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Development of New g-function Data for Simulating a Novel Shallow Bore Ground Heat Exchanger

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ABSTRACT

Geothermal heat pump (GHP), which is also referred as ground source heat pump, is the most energy-efficient technology for space heating and cooling. However, the application of GHP is hindered by its high initial cost, of which approximately 30% is for the ground heat exchanger (GHE). In recent years, researchers have developed different types of shallow bore ground heat exchangers (SBGHE) intending to reduce the cost of drilling. The ability to predict the thermal response of an SBGHE is critical for sizing SBGHE. While g-functions have been commonly used for predicting the thermal response of conventional vertical bore ground heat exchangers (VBGHE), they cannot be directly used for predicting the performance of SBGHE because they did not account for the impacts of the seasonal variation of the soil temperature along with the depth of an SBGHE. In addition, an SBGHE has a larger thermal mass within the borehole than the VBGHE due to the larger borehole diameter of SBGHE. This study develops new g-function data pairs for a new design of SBGHE, which is named Underground Thermal Battery (UTB). Impacts of the seasonal variation of soil temperature on the thermal response of UTB were accounted for by superposing a time-dependent soil temperature onto the g-functions calculated with a numerical model that assumes constant undisturbed soil temperature. The TOUGH program was used to predict the thermal response of several configurations involving multiple UTBs. The results indicate that the proposed methodology is appropriate to generate g-functions for the UTB, and the g-function value of UTB is much lower than that of VBGHE in the time range of 15 min to 1 year due to the large thermal mass and convection heat transfer within the UTB.

1. Introduction

Geothermal heat pump (GHP), which is also referred as ground source heat pump (GSHP), is an energy-efficient technology for space heating and cooling. Since the soil temperature is more stable than the ambient air temperature throughout the year, the efficiency of the GSHP is typically higher than the air-source heat pump (ASHP). However, the market share of the GSHP is much lower than that of the ASHP due to the high initial cost of GSHP.

The ground heat exchanger (GHE) usually accounts for 30% of the total cost of a GSHP system (NYSERDA 2017). Vertical bore ground heat exchanger (VBGHE) dominates the market in the United States, and the expensive drilling for the vertical borehole (typically 60-120 m depth) is the primary factor for the high initial cost (Liu et al. 2018). In recent years, researchers developed several shallow bore ground heat exchangers (SBGHEs), which can be installed in boreholes with a larger diameter and shallower depth (e.g., 6 m) to reduce the initial cost of the GSHP (Cimmino and Eslami-Nejad 2017, Bertermann et al. 2018, Najib et al. 2019, Warner et al. 2020). Among them, a novel SBGHE design named underground thermal battery (UTB) proves to have equivalent performance compared with conventional VBGHE (Warner et al. 2020). The main configuration is a helical coil heat exchanger immersed in a cylindrical water tank and installed in the shallow sub-surface of the ground. The helical heat exchanger connects to the source side of the heat pump and exchanges heat with the tank water, and ultimately with the surrounding soil. This design utilizes the large thermal capacity of the tank water to buffer thermal inputs and thus ensures its performance equivalent to VBGHEs. In UTB, phase change materials were incorporated into the tank to further increase its capacity. This novel SBGHE design was further integrated with a thermal storage tank and formed a design named DPUTB to enhance the flexibility and the thermal efficiency of the heat pump system (Shi et al. 2021a).

The ability to predict the thermal response of the GHE is essential to the design, control, and energy analysis of the GSHP systems. For VBGHEs, g-function is a computationally efficient approach for predicting the performance of GHEs. The g-function is a series of pre-calculated non-dimensional response factors of the borehole wall temperature in response to a constant heat input to the borehole. It covers a range of times – at short times (minutes to hours), factors such as fluid transition time, heat transfer within the borehole, and the heat transfer in the surrounding soil of the borehole affect the response. At longer times, borehole-to-borehole interference and the end effects (i.e., heat transfer from/to the ground surface and the ground formation beneath the boreholes) become more important.

Eskilson (1987) developed g-functions for long time steps, and later short time response factors for VBGHE were developed by Yavuzturk and Spitler (1999). The method was further modified by Xu and Spitler (2006) considering time-varying thermal resistance and fluid thermal mass. The existing g-functions cannot be directly used for modeling SBGHE for several reasons. First, the heat fluxes at the ground surface have significant impacts on SBGHE performance, however, they were not accounted for in existing g-functions because the impacts of ground surface heat fluxes are not significant for the VBGHE, which is installed in boreholes much deeper than the SBGHE. Second, SBGHEs are installed in boreholes with a larger diameter and shallower depth than those for VBGHEs. Specific to UTB, the thermal capacity of the borehole is greater by involving tank water, and the heat transfer mechanism is different from conventional VBGHEs. Thus, a new approach or a new g-function generating method is in demand.

This study develops a method for calculating g-functions for UTB. A numerical model was developed to predict the thermal response of UTB. The superposition method was used to account for the time-varying soil temperature along the shallow boreholes. The simulation results were used to generate a g-function for a single borehole. The TOUGH program was used to generate g-functions for various multiple-borehole configurations.

2. Methodology

2.1 Modeling of UTB

Typically, the thermal response of the VBGHE is reflected using the borehole wall temperature. For UTB, the temperature of the tank water is deemed equivalent to the borehole wall temperature because the tank temperature is almost uniform due to the convection movement of water in the tank caused by heat rejection or extraction. The methodology of modeling a single UTB borehole was described by Shi et al. (2021b). The thermal response of the UTB is weather-sensitive due to its shallow depth. Notice that the current model is specific for UTB, for other types of SBGHEs, different models considering their heat transfer characteristics should be developed.

2.2 Superposition

To avoid repeatedly generating massive g-functions for UTB with different climates, the effect of the heat flux at the ground surface and the consequential undisturbed soil temperature gradient was separated from the single borehole model mentioned in section 2.1 by using the principle of superposition. The same numerical model with simple boundary conditions (weather-free) was first developed to generate the g-function, and the effect of the complex boundary conditions was added later. Figure 1 shows the principle of superposition for this study.

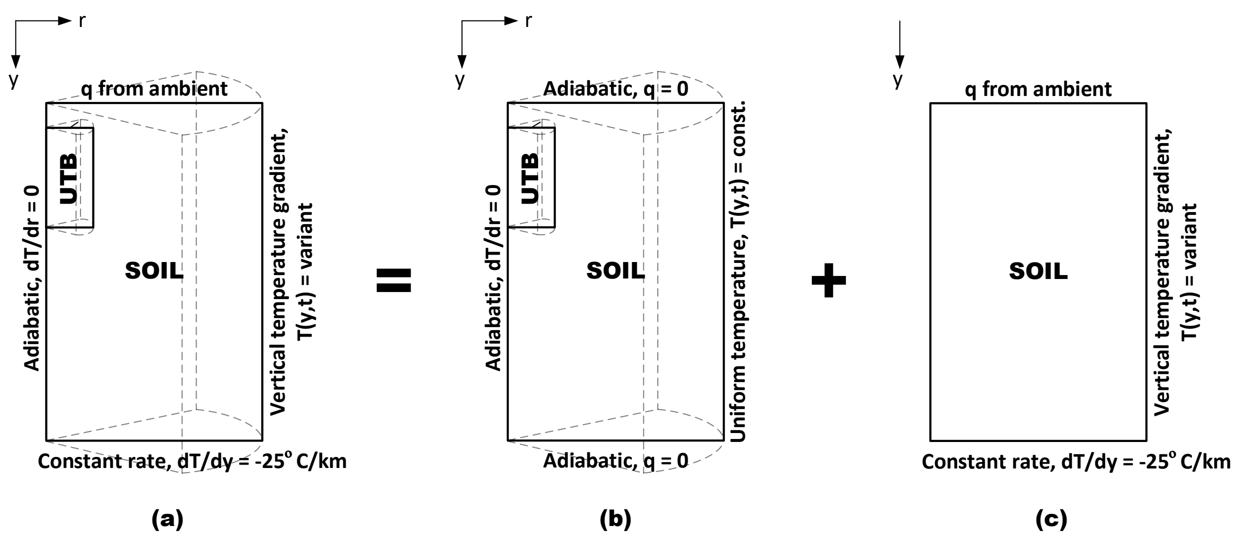

Figure 1: Schematics of superposition principle.

The thermal response of the UTB (tank water temperature) with complex boundary conditions (Figure 1a) is a superposition of its thermal response with simple weather-free boundary conditions (Figure 1b) and the impact of the undisturbed soil temperature (Figure 1c). In this way, the weather impact to the UTB thermal response is decoupled, and the g-function can be retrieved from a weather-free model (Figure 1b).

Thus, the expression of the g-function for a UTB type SBGHE can be:

$$T_{bore}(t) = T_{I.C.} + \sum_{i=1}^{n} \frac{Q'_i - Q'_{i-1}}{2\pi k_s} g\left(\frac{t_n - t_{i-1}}{t_s}\right) + \mathrm{d}T_{weather}(t) \quad (1)$$

where T_{bore} is the borehole temperature which is equivalent to the tank water temperature, $T_{I.C.}$ is the initial temperature for the simple boundary condition in Figure 1b, Q' is the heat transfer rate per unit length of GHE, k_s is the thermal conductivity of the soil, t is time, t_s is the soil time scale to steady state, $g()$ is the g-function, $\mathrm{d}T_{weather}$ is the impact of the weather, i is the step when heat pulse changes, and n is the total number of such steps.

Notice that the sum of the 1st and the last terms on the RHS of Eq. 1 is the undisturbed soil temperature, and the g-function can be determined from the simulation results using the model with simple boundary condition. Given simulated borehole temperature profile, the g-function can be calculated using:

$$g\left(\frac{t}{t_s}\right) = 2\pi k_s\left(\frac{T(t) - T_{I.C.}}{Q'}\right) \tag{2}$$

2.3 TOUGH model for multiple boreholes

iTOUGH2/EOS3 software is used in this study to create accurate water tank temperature evolution for large-scale (multiple) deployment of UTB boreholes. The TOUGH ("Transport Of Unsaturated Groundwater and Heat") suite of software codes are multi-dimensional numerical models for simulating the coupled transport of water, vapor, non-condensable gas, and heat in porous and fractured media (Pruess et al. 2012). iTOUGH2 provides inverse modeling capabilities for the TOUGH codes (Finsterle et al. 2014). The equation of state module 3 (EOS3) provides accurate thermodynamic fluid properties for a system with water, air and heat. When used for the purpose of this study, the fluid flow is disabled (by setting a zero permeability in the system), i.e., there is no heat convection in the soil, only heat conduction is considered.

When multiple UTBs are considered in a model, a global radial mesh cannot be used because the radial symmetry around the center of one UTB does not exist anymore. Instead, a rectangular mesh is used for the entire model domain. The water tank along with a few soil layers can then embedded into the TOUGH mesh, as shown in Figure 2. The scheme has been used by Zhang et al. (2021) previously.

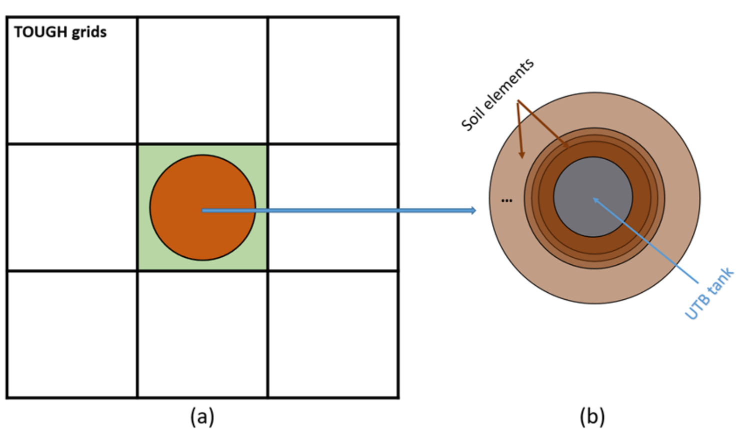

Figure 2: Schematics showing how an UTB is embedded into a TOUGH model.

In theory, the soil layer is not needed. However, there is material change and sharp temperature gradient is expected right at the tank-soil interface. A very fine grid is needed. Without some layers of radial soil elements, the created mesh could be very large. For this study, after comparison of a few scenarios with different soil layer thickness in the radial mesh, it is decided the distance between the two UTBs (6.1 m) will be used for the diameter of the soil layer diameter. A schematic of the two UTB mesh is shown in Figure 3.

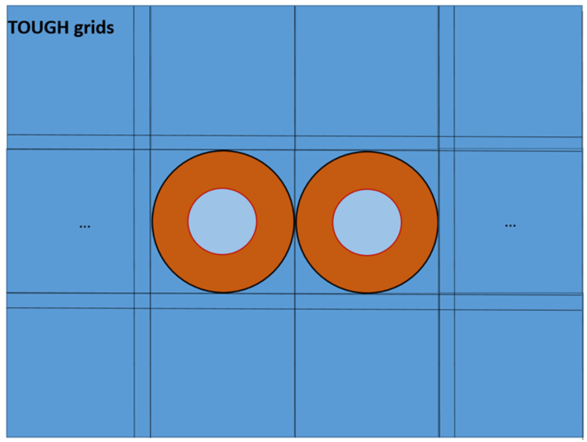

Figure 3: Schematics of the TOUGH grids for two UTBs.

3. Results and Discussions

A case study was implemented using the model mentioned in section 2.1 to validate the superposition principle and to generate g-function for a single UTB. The g-functions for multiple UTBs were generated using TOUGH models. Detailed information of the simulation is listed in Table 1.

Table 1: Model configuration for single borehole.

Parameter/Data	Unit	Value/Description
UTB diameter	[m]	0.76
UTB length	[m]	6
buried depth	[m]	0.5
soil domain diameter	[m]	39
soil domain depth	[m]	20
soil conductivity	[W/m K]	1.7
soil density	[kg/m^3]	1602
soil specific heat	[J/kg K]	935
constant thermal input	[W]	500
weather	[-]	TMY3 for Knoxville, TN

3.1 Superposition validation

Three models shown in Figure 1 were developed and an annual simulation was implemented. The results are shown in Figure 4.

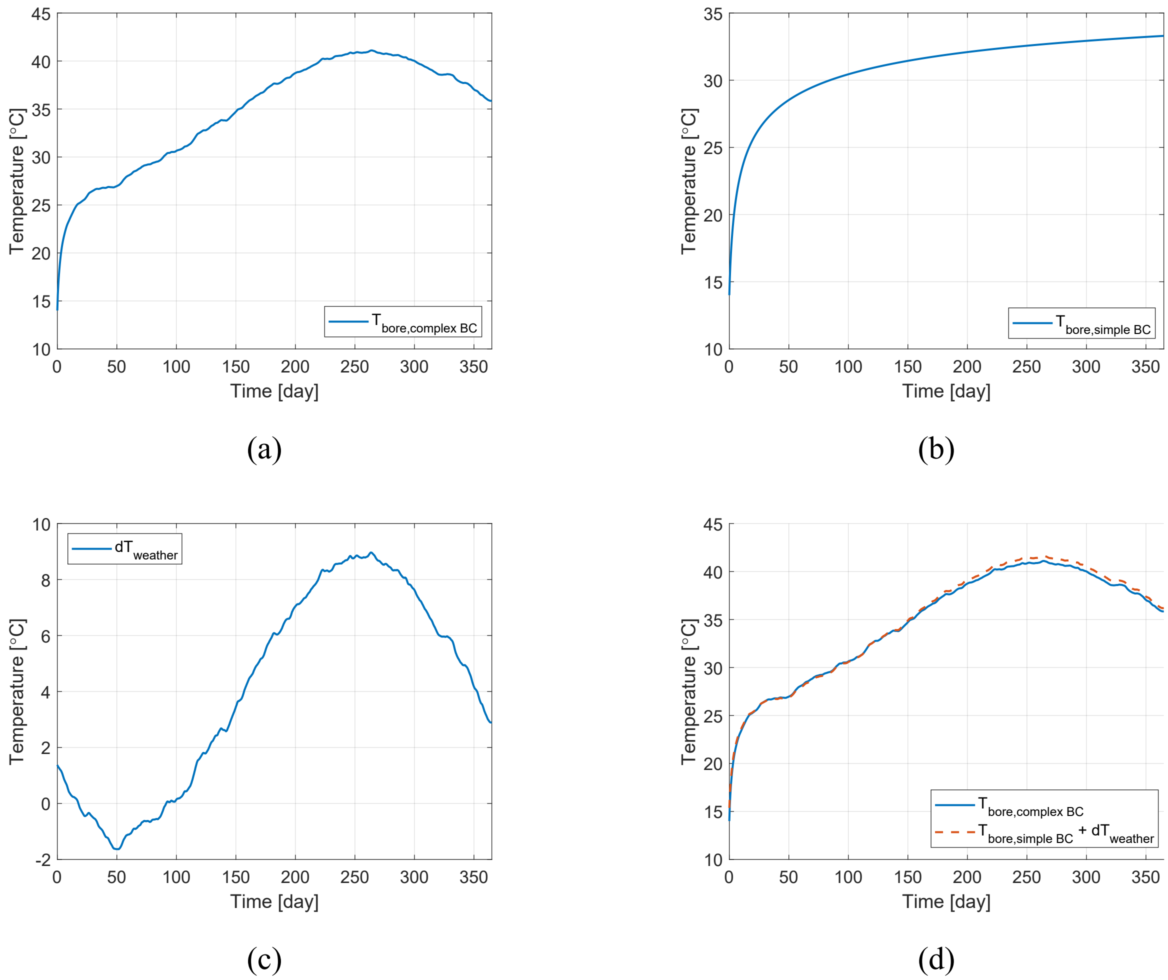

Figure 4: Simulation results of (a) UTB tank water temperature resulting from time-varying soil temperature, (b) UTB tank water temperature resulting from constant soil temperature, (c) Difference between the time-varying average soil temperature along with the depth of the UTB and the constant soil temperature, and (d) UTB tank water temperature predicted with superposition.

Figure 4 a-c are simulation results corresponding to models illustrated in Figure 1 a-c. If the superposition principle holds, the temperature profile in subfigure 4a should be similar to that of the superimpose of the subfigures 4b and 4c. The comparison results are shown in Figure 4d. It can be observed that the two curves are almost identical, the root-mean square error (RMSE) between them is 0.35 °C. It indicates that the proposed superposition principle to decouple the weather impact from the g-function generation works.

3.2 G-function generation

Data from Figure 4b were used to generate g-function for a single UTB using Eq. 2. With a different modeling mechanism, the thermal response of the single UTB was also simulated using a TOUGH model with the same configuration (Table 1). The g-function curves generated by these two methods were plotted in Figure 5. Since the model described in section 2.1 was developed in MATLAB, here we name this method as 'MATLAB'. The results in Figure 5 show that the two methods correspond with each other very well.

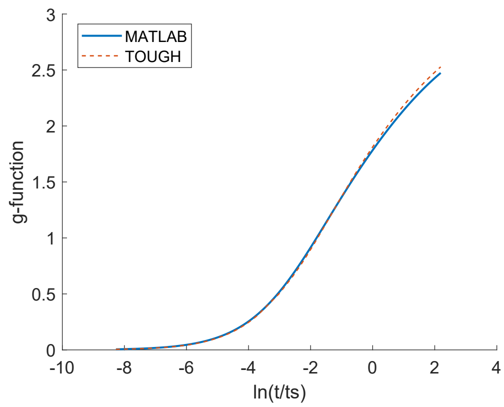

Figure 5: The g-function curves for a single UTB using two simulation methods.

Further, revised TOUGH models were developed according to section 2.3 to generate g-functions for multiple UTB boreholes. Three gridding configurations were implemented: 2 boreholes in a line (2x1); 2 by 2 (2x2); and 6 by 6 (6x6). Notice that for all cases, the borehole spacing is 6.1 m. For comparison, g-function curves for conventional VBGHEs with the three layouts of boreholes were generated from the g-function Library for Modeling Vertical Bore Ground Heat Exchanger (ORNL 2021), which is available in the U.S. Department of Energy's Geothermal Data Repository. Figure 6 shows the generated g-function curves for various UTBs, and g-function curves of VBGHEs with the same borehole layouts. For VBGHEs with 60 m borehole depth, the borehole diameter is 15 cm. The borehole configurations available in the g-function library for VBGHE have a fixed ratio of 0.1 between the borehole spacing and the borehole depth. Since the borehole depth is typically 60 m, the spacing for VBGHE is around 6 m. Therefore, with the same borehole layouts, VBGHE and UTB use almost the identical land area.

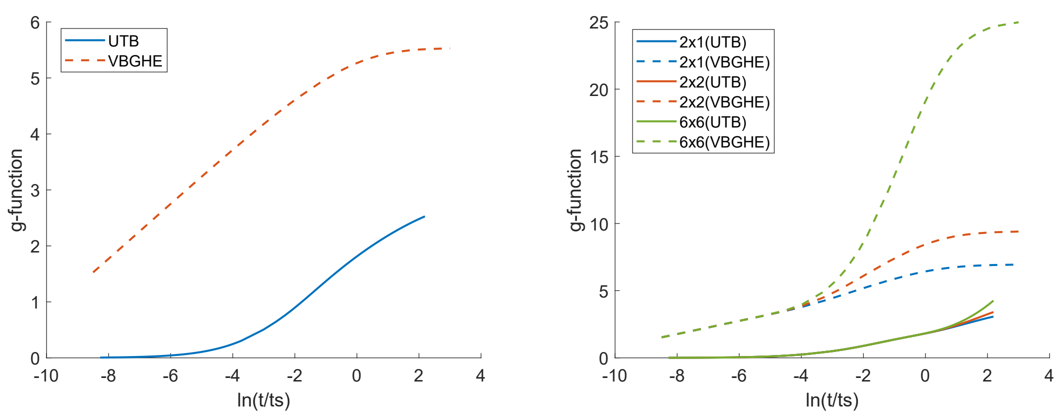

Figure 6: Comparison of g-functions curves between UTB and conventional VBGHE. Left: single borehole. Right: multiple boreholes.

As can be observed from Figure 6, compared with conventional VBGHE, the g-function value for the UTB is much lower than that for VBGHE in the time range of 15 min to 1 year. It indicates that the borehole temperature of the UTB will not fluctuate as much as that of the VBGHE, which is due to a greater thermal capacitance of the UTB borehole. The g-functions for a longer time range (multiple years) will be generated in the future study.

4. Conclusions

This study explored a method for generating new g-functions for simulating a novel SBGHE – namely 'UTB'. The impact of the nonnegligible weather impact on the GHE thermal performance was decoupled from a weather-free model based on the superposition principle. New g-functions for single and multiple UTB were generated. The conclusion of this study includes:

- Superposition principle works well to decouple the weather impact on the UTB thermal response. A weather impact-free model can be used to develop g-functions for UTBs, and the weather impact on the thermal response can be superimposed with the time-varying average value of a temperature profile along with the depth of the UTB, which is generated with a simple 1D soil model.
- TOUGH models successfully generate g-functions for cases with multiple UTBs boreholes. The g-function value of UTB is lower than that of conventional VBGHE in the time range of 15 min to 1 year due to a greater thermal capacitance of the UTB borehole.
- The g-functions generated in this study are specific for UTB. To generate g-functions for other types of SBGHEs, both the short-term (hours) and long-term (years) heat transfer performance of the SBGHEs should be modeled numerically or analytically.

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