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Authors
Baser, Tugce
McCartney, John S

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Development of a Full-Scale Soil-Borehole Thermal Energy Storage System

Tugce Baser[1], M.S., S.M.ASCE and John S. McCartney[2], Ph.D., P.E., M.ASCE

[1]Graduate Research Assistant, University of California San Diego, Department of Structural Engineering, 9500 Gilman Dr. La Jolla, CA 92093-0085, tbaser@ucsd.edu.
[2]Associate Professor, University of California San Diego, Department of Structural Engineering, 9500 Gilman Dr. La Jolla, CA 92093-0085, mccartney@ucsd.edu.

ABSTRACT: This study involves an evaluation of the design and construction process for a soil-borehole thermal energy storage (SBTES) system installed in a sandy-silt deposit. A series of simplified numerical simulations were performed to understand the role of different variables on the heat storage in the SBTES system. The results indicate that soils with lower thermal conductivity have less lateral heat loss, and that arrays with smaller borehole spacings permit more concentrated storage of heat at higher temperatures.

INTRODUCTION

Soil-borehole thermal energy storage (SBTES) systems are an approach to provide efficient renewable resource-based thermal energy to heat buildings (Gabrielsson et al. 2000; Sibbit et al. 2007; Zhang et al. 2012; McCartney et al. 2013). They function in a similar way to conventional ground-source heat pump (GSHP) systems, where a fluid is circulated within a closed-loop pipe network installed in vertical boreholes to shed or absorb heat from the surrounding subsurface. Different from conventional GSHP systems, SBTES systems are configured to store thermal energy collected from solar thermal panels during the summer, and discharge the heat to buildings during the winter. The boreholes are typically spaced much closer together in an SBTES system than in a conventional system. The temperature of the ground within the borehole array increases from its ambient temperature (approximately 10-20 °C) to 60-90 °C during heat injection. SBTES systems are a convenient alternative to other energy storage systems as they are relatively inexpensive, involve storage of renewable energy (solar thermal energy), and are space efficient as they are underground. Most SBTES systems involve direct circulation of fluid through the closed-loop boreholes during heat injection and extraction, without the use of a heat pump.

Although soil-borehole thermal energy storage (SBTES) systems have been shown to be an effective tool for storing thermal energy collected from renewable sources such as solar panels (Sibbit et al. 2012), their transient response during heat injection is not well understood. The lack of understanding of their response prevents evaluation of strategies to minimize the lateral loss of heat from the borehole array, improving the efficiency of heat storage (i.e., difference between heat injected and heat extracted), and improving the rates of heat injection and extraction. Sizing of the borehole field is critical as an undersized borehole field may not provide the required heat capacity, while too large of a field will result in higher costs and a lower rate of heat transfer. To better understand these different issues, preliminary numerical analyses were performed to evaluate the role of different variables (heat injection rate, heat injection duration, ground thermal conductivity, borehole spacing) on different performance variables for SBTES systems. These analyses were used for sizing of a full-scale, instrumented SBTES system was constructed at the Colorado School of Mines in Golden, CO.

BACKGROUND

There are two main examples of successful SBTES systems. The first is the Drake Landing Solar Community (DLSC) in Alberta, Canada. This system supplies heat from solar thermal panels to an array of 144 boreholes that are 35 m deep, within a 35-m wide grid. The SBTES system at this site has provided more than 90% of the heating requirements to 52 houses for the past 6 years (Sibbit et al. 2012). Zhang et al. (2012) analyzed the heat exchange processes at the Drake Landing site using TOUGH2, and found that the efficiency of heat transfer defined as the amount of heat extracted divided by the amount of heat injected is approximately 27%. Although this amount seems low, the thermal energy injected into the SBTES system is obtained freely from a renewable source. The second example of a successful SBTES system is in Braedstrup, Denmark (Bjoern 2013). This system also supplies heat from 18,000 m^2 of solar thermal panels to an array of 50 boreholes with a depth of 47-50 m installed across an area with a width of 15 m. This system provides 14000 homes with 20% of their heat. At both sites, the heat is not constrained laterally within the SBTES array. The DLSC site includes a hydraulic barrier to minimize evaporation of water from the soil (the groundwater table is 6 m below the ground surface).

SBTES systems in the vadose zone may be able to take advantage of phase change phenomena in the pore water to obtain greater heat injection and extraction rates by formation of a convective cell between the borehole heat exchangers to make the SBTES system more efficient. Convection plays a major role in transporting energy in unsaturated soils subject to a temperature gradient. Smits et al. (2013) observed that the apparent thermal conductivity of unsaturated soils under elevated temperatures may be 40% greater due to the effects of thermally induced water flow in the soil. The water around the heat exchanger array is heated, vaporizes then moves upward due to buoyancy and toward colder regions away from the heat source, releasing latent energy while it cools. The water then condenses and flows downward due to gravity and back toward the dry soil around the heat source via capillarity. This process is referred to as a convection cell. Lu (2001) found that the rate of heat transfer in a convective cell in an unsaturated soil layer may be up to 10 times faster than assuming that heat conduction is the only means of heat transfer. Traore (2013) evaluated the behavior of SBTES systems in the vadose zone using a series of tank-scale physical modeling tests, and observed that a convection cell formed in a borehole array with a spacing of 300 mm, leading to an increase in the apparent thermal conductivity by about 7%, along with a slight increase in specific heat capacity of 4%. However, when the array spacing was decreased to 80 mm, the soil within the array experienced permanent drying and a reduction in thermal properties.

SIMULATION OF SBTES SYSTEMS

Model Description

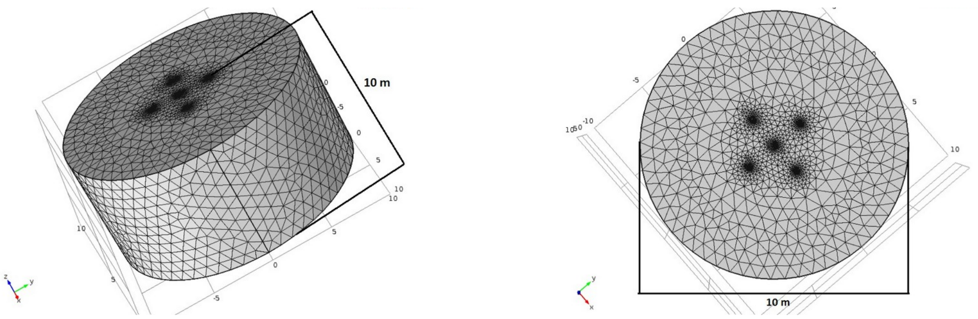
A three-dimensional (3D), transient finite element model developed in COMSOL Multiphysics was used to quantify the temperature response of the soil within and around an array of geothermal boreholes constituting an SBTES for design purposes. As this analysis is preliminary, heat transfer was assumed to be due to conduction alone. Although the goal of the field test is to evaluate the impact of the convective cycle, considering conduction alone still permits evaluation of the role of borehole spacing. The following governing equation was implemented into COMSOL:

$$(1) \quad \rho_t C_p \frac{\partial T}{\partial t} = \nabla(\lambda \cdot \nabla T)$$

where ρ_t is the total density of the soil (kg/m^3), C_p is the soil specific heat capacity (J/kgK), λ is the soil thermal conductivity (W/mK), T is absolute temperature (K), and t is time (s). The model geometry in COMSOL consists of 5 boreholes that are 10 meters in depth and 0.14 meters in diameter arranged in a triangular array, as shown in Figure 1. Different array spacings were evaluated in the simulations. Thermal insulation was applied on the top of the soil surface (zero heat flux), which is consistent with the insulation layer used in the SBTES systems in the field, and the initial ground temperature is assumed to be uniform and equal to 10°C for simplicity. The fluid flow through the heat exchanger tubing in the boreholes was not simulated in the simplified simulations presented in this study. Instead, a constant boundary heat flux was applied to the inside of the boreholes uniformly during heat injection. The boundary heat flux ($\dot{q}$) applied to the outside area of each borehole (W/m^2) was calculated for values of inlet and outlet fluid temperatures and fluid flow rates representative of typical SBTES systems (Schiavi 2009; Acuna and Palm 2012) using the following equation:

$$(2) \qquad \dot{q} = \frac{\dot{V} C_p \Delta T}{2\pi r L}$$

where $\dot{V}$ is the volumetric flow rate (m^3/s), ΔT is the temperature difference between inlet and outlet fluid (°C), r is the radius of the borehole heat exchanger (m), and L is the total length of the borehole heat exchanger (m). For values of $\Delta T = 2$ °C and $\dot{V} =$¿0.3 m^3/s typical of SBTES systems, along with a heat exchanger pipe having an inner radius of 0.016 m, and a total heat exchanger length of 200 m (five 10 m-deep boreholes with 20 m of heat exchanger in each), a boundary heat flux of 30 W/m^2 was calculated. This boundary heat flux was used as the baseline input heat flux in the simulations.



(a) (b)

Fig. 1: SBTES system in COMSOL: (a) Isometric view; (b) Plan view

Performance Variables for SBTES Systems

The main outputs of the COMSOL analysis are the spatial and temporal variations in soil temperature. Although evaluation of the temperature distribution can be useful in qualitatively evaluating SBTES systems, it is also important to define a new set of variables that can be used to assess the relative performance of SBTES systems with different configurations and soil properties. The first performance variable is referred to as the temperature density (*TD*), which is defined as:

$$(3)\quad TD=\frac{T_{ave}}{V_{storage}}$$

where T_{ave} is the average temperature of the soil (℃) within the heat storage volume $V_{storage}$ (m^3), which is defined as the volume of soil within a cylinder that is 2 borehole spacings from the center of the array. The TD parameter is useful because the goal of SBTES systems is to increase the temperature of the soil to as high of a value as possible by direct circulation of heated fluid through the heat exchangers. SBTES systems do not employ a heat pump, so the soil temperature must be much higher than in typical geothermal systems in order to facilitate heat extraction during the winter.

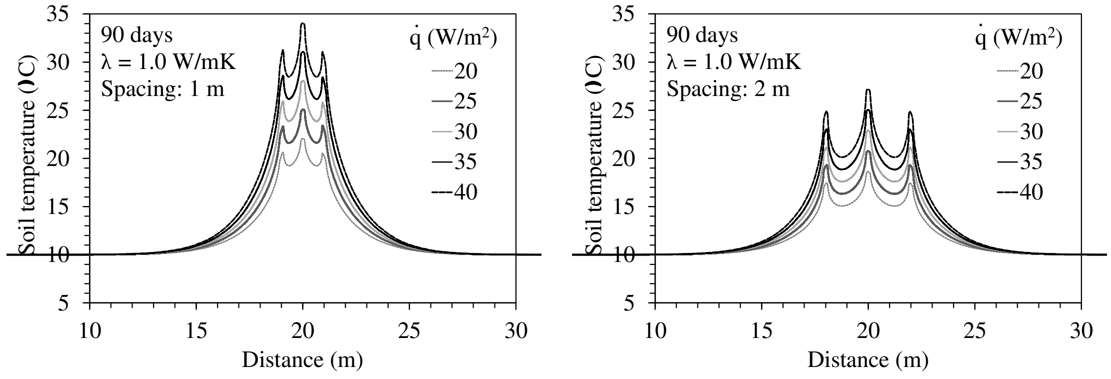
The efficiency of a heat storage system depends on the heat stored within the borehole array. Knowing the heat injected into the array Q_{inject} and the heat lost from the boundaries of the array Q_{lost}, the heat stored, Q_{stored} (J) can be calculated as:

$$(4)\qquad Q_{stored}=Q_{injected}-Q_{lost}$$

The heat injected can be calculated by integrating the boundary heat flux applied to the five boreholes over the duration of heat injection, while the heat lost from the array is the sum of the upward heat loss, downward heat loss and lateral heat loss.

Parametric Evaluation

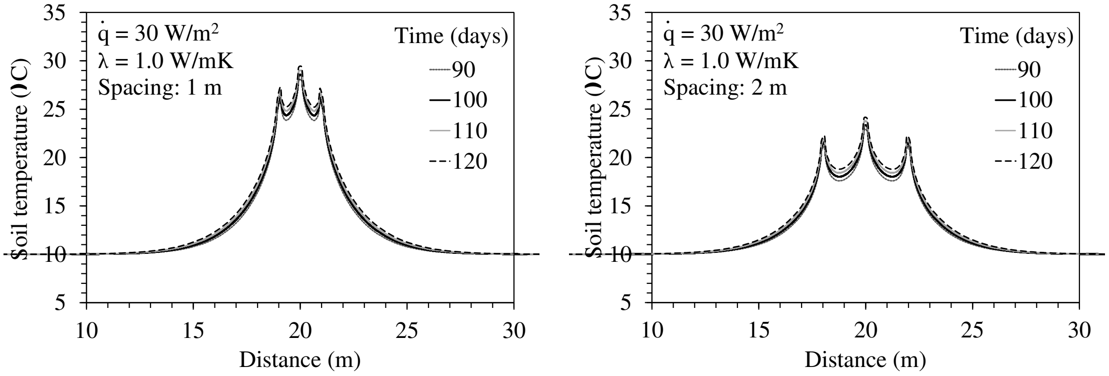
The first variable that was investigated is the magnitude of the boundary heat flux used in the analysis. In an SBTES system, the heat injection rate is dependent on the solar fraction, so the boundary heat flux is a function of time and climatic setting. The results in Figures 2(a) indicate that an increase in the input boundary heat flux of 5 W/m^2 results in an increase in ground temperature of approximately 3.0 ℃ for an array spacing of 1 m, while the results in Figure 2(b) indicate a smaller increase of 2.0 ℃ for the same increase in input boundary heat flux for an array spacing of 2.0 m.



(a) (b)

Fig. 2: Role of heat flux on soil temperature for spacings of: (a) 1.0 m; (b) 2.0 m

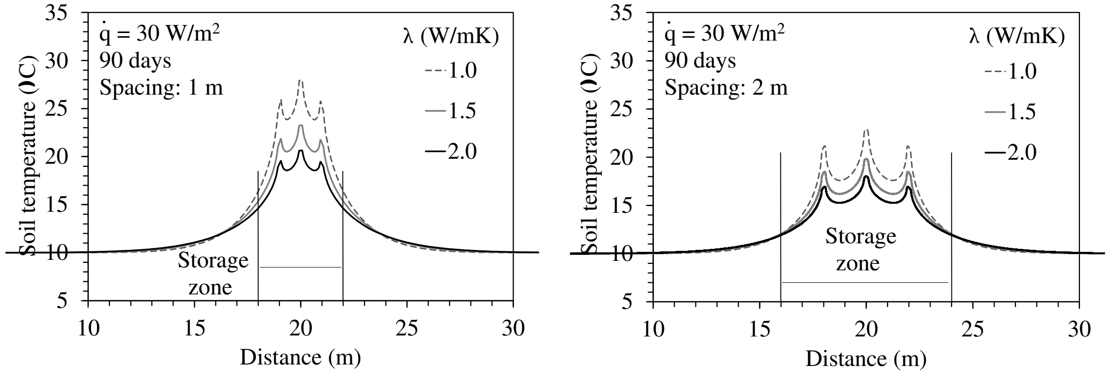
The average duration of heat injection for SBTES systems ranges from 90 to 120 days. The results in Figures 3(a) and 3(b) show the effect of the duration of heating, and confirm that the highest temperature was observed after 120 days of loading. However, the increase in temperature is not significant (only 1℃ in the center of the array) for more than 90 days of heating for the arrays under investigation.



(a) (b)

Figure 3: Effect of heating duration for array spacings of: (a) 1.0 m; (b) 2.0 m

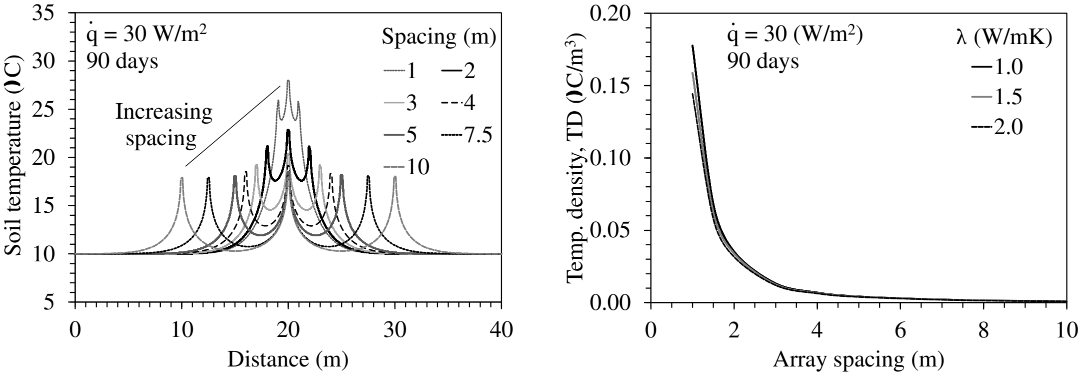
The distributions in temperature after 90 days of heat injection are shown in Figures 4(a) and 4(b) for arrays with borehole spacings of 1.0 m and 2.0 m, respectively and for three different soil thermal conductivity values. The temperature of the ground nearest the boreholes was greater in the soil with the lowest thermal conductivity, which indicates that the lowest amount of heat escaped laterally from this array.



(a) (b)

Figure 4: Thermal conductivity effects for array spacings of: (a) 1.0 m; (b) 2.0 m

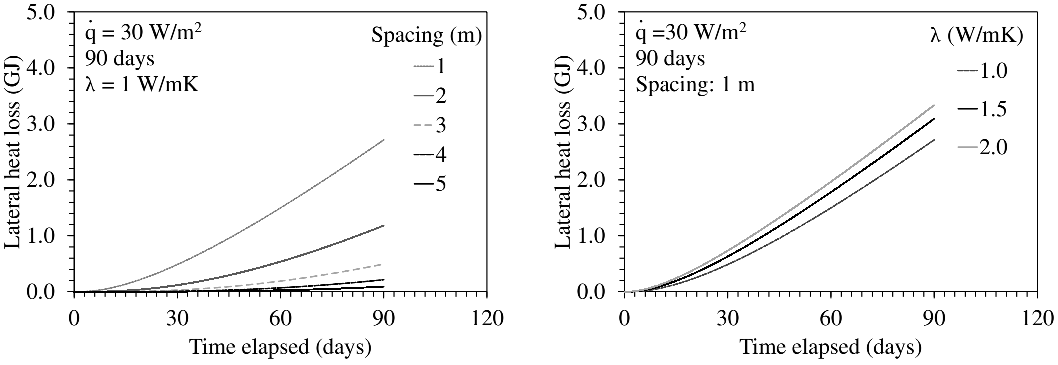
Selection of storage size is very important for SBTES systems. One objective of the numerical simulations is to decide the best ground-borehole configuration to make the storage of thermal energy as dense as possible. Also, the spacing should be as uniform as possible throughout the storage volume (Pavlov and Olesen 2011). An evalutaion of the borehole array spacing is shown in Figure 5(a). A smaller borehole array spacing will be able to store a greater energy density within the array, despite the fact that there is a greater thermal gradient driving heat loss from the array. The temperature density (TD) values for these arrays are shown in Figure 5(b) for soils with different thermal conductivity. For an increase in array spacing of 10%, the TD decreases by 90%. The value of TD decreases nonlinearly with increasing soil thermal conductivity, and approaches zero with increasing array spacings (due to the large value of volume in the denominator of Equation 3).



(a) (b)

Figure 5: Impact of borehole spacing: (a) Temperature distribution; (b) Temperature densities for different array spacings

The heat loss from an SBTES system is expected to increase over time during heat injection due to the higher thermal gradient between the array and the free field ground temperature (Chapius and Bernier 2009). When the SBTES system has reached its thermal storage capacity, the rate of lateral heat loss is expected to approach the rate of heat injection (depending on how the storage volume is defined). Due to the surface insulation the vertical heat loss is assumed to be negligible, while the downward heat loss is expected to be relevant only at the heat exchanger locations and will not change with array spacing. The lateral heat loss was calculated by integrating the boundary heat flux output from COMSOL across a cylindrical plane that is 1 spacing from the outside heat exchanger over time. For a total heat input of 5.13 GJ into the five heat exchangers over the course of 90 days, the heat loss results shown in Figure 6(a) indicate that arrays with smaller spacing will have greater heat loss as they reach higher temperatures. The results in Figure 6(b) indicate that heat loss is greater in soils having relatively higher thermal conductivities as the heat escaping from the storage is greater.



(a) (b)

Figure 6: Lateral heat loss values for: (a) Different array spacings; (b) Different soil thermal conductivity values

CONSTRUCTION OF THE SBTES SYSTEM

Site Description

The full-scale SBTES system was installed at the Mines Park site on the Colorado School of Mines Campus. The subsurface at the site consists of 8.2 m of silty sand with cobbles (colluvium) underlain by 3 m of clean sand, underlain by claystone bedrock. The water table was encountered at a depth of approximately 6 m from the surface. The thermal conductivity of the unsaturated colluvium measured using the thermal needle method in-situ was approximately 1.1 W/mK, while the thermal conductivity of the saturated sand measured on a reconstituted specimen was approximately 1.2 W/mK.

Solar Thermal Characterization

Although the heat injection period has not yet started for the SBTES system, the behavior of an evacuated tube solar thermal panel (model NGE-224-TU from Next Generation Energy of Lafayette, CO) having a collector area of 3.5 m^2 was evaluated at the site. A 20% propylene glycol-water solution was circulated through the panel at a flow rate of 3.4 ml/s, then through a copper tube within a chiller cabinet that acts as a heat sink. The outlet fluid temperatures shown in Figure 6 indicate that the radiative heat transfer in the panel regularly lead to superheated fluid temperatures exceeding 100 °C. The thermal energy collected from the panel was about 12 kWhr per day.

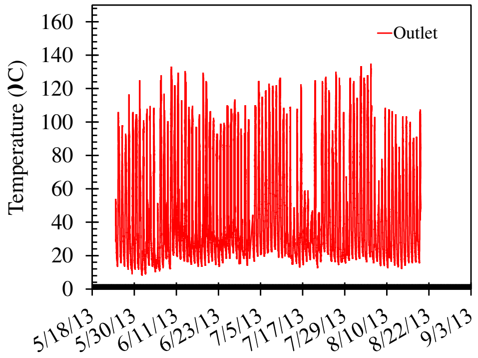
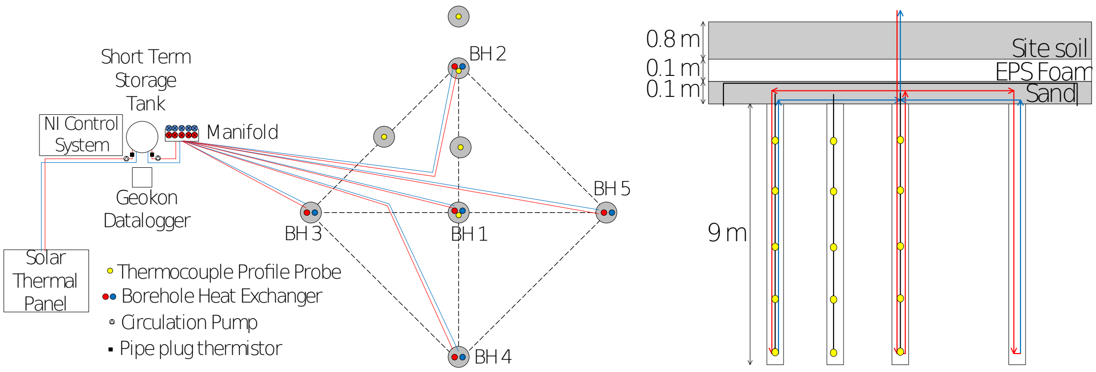


Figure 6: Solar thermal panel evaluation

SBTES System

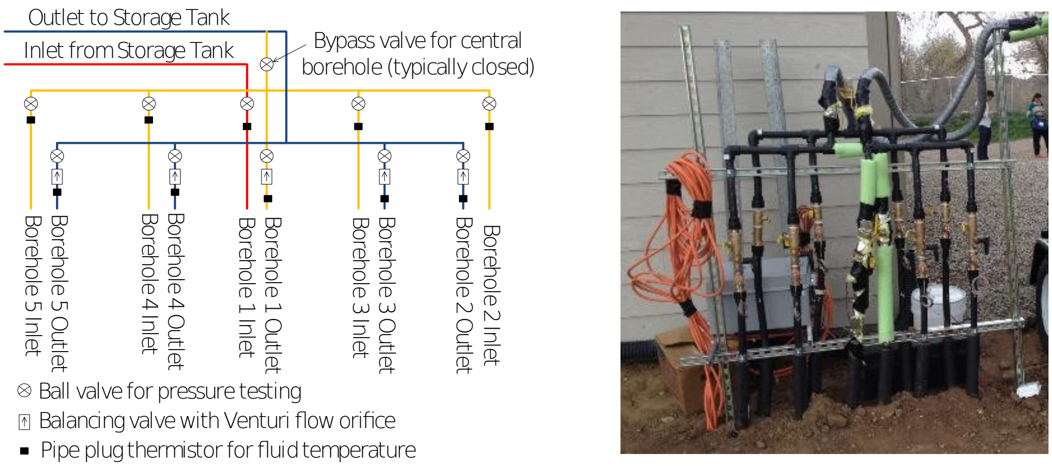
The SBTES system includes 5 borehole heat exchangers in a triangular array with a spacing of 2.5 m, as shown in Figure 7. The heat exchangers consist of high density polyethylene tubing with a “U”-shape coupling at the base. Although Figure 5(b) indicates a smaller spacing will lead to higher temperatures, this spacing was selected to permit inclusion of instrumentation in the array. Three additional boreholes included thermistor strings, which have five thermistors connected to a single cable. Their purpose was to measure the temperature distribution to infer heat transfer processes within the array and out of the array. Another purpose is to observe if a convective cell is forming as the soil nearer the surface will become wetter over time. Sensor data will be compared with COMSOL analyses of the coupled water flow in unsaturated soils to evaluate differences over time. The array was configured so that heat would be injected into the central borehole first, then into the surrounding four boreholes. This is different from the simulations, but permits heat to be concentrated in the center of the array.



(a) (b)

Figure 7: SBTES at CSM: (a) Plan view with control system; (b) Elevation view

The layout of the manifold used to route the fluid in the system is shown in the schematic in Figure 8(a) and in the picture in Figure 8(b). Balancing valves with a Venturi flow orifice are installed on one leg of the "U" tubes to monitor the flow rate in each loop. The pressure drop across the orifice is measured using a differential pressure transducer, which can be used to estimate the flow rate at any time. It is expected that the flow rate will vary due to the temperature fluctuations of the fluid during heat injection and extraction. The temperatures of the fluid entering and exiting each of the five loops are monitored using pipe plug thermocouples. The difference in the inlet and outlet fluid temperatures (T_{in} and T_{out}) along with the fluid flow rate and heat exchange fluid properties (summarized in Table 1) can be used to calculate the heat flux $\dot{q}$ using a modified form of Equation 2.



(a) (b)

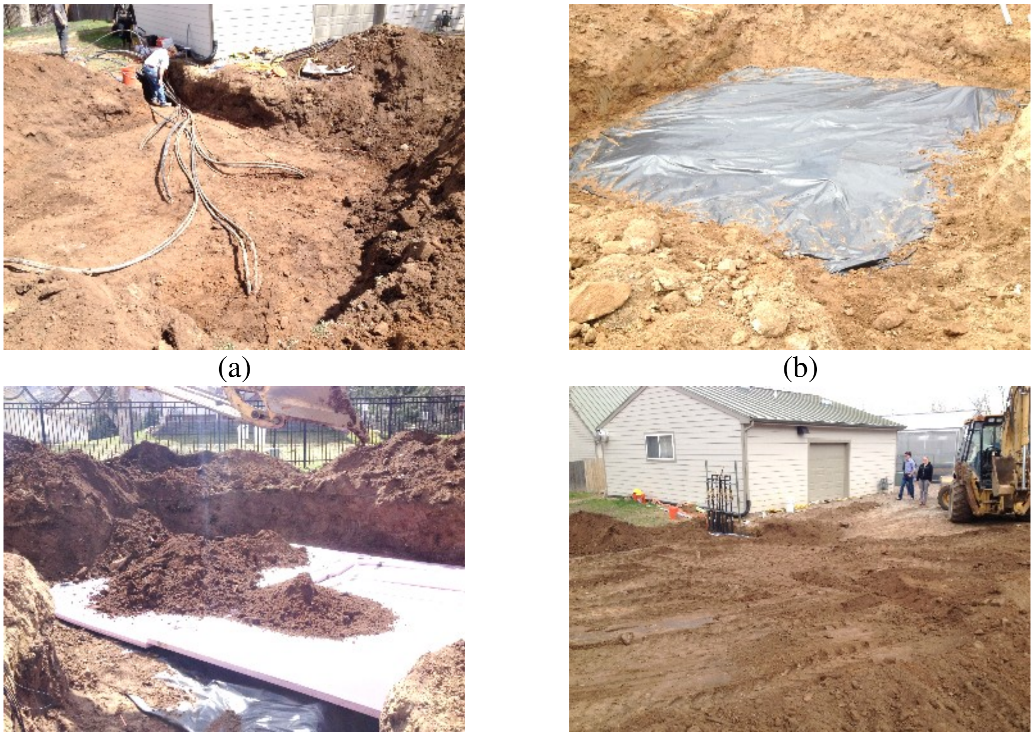
Figure 8: Heat exchanger manifold configuration: (a) Schematic; (b) Picture

Table 1: Heat exchange fluid properties

Water to Propylene Glycol Ratio	Molar Heat Capacity (J/molK)	Molecular Weight (g/mol)	Specific Heat Capacity (J/kgK)	Fluid density (g/ml)
5:1	98	30	3267	1.008

Construction Process

After drilling the boreholes having a diameter of 100 mm using the slurry method, the heat exchangers and/or thermistor strings were pushed into the holes using a “stinger” to the target depth. A tremie pipe is also installed into the hole at this time. A 50-50 mixture of sand and bentonite grout was then pumped into the hole to displace the slurry. Next, a 7-m square was excavated around the heat exchangers, as shown in Figure 9(a) and the heat exchangers were routed toward a manifold area. After placing a layer of site soil to level the area around the heat exchangers, a hydraulic barrier having a thickness of 30 mils was placed on the soil surface, as shown in Figure 9(b). A layer of expanded polystyrene (EPS) insulation was placed on top of the hydraulic barrier, as shown in Figure 9(c), and the site was leveled. After installation, only the manifold is visible on the surface, as shown in Figure 9(d).



(a) (b)

(c) (d)

Figure 9: Pictures of the SBTES installation

SBTES Heat Injection System

The layout of the heat injection system is also shown in Figure 7(a). The propylene glycol-water mixture is circulated through the solar thermal panel on the roof of an adjacent building using a circulating pump. The temperature of the fluid is monitored constantly, and a National Instruments (NI) control system is used to operate a solenoid to circulate the fluid within the panel when the temperatures are below a target value, or circulate the fluid through a short term storage tank. A closed-loop heat exchanger within the tank will transfer the stored heat into the borehole array by circulating fluid using a second circulating pump. The NI system can also be used to control a second solenoid to transfer heat into the ground, or to keep the fluid circulating in the tank so that the ground is not cooled off during cold time periods.

CONCLUSIONS

A simplified numerical simulation of SBTES systems in COMSOL indicates that they will have better performance in soil layers with lower thermal conductivity, such as those encountered in the vadose zone above the water table. This is primarily due to the lower amount of lateral heat loss. Borehole arrays with smaller spacings also store a more concentrated amount of heat. This paper shows the construction details of a SBTES system, along with the details of the heat transfer control.

ACKNOWLEDGEMENTS

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