. These results do not necessarily validate the boundary conditions, soil properties and dimensions assigned to the model, however. The model results vary from the measured results in the following ways: 1) The computed temperature fluctuations adjacent to the panel appeared to be more prominent (i.e. the computed “highs” and “lows” in response to the temperature flux pulses at the panel are greater and lesser, respectively) from those measured during the prototype test. 2) The temperature decay, or dissipation, adjacent to the heat exchanger panel appears to occur relatively faster in the computed model than what was measured during the prototype test.

Sensitivity Analyses

The differences between the computed model results and those measured in the field prototype test could be attributed to incorrect assumptions regarding the soil properties, boundary conditions, or other considerations, such as the soil profile or its homogeneity. In order to evaluate the effect of varying some of these assumptions, several sensitivity analyses were performed within the model, summarized below.

Sensitivity analysis of soil properties. A sensitivity analysis was performed to evaluate the effects of changing the various soil thermal properties. Eight model runs were performed in which the far-field and backfill sand and clay properties were varied, either with the thermal conductivity or volumetric heat capacity increased or decreased to their highest or lowest conceivable properties, according to those listed in Tables 1 and 2. The results of the sensitivity analysis of the soil properties are presented in Figures 11 through 18.

The results of the sensitivity analysis of the soil properties are telling regarding the effects of variations in the soil properties on the calculated performance of the system. Specifically, it was determined that the variation of the thermal conductivities of the soils had a much more significant impact with regard to the the performance of the GCHP heat exchanger than variations in the volumetric heat capacity. While this confirms what was already known: that the thermal conductivity plays a much larger part in soil heat flow problems; this is also obviously a consequence of the much smaller variation in potential volumetric heat capacities versus thermal conductivities.

Sensitivity analysis of boundary conditions. A sensitivity analysis was also performed to evaluate the effects of variation of the external boundary conditions on heat exchanger performance. The soil properties used in the initial prototype model were used in these sensitivity analyses. While the boundaries along the line of symmetry of the model (the left boundary in Figure 9) were unchanged, the sensitivity of the heat flow system to variations in the surface climate model and the static earth temperature assumptions was examined. Four additional model runs were performed in which the surface and static earth temperatures were increased or decreased to their highest or lowest practical levels. The surface temperature was a varied from 0 and 37.8 degrees Celsius, which are the assumed upper and lower boundaries of the seasonal air temperature at the Stanford University campus in California (equivalent to 32 and 100 degrees Farenheit, respectively) (PEC, 2006). While a surface temperature below 0 degrees Celsius is certainly possible in this part of the world, it is very rare, and it is important to limit this analysis to temperature ranges where frozen soils do not require consideration. The ambient static earth temperature was varied within a range of a 10 degrees Celsius above and below the originally assumed ambient earth temperature. This limited range was selected due to the relative shallow placement of the GCHP panel, and based on the average yearly temperature variations as shown in Figure 1. The results of the various sensitivity analyses of the boundary conditions are presented in Figures 19 through 22.

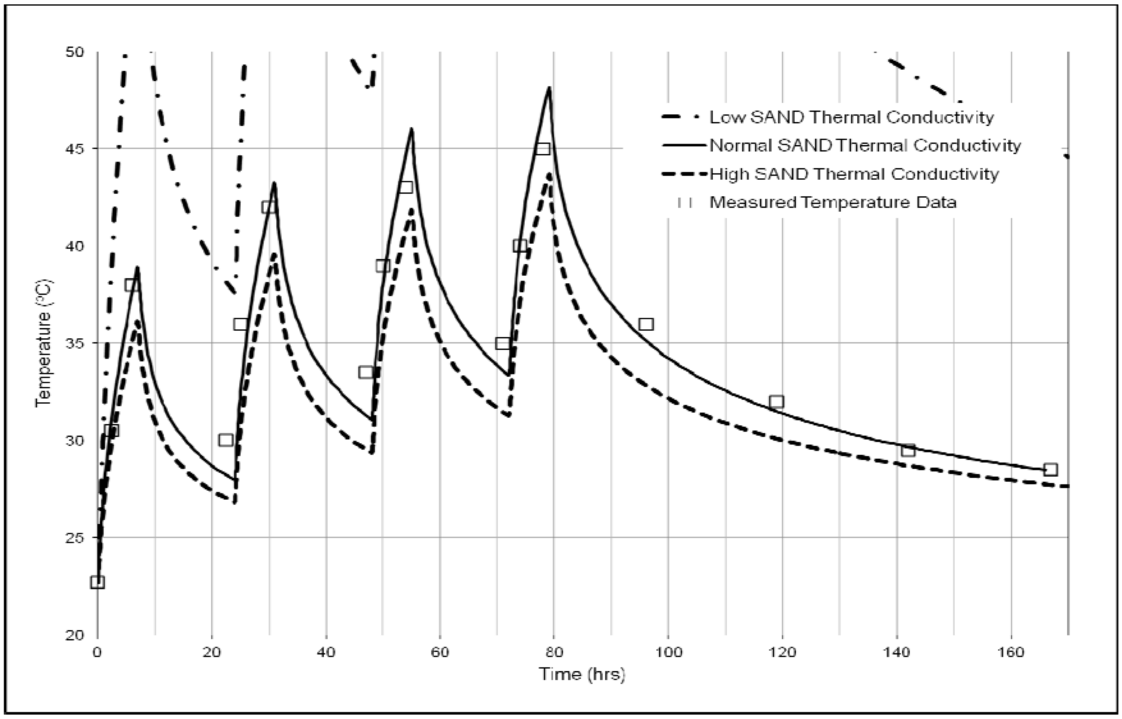


Figure 11. FEM results adjacent to panel for varied sand thermal conductivity.

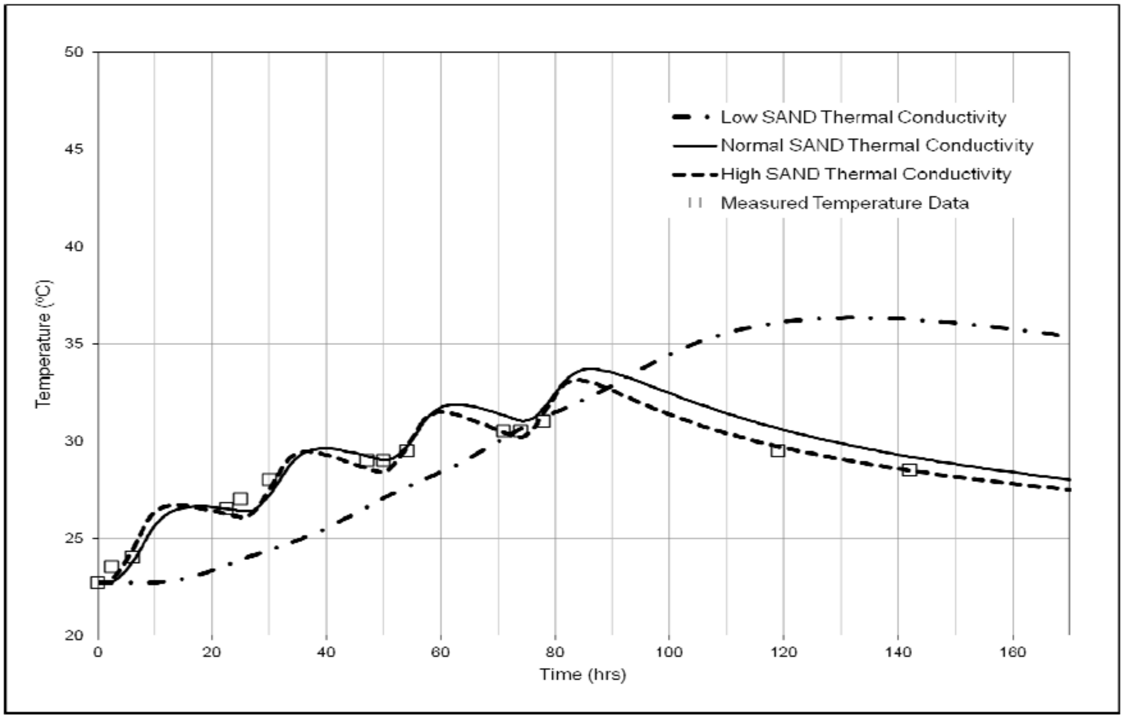


Figure 12. FEM results 0.3 m from panel for varied sand thermal conductivity.

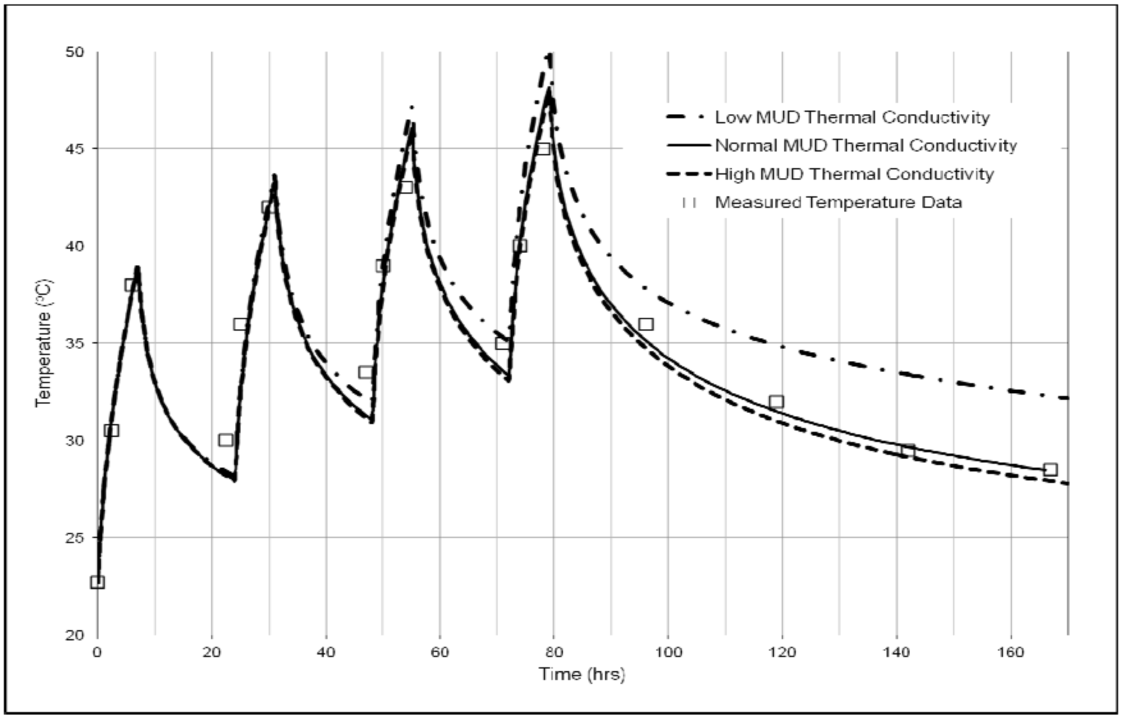


Figure 13. FEM results adjacent to panel for varied clay thermal conductivity.

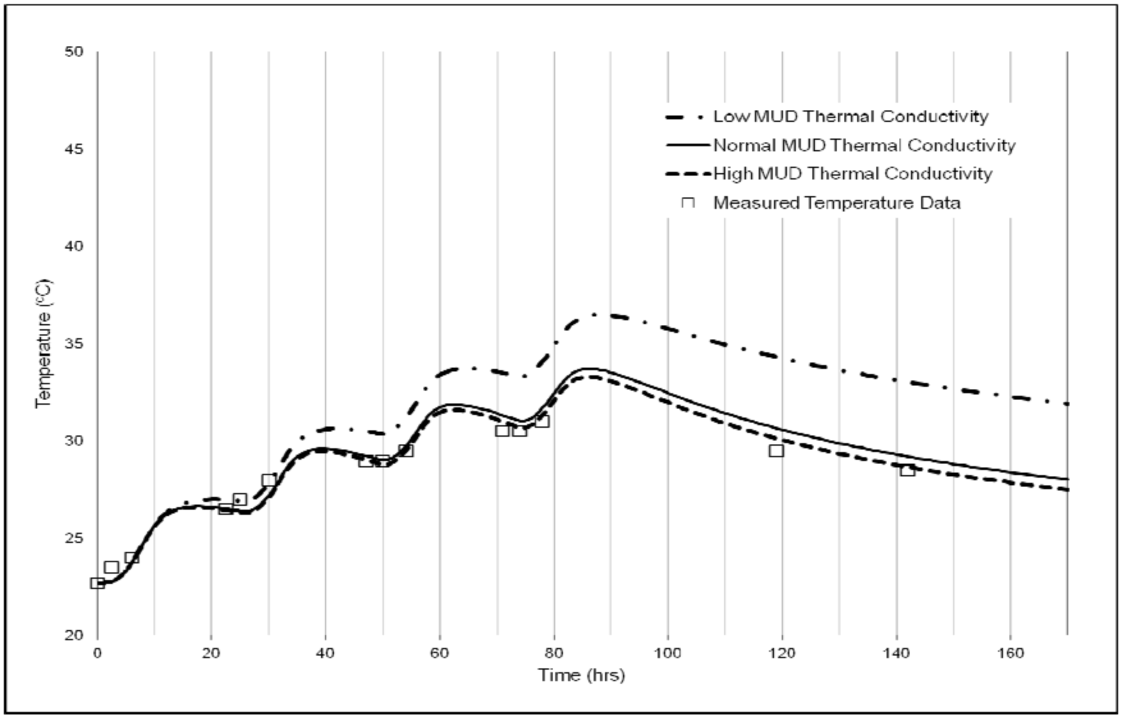


Figure 14. FEM results 0.3 m from panel for varied clay thermal conductivity.

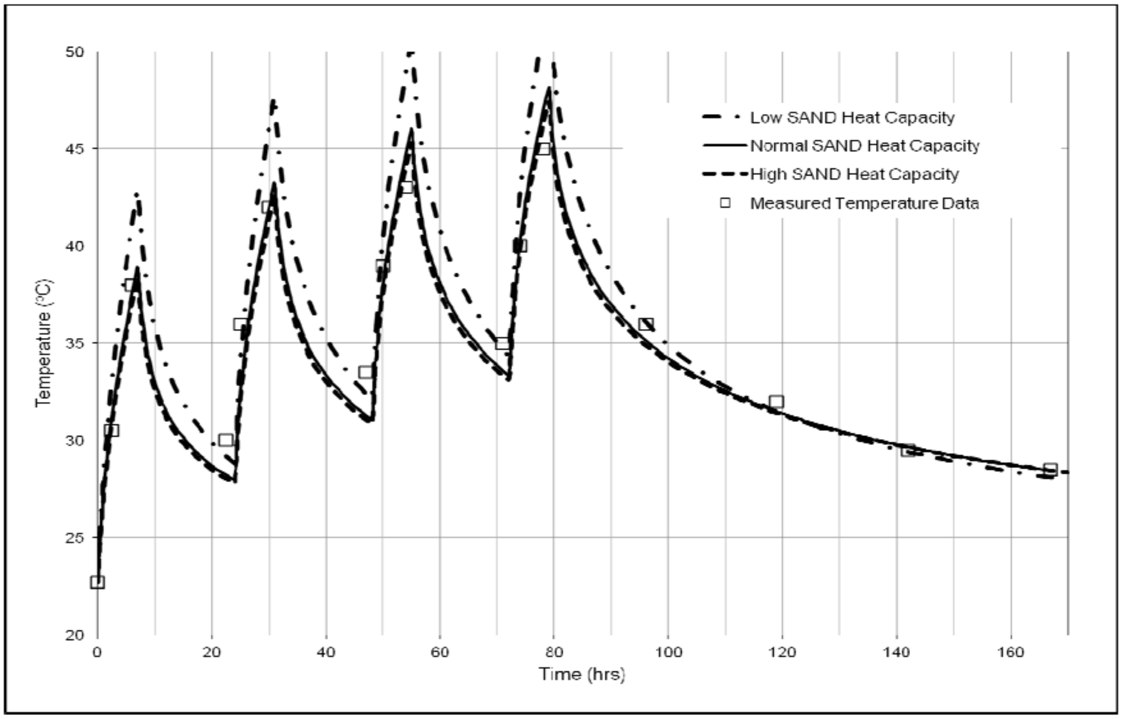


Figure 15. FEM results adjacent to panel for varied sand heat capacity.

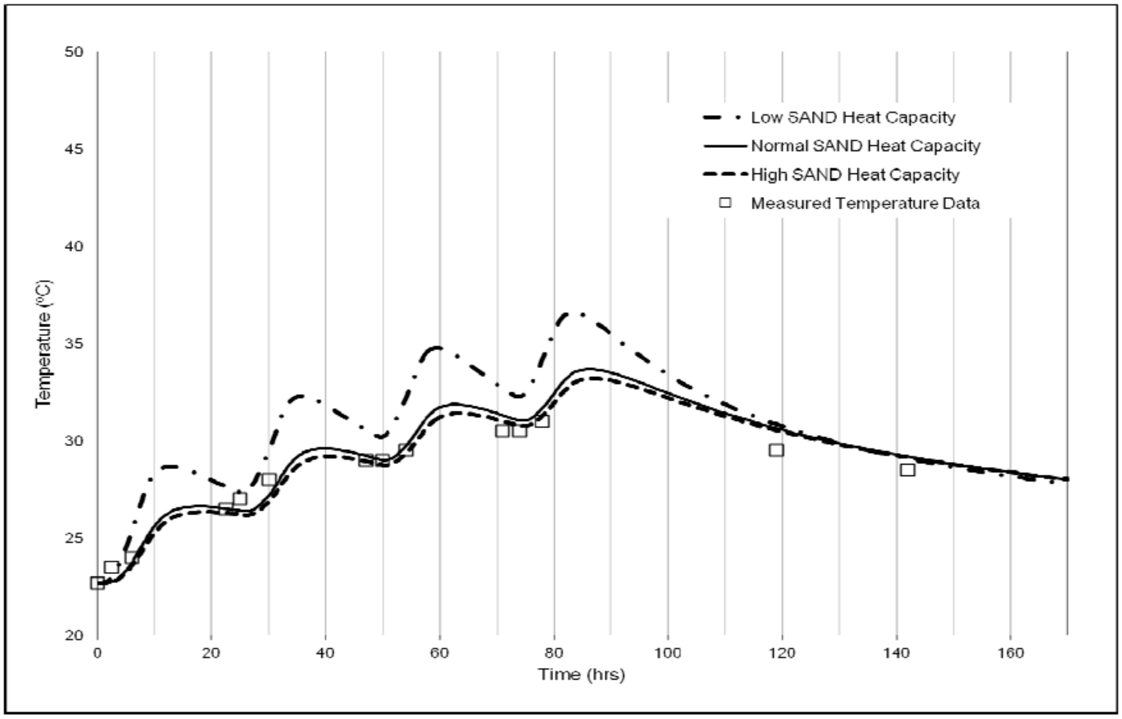


Figure 16. FEM results 0.3 m from panel for varied sand heat capacity.

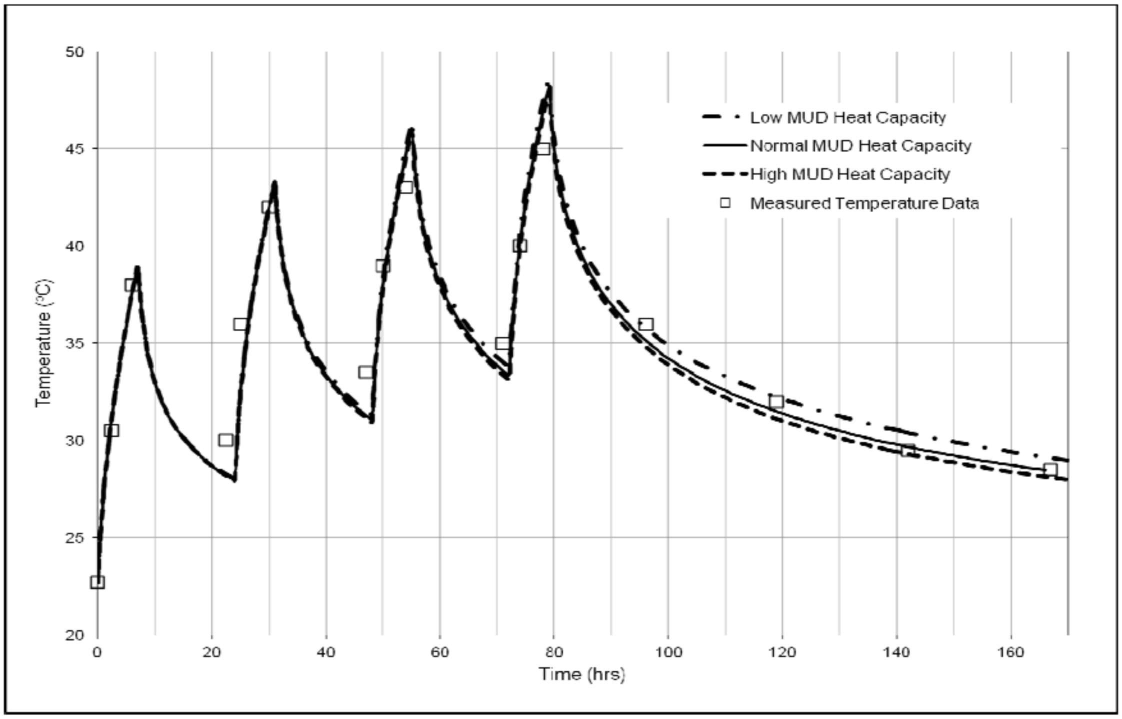


Figure 17. FEM results adjacent to panel for varied clay heat capacity.

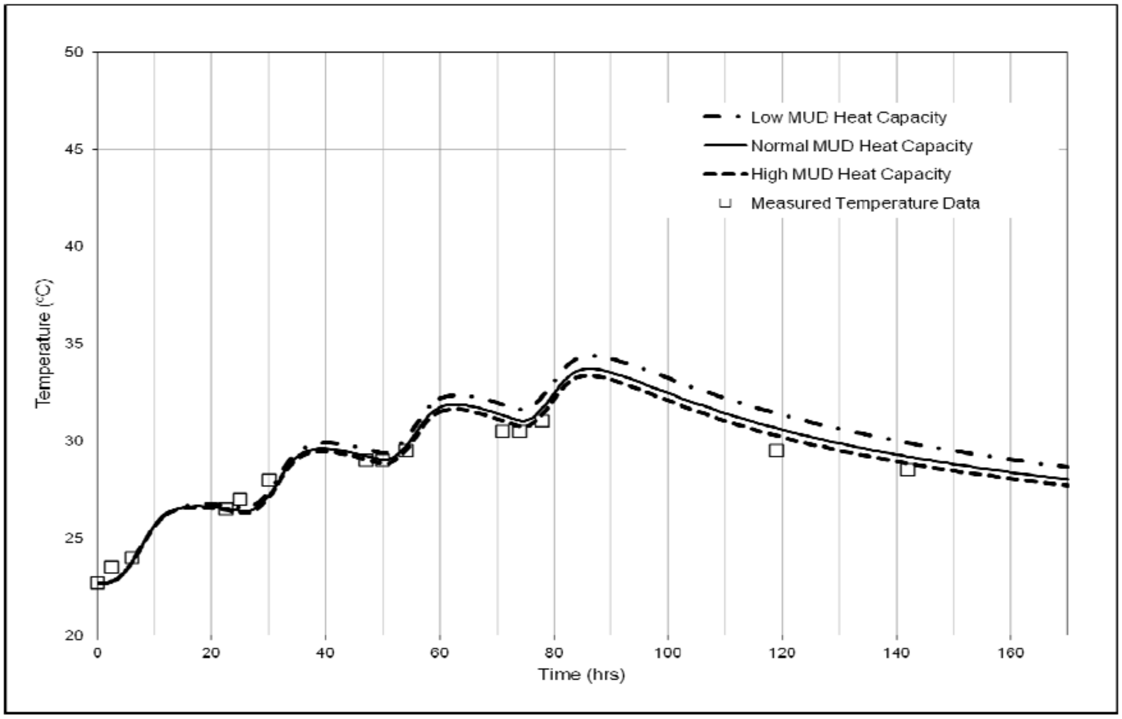


Figure 18. FEM results 0.3 m from panel for varied clay heat capacity.

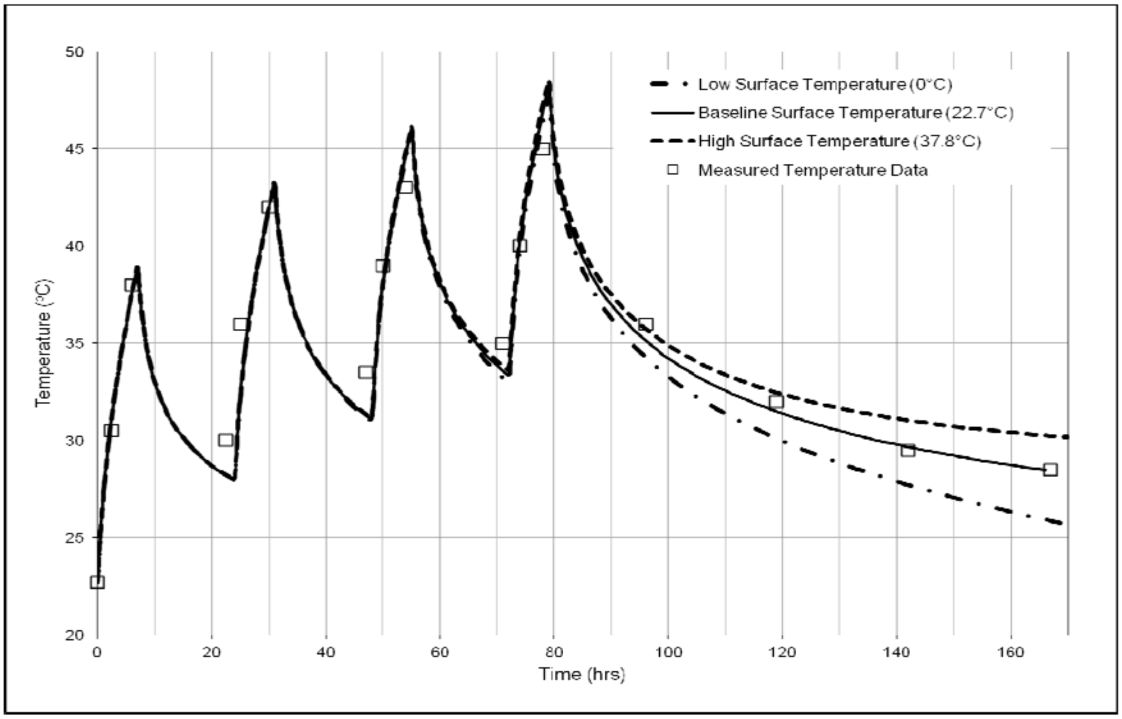


Figure 19. FEM results adjacent to panel for varied surface temperature.

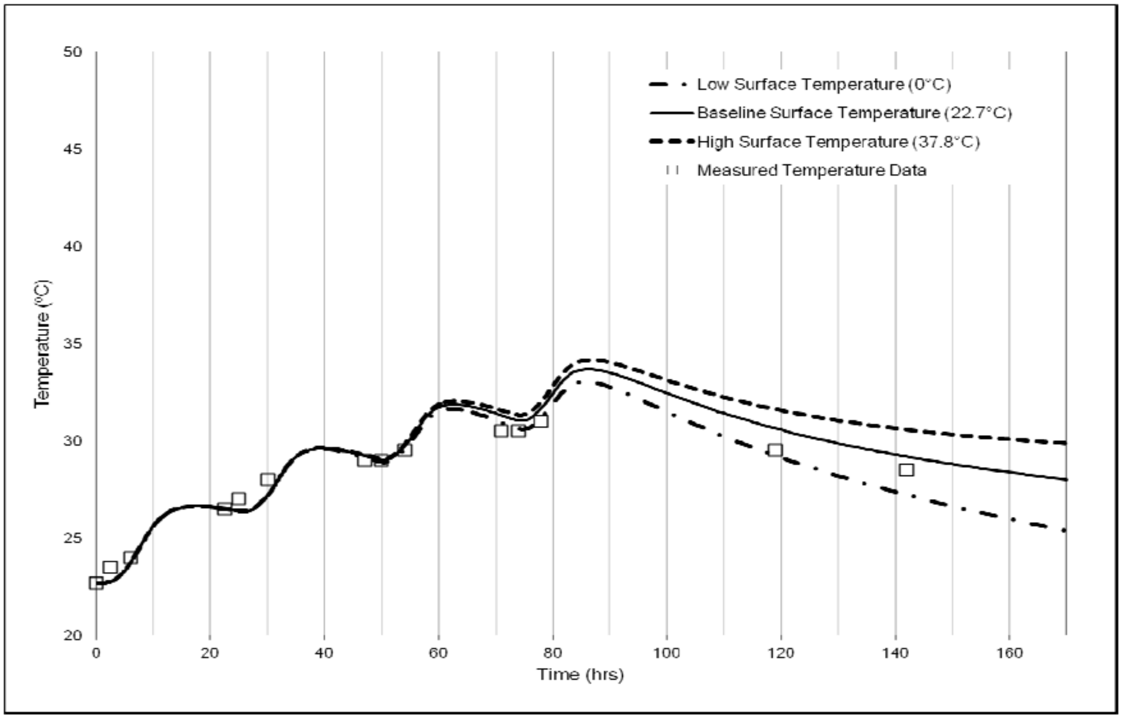


Figure 20. FEM results 0.3 m from panel for varied surface temperatures.

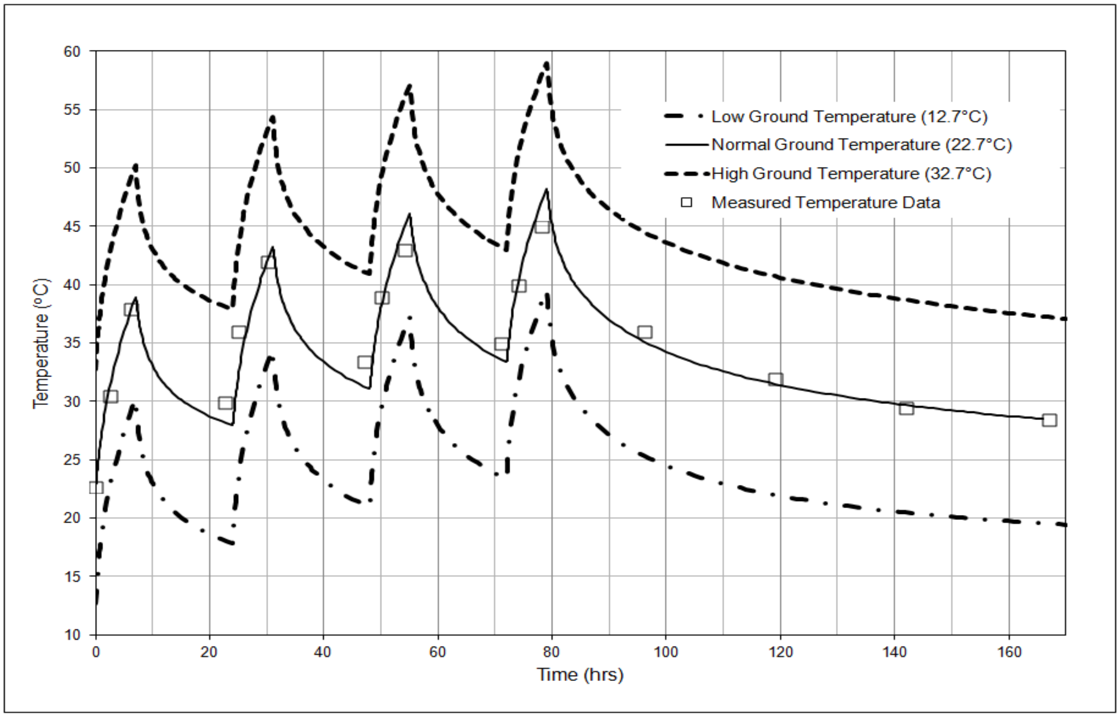


Figure 21. FEM results 0.3 m from panel for varied surface temperatures.

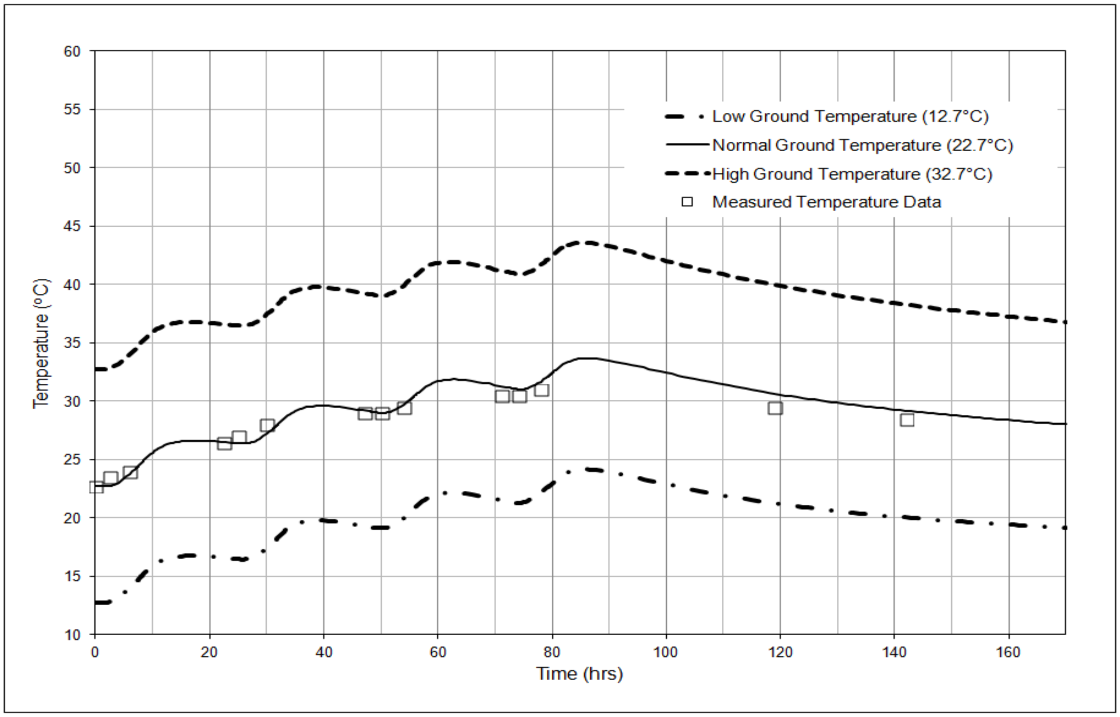


Figure 22. FEM results 0.3 m from panel for varied surface temperatures.

As discussed in previous sections, while surface temperatures do ultimately have an effect on subsurface temperatures, the effects are significantly delayed due to the time required for the heat to transfer through the insulating soil mass. When the effects do reach the depth of the panel, they are significantly muted, and the overall temperature regime of the surrounding soil is still dominated by the thermal output of the panel and the ambient temperature of the surrounding soil.

Variation of the subsurface boundary conditions and the initial subsurface temperature does however have a profound effect on the internally calculated temperatures throughout the test. This should be obvious. What is also shown is that without variation of the soil thermal properties as a result of potential thermal instability, the result of the model are virtually the same, simply shifted upward or downward by the magnitude of the difference in the initial temperature. Here the model does not accurately represent real-world conditions, as it is know that the increased ambient soil temperature will, over time, would result in degraded heat diffusion properties due to a loss in moisture, increased air voids, etc. SVHeat does include a module for variation of soil thermal properties with temperature, but it is designed to be used with frozen soil conditions, not unfrozen dry soils, and delving into such an analysis is considered beyond the scope of this study.

Sensitivity analysis discussion. The results of the various sensitivity analyses show that the computed results for the modeled prototype GCHP heat exchanger do, in fact, appear to represent the measured data relatively closely. While it may certainly be possible to adjust the thermal properties of the soils or the boundary conditions to more closely match the measure data points, it has been decided that for the purposes of this study, the originally assumed model parameters are sufficient for the subsequent analysis. The peaks and troughs of the computed temperature adjacent to the panel are likely exaggerated, due to the fact that the heat flux in the panel originating from the solar-heated water cannot be simply “switched” on and off, and more likely exhibited more gradual warm-up and cool-down periods between each cycle. Unfortunately, without the actual measurement data from the original prototype test, further investigation into this would be speculative, with little benefit to the further analysis.

4 ESTABLISHING RELATIVE EFFECTIVENESS OF HEAT DISSIPATION

Coefficient of Performance (COP) calculations for a GCHP systems operating in cooling mode are based on a comparison of the cooling load and the energy consumed by the system, as discussed earlier in this thesis. As discussed in the introduction of this study, the aspects of the GCHP model considered in this study are confined to the subsurface components of the system. As the energy consumption of the above-ground portion of system is not being considered, no value is available for input into the traditional COP calculation shown in equation 1 and an alternative method of determining the effectiveness was established.

The performance of the subsurface components GCHP cooling system is dependent on the ability of the system to direct the collected heat away from the buried sink into the surrounding soils. A method for assessing the effectiveness of the dissipation of heat through the soils was developed to take this into account.

Steady-State Model

To simplify the heat dissipation analysis, the transient model was simplified to a steady-state model. A steady-state model allows for easier data comparison and faster modeling. To establish a baseline, the original soil properties applied to the prototype system were used, as shown in Table 4. The boundary conditions remained the same, with the exception of the surface boundary condition and the boundary condition at the centerline of the panel. Steady-state models do not allow for time-dependent variables, such as climate and heat output functions. The surface boundary condition was assigned a constant temperature value of 22.7°C. A relatively arbitrary constant temperature boundary condition was applied at the centerline of the panel to represent the heat output of the system during a period of high demand. A constant temperature of 95° C was selected to represent the average heat rejected from the panel. This value was selected to represent a system operating at high capacity, with the internal fluid (water) near its boiling point.

Surface Boundary Condition. In order to ensure that the constant temperature surface boundary condition selected was representative of the climate boundary used in the transient analysis, a transient analysis was completed that extended the cyclic flux cycle for 100 cycles instead of 4, which allowed the temperature increases between to stabilize and begin to approach a steady-state of their own. A comparative steady-state model was run by converting the heat flux value used over the 7 hour heating period to a smaller average hourly value for a 24 hour period.

The steady state model temperature results adjacent to the center of the panel and 0.3 meters away from center of the panel appeared to agree closely with the average temperature values at those locations in the transient model, as shown in Figure ??. This would appear to confirm that the selected temperature boundary condition at the top of the steady-state model is a relatively accurate substitute for the transient climate boundary.

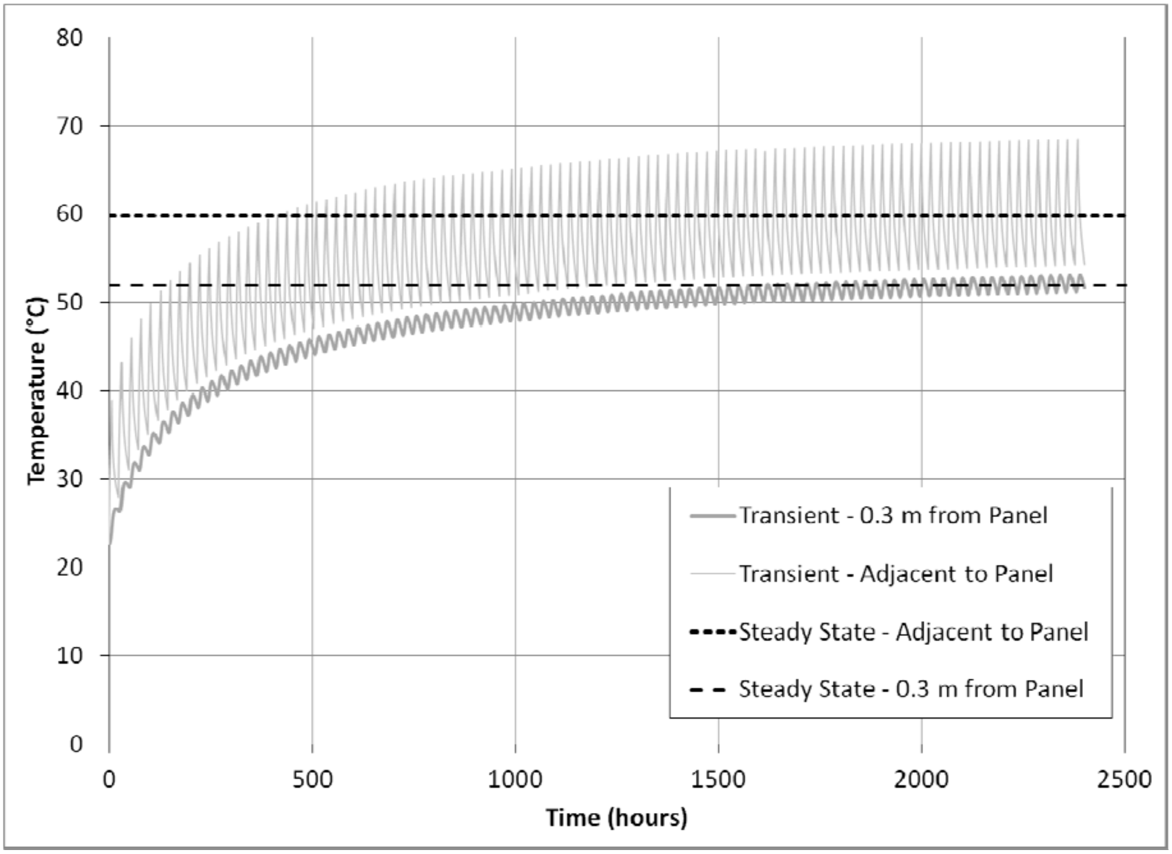


Figure 23. Comparison of transient and steady state temperature results for prototype system using panel flux values.

Measurement of Relative Effectiveness of Heat Dissipation

As mentioned above, the COP of the GCHP system cannot be determined without knowledge of the energy input into the system in the form of electrical energy. For the purposes of this model, it will be assumed that the above-ground equipment and corresponding energy input will remain constant regardless of the subsurface soil conditions. This is represented in the steady-state model with a constant temperature value assigned to the boundary condition representing the GCHP coils. This simplifies the system and allows for a direct comparison of the relative effectiveness of heat dissipation for various subsurface materials.

It has been demonstrated in previous literature (Delaleux, 2012), that improvement in the heat dissipation of the GCHP system will manifest itself in the soil model as a decrease in the temperature at the panel/backfill interface and with a corresponding increase in the temperature at the backfill/soil interface. The relative temperature loss (in a GCHP operating in the cooling mode) between the center of the panel (i.e. the boundary condition representing the panel, a constant temperature) and the panel/backfill interface represents the heat flux away from the panel into the surrounding subsurface materials. The greater the heat flux, the greater the effectiveness of the subsurface components of the GCHP system at dissipating heat, and hence the higher the temperature of the surrounding soils, which are receiving increased dissipated heat from the panel.

To illustrate this point, the steady state model of the prototype system was re-run several times with backfill thermal conductivity values ranging from 0.5 to 5 W/mK. As shown in Figure 24, the higher backfill thermal conductivities resulted in greater flux (demonstrated by increased temperatures at the backfill/soil interface). Figure 25 shows the increase in thermal flux (in J/m of horizontal panel) with respect to increased thermal conductivity at the panel-soil interface.

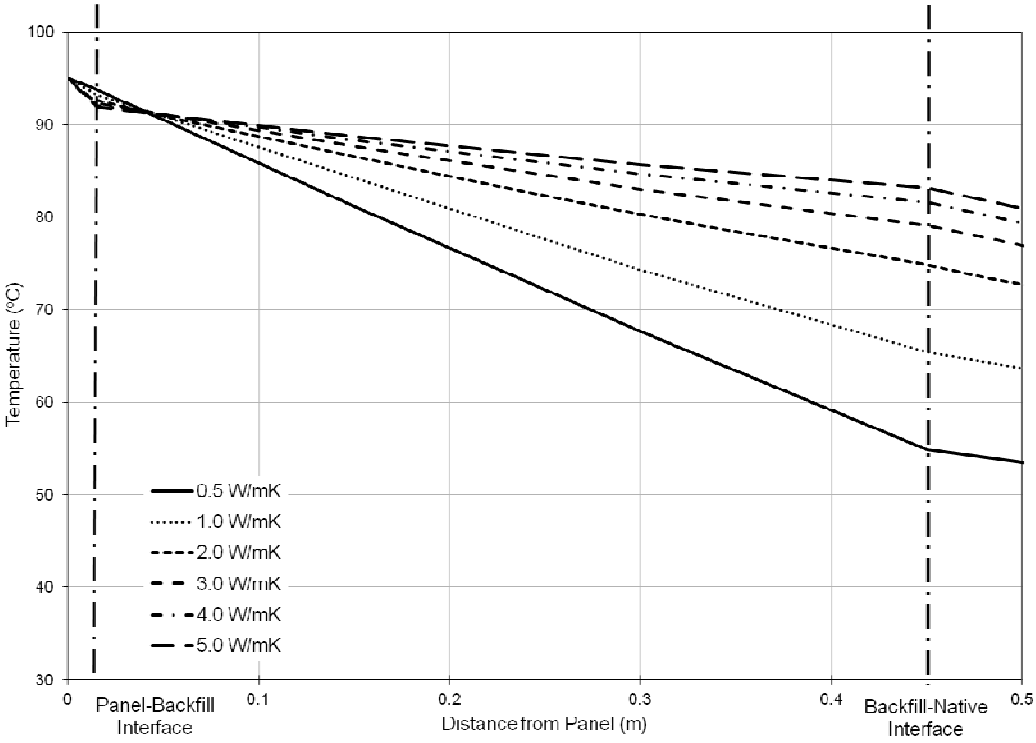


Figure 24. Temperature in the backfill for various backfill thermal conductivity values.

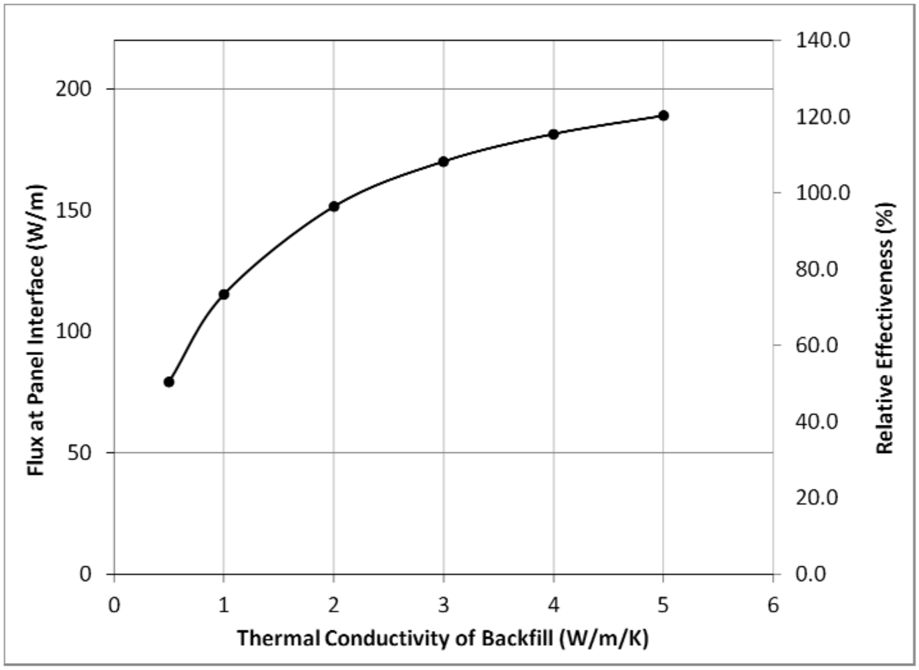


Figure 25. Flux and relative effectiveness for backfill thermal conductivity values.

For the purposes of this study, the baseline value to which all subsequent systems are compared will be the prototype system installed near the Stanford University campus in California, discussed earlier. The relative effectiveness of any considered system will be compared, in percentage, to the effectiveness of that system. Effectiveness, in this study, will be represented by the flux (in W/m of horizontal panel) at the panel-soil interface. Using the data shown in Figure 22 above, for example, Table 5 has been created to show the relative effectiveness of the system using various backfill thermal conductivity values.

Table 5.

Relative Heat Dissipation Effectiveness Results for Various Backfill Thermal Conductivity Values.

Backfill Thermal Conductivity, λ (W/mK)	Flux at Panel Interface (W/m)	Relative Effectiveness (%)
2.25 (Prototype)	155.0	100*
0.5	78.2	50.4
1.0	113.8	73.4
2.0	149.5	96.4
3.0	167.8	108.2
4.0	179.0	115.4
5.0	186.4	120.2

The data presented in Table 5 show the influence that changes in the thermal conductivity of the backfill material can have on the ability of the GCHP system to dissipate heat into the surrounding soils. A decrease in the backfill thermal conductivity of approximately 78 percent results in a decrease in flux of almost 50 percent. An increase of over 100 percent in thermal conductivity of the backfill, only results in an increase in flux of 20%, however. While decreases in the backfill soil thermal conductivity can significantly affect the ability of the soil to dissipate heat outwards, increases in the backfill soil thermal conductivity has diminishing returns.

5 ADAPTING THE MODEL TO ARID CLIMATE CONDITIONS

In Section 3 of this thesis, the calibration of the SVHeat model using the prototype system, it was shown that the numerical (finite element) the model was able to represent the temperature response of the ground for a prototype GCHP system with reasonable accuracy. In Section 4, a metric for quantifying the relative efficiency of the modeled GCHP system as a function of backfill and native soil properties was established bqased upon the steady-state thermal flux at the panel-backfill interface. In this Section, the performance of the same GCHP heat exchanger in an arid soil environment is modeled in order to evaluate the efficiency of such a system in rejecting heat from a cooling system in an arid climate.

Selection of Arid Climate Region Soil Properties

Dry arid region soils are some of the least conducive soils with respect to heat dispersion. As discussed previously, this is due to the relatively high ambient heat environment and the resulting low moisture content of typical near surface soils due to high evaporation and low infiltration. Furthermore, coupled flows of soil moisture and heat drive moisture away from the heat exchanger when it is operated in the heating mode, exacerbating the tendency for soils to dry out. Coarse-grained backfill soils placed under favorable moisture conditions will dry out quickly due to the environment, resulting in a soil with air-filled voids, which is a soil with poor thermal conductivity. Additionally, fine-grained soils are subject to shrinkage during drying, which can lead to cracking and separation of the soil surface from the conducting coils of a GCHP system efficiency, further degrading syste. In both cases the resulting air pockets serve as insulators, further reducing heat dispersion capabilities in these soils.

For the arid soil baseline model, soil properties from Tables 1 and 2 representing soil in their dry conditions (i.e. low thermal conductivity and heat capacity) were employed. In the Phoenix, Arizona area, the arid region of most concern for this study, the types of soils encountered in the top 20 feet of the soil profile can vary widely. Generally, the soils consist of either 1) fine-grained silts and clays, or 2) coarser sands with gravel. Among each of these two soil types, the thermal properties can vary significantly, depending on a variety of factors, including depositional environment, climate conditions, mineral geology. For the purposes of this study four arid soil profiles, one, each, for the two characteristic soil types using upper bound thermal properties and one for each characteristic soil type using lower bound thermal properties (i.e. more and less favorable conditions), were modeled. As the model is not able to accurately represent some of the shortcomings of arid soils mentioned above (separation of the soil from the conducting surfaces, cracking, etc.), even using lower bound soil properties may still represent an optimistic approach to predicting performance. A summary of the selected soil properties for the arid soil baseline model is presented in Table 6.

Table 6.

Arid Climate Region Baseline Far-Field Soil Properties (Upper and Lower Bounds).

Material	Thermal Conductivity, λ (W/m/k)		Volumetric Heat Capacity, λ ($J/m^3/K$)	
	Upper	Lower	Upper	Lower
Backfill Sand, Native and Disturbed Sand	1.04	0.30	1.26×10^6	1.47×10^6
Native and Disturbed Clay	0.52	0.36	1.26×10^6	1.34×10^6

Selection of Arid Climate Region Boundary Conditions

The boundary conditions employed for the arid region model do not vary significantly from those employed in the prototype model. The primary difference in boundary conditions is the increase in the ambient temperature in the subsurface and at the ground surface in the arid region model. For the purpose of this study, an initial ambient temperature of 38.7°C was assigned to both the surface and subsurface boundary conditions. This value was selected based on the average summer daytime air temperature in the typically arid region of Phoenix, Arizona.

Arid Climate Region Model Results and Heat Dissipation Effectiveness

Compared to the prototype system, it is clear that the far-field properties assigned to the soils used in the arid climate region model result in a system far less effective at dissipating the heat energy from the panel. Figure 26 shows the temperature results within the backfill for the various arid climate region far-field model conditions. Table 7 presents the relative effectiveness of each profile in dissipating the panel heat, based on the metric outlined in the previous section.

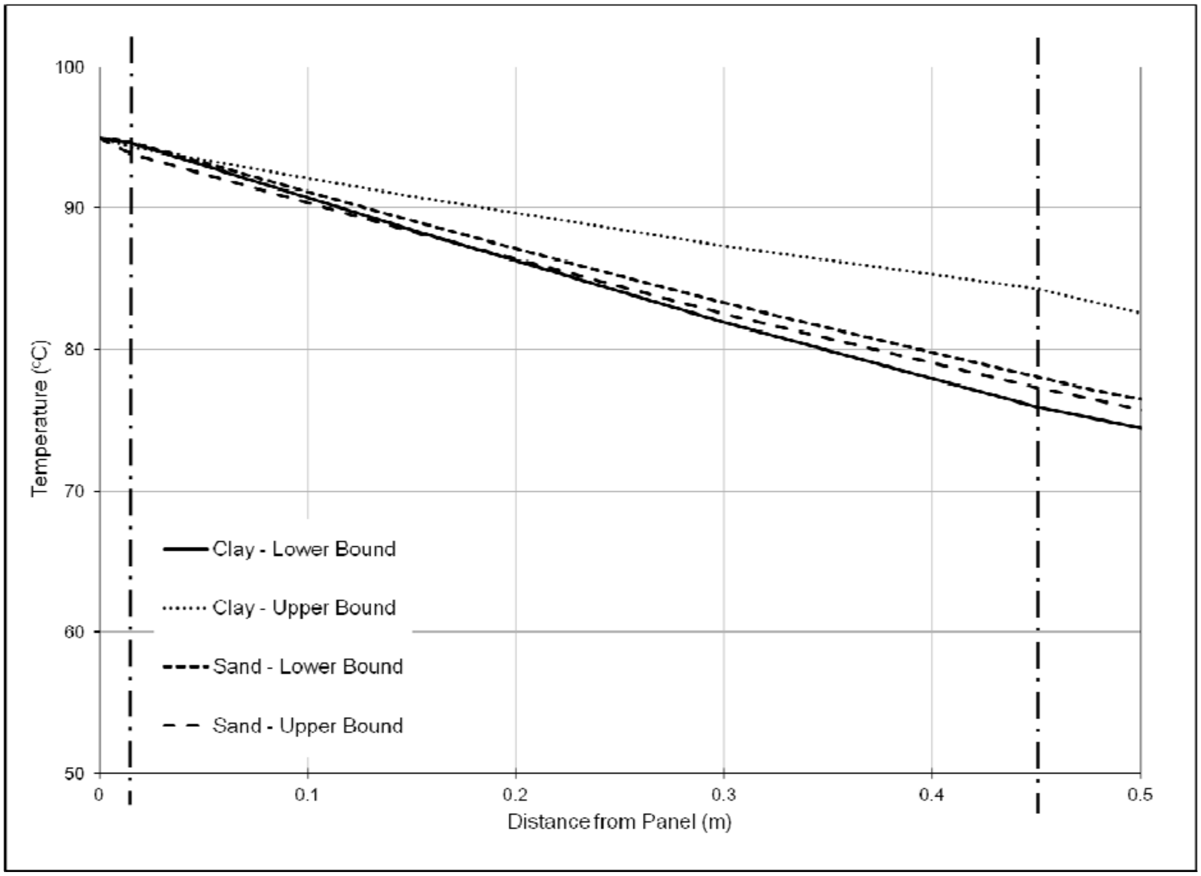


Figure 26. Temperature results within backfill for arid climate region far-field model conditions.

Table 7.

Heat Dissipation Effectiveness of Baseline Arid Soil Models.

Arid Soil Model Conditions	Flux at Panel Interface (W/m)	Relative Effectiveness (%)
Clay, lower bound	24.0	15.5
Clay, upper bound	46.9	30.2
Sand, lower bound	21.6	14.0
Sand, upper bound	73.1	47.0

The arid climate region models that employ the lower bound material properties are extremely inefficient at dissipating heat, as low as 14 percent of the prototype effectiveness for a desiccated sand profile. The upper bound of the sand profile, however, achieves an effectiveness approaching 50 percent of the prototype system. The high variation in effectiveness among the various arid climate region models underscores the importance of properly understanding the thermal properties of the subsurface soils. In the case of the extremely low effectiveness exhibited by the models using the lower bound properties, it is likely that no amount of improvement to the system could prove able to achieve effectiveness even closely comparable to the prototype system. In order to further examine these possibilities, further research and analyses were conducted with respects to improving the thermal properties of the trench backfill to improve the overall performance of a shallow GCHP system in arid climate regions.

6 SYSTEM IMPROVEMENT ALTERNATIVES

As demonstrated in the previous section, GCHP heat exchangers installed in arid climate regions will have reduced effectiveness, due to the low thermal conductivity and the effects of higher initial air and soil ambient temperatures. While it is difficult to represent through modeling, it is also known that the soil properties may further degrade with continued exposure to the higher soil temperature resulting from prolonged operation of the system. Improvement of the thermal properties of the backfill soil surrounding the panel is the only aspect which can be controlled and may have an effect on the ability of the soil to more effectively dissipate the thermal energy input from the panel.

As mentioned previously, various methods exist for improving the soil. The final phase of this study consisted of research into the feasibility and effectiveness of improving the backfill soil properties through various methods.

Backfill Improvement

Replacing or modifying the backfill soils used in the trench is a simple way to improve the thermal properties surrounding the panel. It can be done relatively easily by replacing the soils removed during trenching with either new materials or an improved form of the excavated material.

A variety of soil improvement options are available for trench backfills. In the case of buried GCHP panels, coils or other piping, the main factors for consideration are: 1) the thermal properties of the improved soil or replacement backfill materials, including thermal conductivity, heat capacity and the thermal stability (that is, the ability of the backfill to retain the improved thermal properties through heat cycles and time); 2) the ease of installation of the proposed backfill material; 3) the ability to protect the buried piping; 4) the ease of later excavation in the case of repairs or replacement of the buried piping; and finally, 5) the costs of design, materials, installation, and maintenance.

Evaluating the effectiveness of each alternative improvement method individually with respect to the above factors was beyond the scope of this study. In this study, only the effect of variation in the backfill thermal properties on heat dissipation effectiveness was examined. Table 8 and Figure 26 present the results from the model for various trench thermal properties, applied to all four of the arid climate region far-field soil condition models using the same model dimensions as in the prototype system.

Table 8.

Comparison of Heat Dissipation Effectiveness of Arid Climate Region Models for Various Backfill Thermal Properties.

Backfill Thermal Conductivity (W/m/K)	Relative Effectiveness (%)			
	Clay, Lower	Clay, Upper	Sand, Lower	Sand, Lower
1.0	22.9	29.9	19.9	-
2.0	25.8	34.8	22.1	57.9
3.0	26.8	36.7	22.8	66.0
4.0	27.3	37.8	23.2	69.3
5.0	27.5	38.3	23.3	71.3
6.0	27.6	38.6	23.3	72.7
7.0	-	-	-	73.6

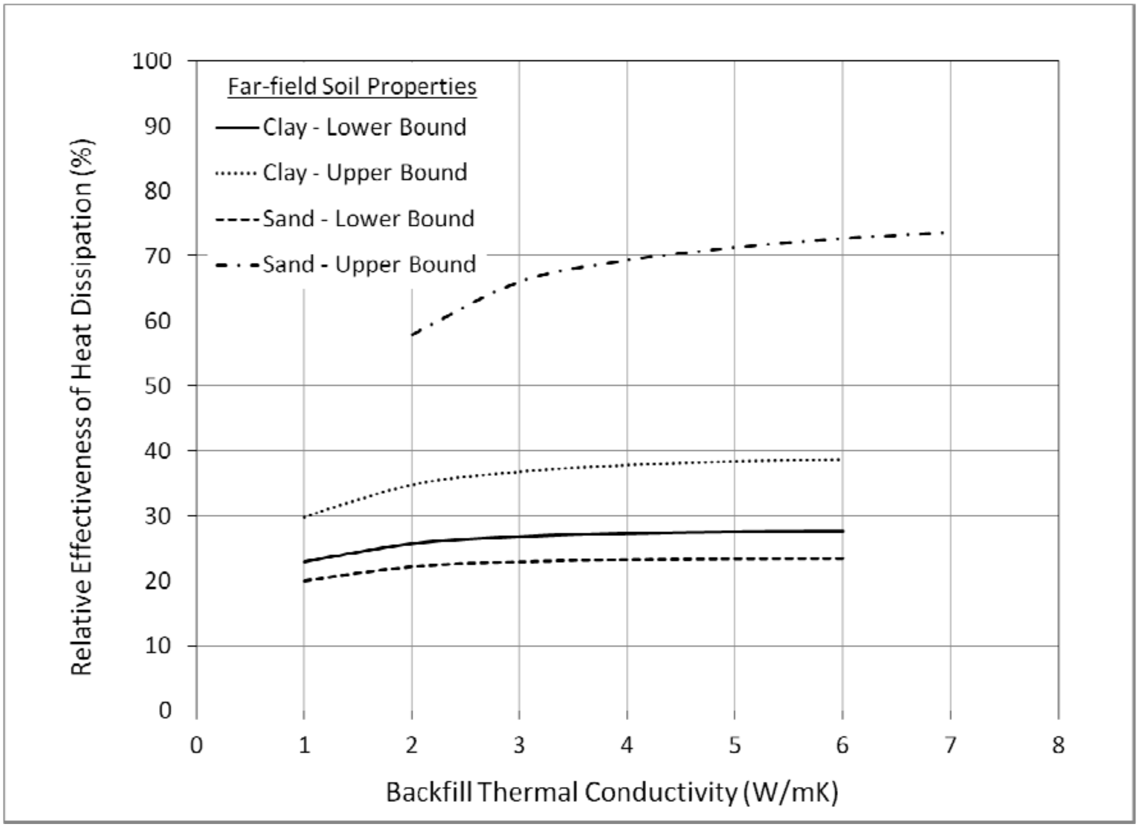


Figure 27. Heat dissipation effectiveness as function of backfill thermal conductivity for various far-field soil properties.

Two points are evident in Figure 27: 1) in models where the initial overall soil profile has less favorable thermal properties, improvements of the thermal properties of the backfill material tend to have less of an impact on the overall effectiveness of the mode, regardless of their magnitude; and 2) improvements to the thermal properties of the trench backfill are only effective up to a point, after which the returns in effectiveness begin to degrade.

Based on the analysis summarized above, improvements in the backfill thermal conductivity are only effective up to a certain level, after which the extra effort and cost is not worth the minor improvement in effectiveness. For most dry clay materials (from the lower to upper bound properties) and less favorable sand materials, any further improvement past 2 to 3 W/m/K is not likely to be cost effective or meaningful. For more favorable sand conditions however, improving the soil to achieve a thermal conductivity on the range of 5 to 6 W/mK can result in improvement gain relative to the prototype model on the order of 25%. While improving the backfill to the point of achieving heat dissipation effectiveness similar to those observed in the prototype system appears unlikely in arid climate regions, significant gains in efficiency could still render them cost effective for general use.

The following subsections detail various backfill improvement alternatives and their relative advantages and disadvantages.

Cementitious grouts. Cementitious grout is also widely used as backfill for conventional deep vertical GCHP systems. The advantage of using a cementitious grout over a soil for backfilling vertical excavations is clear: effective placement and compaction of soils would be impossible in narrow boreholes, and therefore the viscosity and flowability of the borehole backfill material is important to ensure continuity and avoid mechanical failure. While much of the same can be said for horizontally oriented systems, control of the backfill flow and placement is much easier in shallow excavations.

The most basic form of cementitious grout consists of a simple mixture of Portland cement and water, known as "neat" grout. Dried, cured neat grout has a thermal conductivity on the order of 0.45 to 0.7 W/m/K, which is not much different from that of dry sand used in the arid climate region models. For this reason various "fillers" and other additives have been researched and developed that may be added to the mixture. Examples of fillers and additives include: sand, bentonite, fly ash, metals, and ceramics.

Because this material is already being used as a backfill alternative for vertical GCHP systems, a considerable body of research existing already to characterize the heat dissipation properties and other advantages and disadvantages of various fillers and additives.

Sand as filler. Using clean sand as a filler, such as a builder's sand, concrete sand or blasting sand, allows for improvements in the thermal conductivity of a cementitious grout on the order of 200 to 300% (Allan, 1997), which would put the properties in the range of the wet sand used in the prototype model, resulting in a clear improvement in the effectiveness of the system. While in general, the use of sand as cement filler has been shown to improve the thermal conductivity of grouts, the effectiveness of sand as filler is also dependent on the type of sand used. Coarser and more angular sands have a tendency to reduce flowability and result in segregation of the sand within the sand-cement mixture, resulting in poorer thermal properties. In studies by Allan (1997), thermal conductivities for recently-cured saturated sand-cement mixtures have been found to range from about to 1.7 to 2.4 W/mK. The same studies found that depending on the water-to-cement (w/c) ratio, conductivity losses upon oven drying (similar to the moisture losses occurring to soils in arid climate regions) can range from as little as 6 percent for w/c ratios of 0.45 to as great as 31 percent for w/c ratios of 0.75. At higher w/c ratios, excess water not used in the cement hydration process collects in voids, which become air-filled upon drying.

Fly ash and blast furnace slag as cement replacement. Lagoon fly ash, collected from existing coal-burning power plant disposal ponds, and blast furnace slag, a byproduct of iron- and steel-making, are especially attractive as partial cement replacements as they otherwise have little use and have been shown to exhibit have beneficial effects (Kolay & Singh, 2002). Fly ash especially, is considered an unattractive byproduct of an increasingly unpopular electricity generation method. Both fly ash (FA) and blast furnace slag (BFS) do not themselves exhibit extremely favorable thermal properties for GCHP use, and the additional of these materials to cementitious grouts has only a slight improving effect on the internal grout thermal conductivity. FA, however, has been shown to improve the flowability of cement and cement-sand mixes, which along with improved durability and reduced heat of hydration, can lead to a reduction in voids, both within the cement mix itself, as well as at the cement backfill/heat sink contact area (Allan, 1997). BFS has been shown to be especially effective in reducing the heat of hydration of cement mixes in which it is included, which reduces the occurrence of microcracking, as well as also reduce the potential for delamination at the system contact area. Both materials, as industrial byproducts with limited uses otherwise, can also be significantly less costly than cement.

Metals as filler. As, the thermal conductivities of most metals are much higher than that of neat grout and soil, it has been theorized that the addition of metals to grouts may provide for more favorable heat transfer. The metals may come in the form of fibers or grit added to the mixture. Studies performed by Allan (1997, 1999) using both steel microfibers and steel grit revealed challenges arising from the use of such materials in cementitious grouts. Some of the most important challenges presented were: 1) relatively large conductivity losses were realized upon drying metallic filled grouts, 2) significant volumes of metallic filler would be required to have a significant effect on the overall thermal conductivity, and 3) with increases in the volume of fibers beyond even low volume fractions (less than 0.1), the workability of the grout decreased drastically. With respect to the first point, the conductivity losses were not thoroughly investigation, but were attributed to delamination and cracking at the metal-grout interface. With respect to the workability and volume fraction, as the Allan studies were primarily concerned with the modification of cementitious grouts for use in vertical GCHPs, the ability to place the material in deep vertical boreholes was of great importance. Given the problems arising with workability at even low volume fractions, the use of metallic filler was not pursued further in these studies.

While not specifically performed with GCHP backfill in mind, promising research on the use of metallic fillers in concrete has been performed using both steel and copper fibers (Cook and Uher, 1974). It has been shown that using steel fibers in concrete in volume percentages of up to 8 percent could offer thermal conductivity increases of 25 to 50 percent, while increases of 500 to 600 percent were realized with the use of copper in similar volume concentrations.

While delamination and cracking may be reduced with certain additives and workability is much less of a concern for shallow trench placement in horizontal GCHPs, perhaps the greatest obstacle to the use of metallic fibers as a filler in cementitious grouts is the relatively high cost of most metals compared to that of simple sand and cement.

Ceramics as filler. As with metallic fibers, some ceramics exhibit thermal conductivities that are much higher than neat grout. In the Allan (1997, 1999) studies, significant thermal conductivity gains were realized with the addition of alumina and silicon carbide powders. The addition of alumina in filler to cement ratios of 1.3 to 1.9 resulted in thermal conductivities ranging from 2.0 to 2.3 W/m/K, while thermal conductivities ranging from 2.7 to 3.3 W/mK were realized with the addition of silicon carbide in filler to cement ratios of 1.1 to 1.4. Upon oven drying, the grouts with alumina-filled grouts exhibited thermal conductivity losses on the order of 8 to 14 percent, while the silicon carbide filled grouts exhibited much greater losses, on the order of 22 to 25 percent. It would appear that alumina is an appropriate filler, achieving thermal conductivities on the order of those of sand, or even greater, with comparable thermal conductivity losses. Despite the significant losses upon drying, silicon carbide filled grouts still exhibited even greater thermal conductivities than sand or alumina filled grouts. The conductivity loss upon drying is believed to be the result of cracking or delamination of the hydrated cement at the filler-cement contact, which may be improved with further studies using alternative materials or w/c ratios.

Graphite as filler. Another novel substance that has been considered as cementitious grout filler for GCHP applications is graphite. Like most metals and some ceramics, pure graphite exhibits a thermal conductivity much higher than neat grout. Graphite as filler for bentonite grouts used in vertical GCHPs, in the form of both flakes and processed expanded natural graphite (ENG) worms, has been investigated in some detail (Delaleux, 2012).

The addition of graphite flakes in quantities equivalent to 5 to 50 percent by weight to bentonite grouts was found to result in thermal conductivities ranging from 3 to 7 W/mK. Similar gains were observed with the processed expanded natural graphite, but in smaller proportions. As with many of the filler materials, the addition of the graphite was shown to negatively affect workability of the backfill material, but in the case of horizontal trench placement applications, is not as great of a concern.

Discussion

Many options exist for modification of the trench backfill to improve the heat dissipation effectiveness of the GCHP panel, as described in the previous section. Some improvement methods, such as soil cement, bentonite grouts and some forms of cementitious grouts, do not provide adequate improvement to the backfill thermal conductivity to be considered effective for use in arid climate regions. Others, such as the addition of ceramic or sand filler to cementitious grouts can be used to provide limited improvements to the effectiveness. Graphite and metals (particularly copper) show promise as fillers for cementitious grouts that may provide significant gains in thermal conductivity allowing for greater heat dissipation effectiveness. Of course, these materials come with increased costs, and such considerations should be taken into account.

7 SENSITIVITY STUDIES

In the process of completing this study, certain aspects of the model were selected that may not accurately represent real-world GCHP operating conditions and subsurface soil properties and temperature values. In most cases assumptions were made in order to simplify the model or allow for easier comparison between various models. The following sections address these assumptions and provide sensitivity studies to demonstrate their potential effects on the overall study.

Boundary Condition Sensitivity

Three boundary conditions in particular, were assigned values that were likely not reflective of real world conditions: the heat exchanger panel boundary condition and subsurface boundary conditions. To examine the effects of varying these boundary conditions, additional iterations of the steady-state models were completed. For the purposes of comparison, the iterations that were completed were: 1) the prototype model with the initial soil properties, 2) the arid climate region model with the lower bound clay free-field soil properties (worst-case), and 3) the arid climate region model with the upper bound sand free-field soil properties (best-case).

Subsurface Boundary Condition. As discussed in Chapter 2 of this study, the subsurface temperature typically varies with depth. All the analyses completed for this study included models in which the subsurface temperature was kept constant with depth, for the sake of simplicity. In the prototype GCHP model analysis, this was accepted to be a relatively accurate representation of the real-world conditions during the test run, given that subsurface temperatures in the San Francisco Bay area of California do not vary as much seasonally compared to those in arid climate regions. The relative agreement between the measured data and the model results would appear to bear this out. For this sensitivity study, no additional iteration of the prototype system was performed.

In the case of the arid climate region models however, the seasonal variations between the surface and depths of 7.5 meters below the ground surface can be 20 degrees Celsius, or greater. For this sensitivity study, the lower boundary condition of the model was assigned a constant temperature of 23°C was assigned to the lower boundary condition at the depth of 7.5 meters. This temperature value was selected to reflect the mean annual earth temperature in Phoenix, Arizona. The right boundary condition, representing the variation in soil temperature with depth, was assigned a linear increase in the soil temperature starting with 23°C at the bottom and increasing to 37.8°C at the top.

The results of this sensitivity study indicate that modifying the subsurface boundary conditions in the way described above have a modest effect on the existing arid climate region models. The relative effectiveness of the arid model using the lower bound clay soils increased only 0.9 percent from 15.5 to 16.4 percent. The arid model using upper bound sand soils did not result in significantly greater improvements either, only achieving an increase in relative effectiveness of 2.4 percent, from 47.0 to 49.4 percent.

Heat Exchanger Panel Boundary Condition. The boundary condition constant temperature of 95°C assigned to the heat exchanger panel for the steady-state analysis was selected in order to represent extreme conditions in the soil and panel, where the internal fluid (water) was near its boiling point. Typical heat exchanger internal fluid temperatures range between approximately 40 and 45°C, and can be as high as 50°C in arid climate regions.

For this sensitivity study, the heat exchanger panel boundary condition constant temperature was decreased from 95°C to 50°C. All other model properties and conditions were left as is and the steady-state analyses were rerun for the prototype system as well as the two arid climate region models (lower bound clay and upper bound sand).

In all cases, the lowered heat exchanger panel boundary conditions result in greatly reduced flux at the panel interface, but also results in lowered overall relative effectiveness for the arid climate models. The flux at the revised prototype model has been reduced from 155 W/m of panel to just 47.4 W/m of panel. This flux value becomes the new baseline for determining relative effectiveness. Based on this reduced baseline value, the relative effectiveness of the arid model using the lower bound clay soils reduces from 15.5 to 10.3 percent, while the model using upper bound sand soils reduces from 47.0 to 31.2 percent.

Combined Boundary Condition Changes. Combining the two boundary condition changes, reducing the heat exchanger panel constant temperature to 50°C and assigning linearly decreasing temperature with depth in the subsurface soil boundary conditions, in the above discussed models provides further insight into the effect of temperature gradients on the relative effectiveness of GCHP heat exchangers. Changes in the subsurface soil boundary conditions appear to have a greater effect on the relative efficiency of the heat exchanger when the output temperature of the heat exchanger is lower. A summary of the relative efficiency results from the boundary condition sensitivity studies is shown in Table 9.

Table 9

Summary of Boundary Condition Sensitivity Study

	Relative Effectiveness (%)	
	Clay, Lower	Sand, Upper
Initial models	15.5	47.0
Depth dependant subsurface temperatures	16.4	49.4
Decreased heat exchanger panel temperature	10.2*	31.2*
Combined sensitivity studies	13.1*	39.5*

*Comparative effectiveness based on new baseline prototype flux value for decreased heat exchanger panel temperature.

Backfill Trench Width Sensitivity

The backfill trench for the study was kept at a fixed width throughout, in order to simplify the comparison of various soil conditions and backfill improvement techniques. Increasing the width of the backfill trench could have a beneficial effect on the relative effectiveness of a GCHP heat exchanger by increasing the mass of soil with improved soil properties.

A simple sensitivity study of the effect of increasing the backfill trench width was conducted by completing two additional iterations of the arid climate region model using a widened trench. The trench width was widened to 1.8 meters, or twice the current dimension. A backfill thermal conductivity value of 7.0 W/m/K was selected to represent a trench backfilled with the most beneficial improvement option, graphite-filled cementitious grout. Again, the two iterations were completed using the best (sand upper bounds) and worst (clay lower bounds) case arid climate region free-field soil properties.

With the backfill thermal conductivity increased to that of graphite-filled cementitious grout, significant gains in the relative effectiveness results of the GCHP heat exchange panel were obtained. The relative effectiveness of the heat exchange panel in arid climate model using the upper bound sand free-field soil properties increased by about 22 percent, while the model with the lower bound clay free-field soil properties increased by almost 30 percent.

Heat Exchanger Geometry

The panel heat exchanger used in the prototype system and the subsequent studies is not typical of commonly used heat exchangers for shallow horizontal GCHP systems. As discussed in the beginning of this study, horizontal GCHP systems typically employ small-diameter buried pipes that run in parallel trenches or coiled “slinky” pipes.

A simple sensitivity study was performed in which the heat exchanger geometry was modified reflect a buried pip instead of a panel. The heat exchanger pipe was modeled as a half-diamond shaped exchanger with a surface area equivalent to that of a two-inch diameter pipe. The diamond shape was used to allow for easier collection of the output flux data. The output flux, in Watts per meter of surface area was compared to that of the panel.

The model with the heat exchanger geometry representing the small-diameter pipe was found to exhibit a flux per meter of surface area approximately 3 times greater than that of the panel. The magnitude of the increase due to the modified heat exchanger geometry did not appear to increase or decrease greatly with variation in the backfill or far-field soil thermal properties.

8 SUMMARY AND CONCLUSIONS

Due to many reasons, including rising fuel prices and the desire for energy independence, as well as increased interest in improving building efficiency for sustainability and cost-saving purposes, research into alternative and novel heating and cooling systems is receiving greater attention. Ground-coupled Heat Pumps (GCHP) systems can be an attractive alternative to conventional heating and cooling systems in areas where subsurface conditions and energy demands are conducive to their use. In smaller applications, horizontally installed shallow GCHP systems are the most cost effective, as their lower installation costs are recovered more quickly over time. The use of shallow horizontal GCHP systems is limited to areas with shallow groundwater or bedrock however, where the thermal properties are relatively predictable and conducive to heat dissipation. In areas where there is no shallow groundwater or bedrock, particularly arid climate regions such as the Phoenix, Arizona metropolitan area, the coupled flows of heat and moisture can degrade the thermal conductivity of the ground around the heat exchanger, which in turn drastically lowers the effectiveness of the system.

The thesis discussed has addressed the modeling of shallow (less than 25 feet below the existing ground surface), horizontal closed-loop ground-coupled heat pump systems, used a basic installed prototype system to calibrate the model, recreated the model to represent the properties and conditions of soils in arid climate regions, and then evaluated the effectiveness of various backfill improvement methods. Ground modification may be used in arid climate regions to improve the efficiency of GCHPs by providing for more stable and favorable thermal conductivity and heat capacity properties around the heat exchanger.

The objective of the study were: a) apply the SVHeat computer modeling software to represent a prototype shallow horizontal GCHP heat exchanger and calibrate the model by comparing results to those obtained during a monitored run of the prototype system; b) apply the calibrated computer model system to an arid climate region by selecting appropriate soil properties and environmental effects to reflect arid climate conditions; and c) employing the arid climate region model, evaluate the effects of stabilizing and otherwise enhancing the thermal properties of the backfill on the GCHP effectiveness.

Chapter 2 of this study discussed the thermal properties of soil and the modeling approach for heat flows in soils. The explanation of the thermal properties of materials included a discussion of the relative contribution to the properties based on the phase relationships, moisture content, and their geologic origins. The use of partial differential equations for the analysis of heat flow in soils developed by De Vries and Van der Wijk (1965) was summarized. The theory and use of various boundary conditions for constraining a model were discussed, including typical ground surface and subsurface conditions. Finally, the SVHeat software package was introduced, as well as a brief discussion regarding the limitations of the analysis and software.

In the interest of simplifying this study and reducing the modeling to a manageable level, several aspects of heat transfer modeling in soils were omitted or otherwise relegated to simplified constant values. These include:

- The effects of radiation and convection on heat flow were omitted from the discussion, based on their relatively low contribution compared to conductive heat transfer.

- The effect on thermal conductivity of soils made by variation in moisture content was not discussed beyond the listing of typical properties for "saturated" and "dry" soils. This also includes coupled heat and moisture flows, which would require simultaneous examination of moisture migration in soils due to thermal energy loading.
- More complicated boundary conditions were avoided, including seasonal variations in ambient soil temperature with depth at below ground boundaries and evaporation, on ground surface boundaries.

Chapter 3 of this study addressed the verification of the model to be used in the subsequent analysis. The basis of the model was a real-world prototype GCHP system installed near the Stanford University campus in the San Francisco Bay area of California as part of a prior study (Kavazanjian, 1983).

The prototype consisted of a shallow, vertically-oriented panel installed in a 0.9 m wide trench backfilled with compacted sand and subsequently covered with recompacted native fine-grained soils. Thermal energy to the system was provided by way of a coupled solar water heater and storage tank, which was allowed to pump heated water through the panel for seven-hour increments over four days. Thermocouples installed at the panel interface and in the trench backfill provided temperature measurements during the four-day test and following three-day "cool-down" period.

The prototype system was modeled using SVHeat, a finite-element numerical heat-transfer modeling software. A two-dimensional simplification of the model was used, with the cross-section oriented perpendicular to the panel face. Symmetry at the panel face was used to further limit the model to the soils on only a single side of the panel. Thermal properties were assigned to the soils in the model, based on knowledge of the local geologic materials. The results of the initial model appeared to match the data measured during the real-world prototype experiment.

A sensitivity analysis was conducted to examine the effects of varying the soil properties, boundary conditions, initial conditions and the heat loads from the panel. Based on the results of the sensitivity analysis, minor adjustments to the soil properties and boundary conditions were found to be unnecessary, as the results of the analysis using the initial parameters appeared to confirm the relative validity of the model.

There exist several aspects of the prototype model validation and sensitivity analysis exist that may be refined with further research or data gathering. These include:

- Further examination of the soil/heat exchanger interface to better understand and model aspects such as soil/pipe adhesion, shrinkage effects, and other potential sources of conductivity loss.
- Use of soil properties that integrate coupled moisture/heat flows.
- Further experimental investigation with construction of one or more new prototype systems, with carefully obtained, detailed data, including heat output, soil temperature, climate data, soil thermal properties, employing a more common contemporary shallow GCHP system.

Chapter 4 of this study addressed the establishment of a simplified steady-state model of the prototype system, and the further establishment of a system of metrics to compare the effectiveness of the subsurface soils in dissipating input heat from the panel.

It was demonstrated that the effectiveness of heat dissipation in the subsurface portion of the GCHP system can be at least partially represented by the heat flux at the soil/heat exchanger interface, which increases with increasing heat dissipation effectiveness. For the purposes of this study, a simple metric was created to compare the relative effects of variations in the subsurface soil thermal properties and boundary conditions on the ability of the GCHP system to dissipate heat effectively.

The limitations of this metric in truly representing the complete performance of a horizontal GCHP system are relatively clear, and improvements to the modeling and effectiveness evaluation approach could be made with further studies. These improvements include:

- Selection of alternate baseline flux values base on actual performance requirements of existing shallow GCHP systems.
- Coupling the SVHeat model with HVAC modeling software, such as TRANSYS, to provide a comprehensive model that includes both the aboveground, mechanical system and the resulting influence on the underlying soil profile.

Chapter 5 of this study addressed adapting the steady-state model established in the previous chapter to reflect likely subsurface conditions encountered in arid climate regions. This included selecting new thermal properties for the soils in the model, as well as assigning new boundary conditions. Four different arid climate region conditions were modeled to represent typical far-field soil properties, based on the previous research discussed in Chapter 2.

It was shown that the selection of the thermal properties for the soil profile has a significant effect on the relative heat dissipation effectiveness of the model. This underscored the importance of obtaining accurate and reliable data for in-situ soil conditions in designing any future GCHPs in arid climate regions. It was determined that in certain cases, the much poorer heat dissipation effectiveness resulting from extremely unfavorable soil thermal properties in the native subsurface profile will likely outweigh any benefit from improvements to the trench backfill soils. With more favorable soil conditions however, improvement may provide a sufficient boost to the heat dissipation effectiveness of the subsurface profile to make the use of shallow GCHPs in arid climate regions a viable option for cooling applications. Several aspects of the arid climate region model may be refined with further research, including:

- Evaluating a model representing contemporary shallow GCHP systems instead of the prototype vertically-oriented panel.
- More detailed model at soil/heat exchanger interface to represent selection of materials, soil/pipe adhesion, etc.
- Use of soil properties that include coupled moisture and heat flows.

Chapter 6 of this study discussed the use of various soil improvement/ replacement techniques that may be applied to the trench backfill zone and prove beneficial to the operation of GCHP systems in arid climate regions.

A comparison of the effects of increasing the thermal conductivity of the trench backfill material further demonstrated the importance of characterizing the thermal properties of the subsurface soils.

The information discussed in this chapter included of a summary of the most recent relevant research available on soil improvement/replacement techniques for GCHP systems. Much of the information available has been develop for application with vertical GCHP systems and so additional discussion was included that addresses the applicability of the existing research to shallow, horizontal GCHP systems.

Chapter 7 of this study addressed the assumptions and simplifications that were made to the SVHeat mode in order to provide for easier comparison between various model results. Sensitivity studies were performed to evaluate the effect these simplifications and assumptions may have had on the results presented in this study.

The sensitivity studies examined: 1) the selection of the boundary conditions of at the heat exchanger panel and the subsurface boundary conditions in the far-field soils at the outside edges of the model (ambient soil conditions) were examined; 2) the effects of variations in the width of the backfill trench; and 3) the effects that the geometry of the heat exchanger (the panel) had on the results, compared to a more common heat exchanger geometry.

The discussion of the various soil improvement/replacement options for arid climate regions did not delve deeply into the aspects that may dictate the selection and use of any option, such as cost, constructability, etc. and instead only intended to suggest further pathways of study for later researchers. While the conclusion of this study is that limitations imposed on shallow horizontal GCHP systems in most arid climate regions generally makes them inappropriate for use in most cooling application, there still exists a the potential for improving the effectiveness of shallow horizontal GCHP systems with select far-field soil conditions that may be appropriate for further study. If future fuel costs or other sources of energy insecurity so dictate, or the current trend towards more efficient, sustainable energy use persists, further study is certainly encouraged. Some suggestions for further research:

- Refining the list of potential soil improvement methods using models that reflect conventional, commonly-used shallow horizontal GCHP systems.

- Full life-cycle analysis of potential soil improvement methods that includes excavation, installation, materials, and maintenance costs.
- Combining the subsurface effectiveness analysis with HVAC modeling software, such as TRANSYS, to design and analyze a complete GCHP system.
- Laboratory research to refine thermal properties of various cementitious grout fillers and mixes, and other backfill improvement options, that may prove most effective for arid climate region applications.

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