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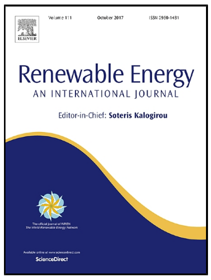

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PII:	S0960-1481(17)30526-8
DOI:	10.1016/j.renene.2017.06.025
Reference:	RENE 8889
To appear in:	*Renewable Energy*
Received Date:	10 November 2016
Revised Date:	26 May 2017
Accepted Date:	04 June 2017

Please cite this article as: Chanjuan Han, Kevin M. Ellett, Shawn Naylor, Xiong (Bill) Yu, Influence of Local Geological Data on the Performance of Horizontal Ground-coupled Heat Pump System Integrated with Building Thermal Loads, *Renewable Energy* (2017), doi: 10.1016/j.renene. 2017.06.025

Influence of Local Geological Data on the Performance of Horizontal Ground-coupled Heat Pump System Integrated with Building Thermal Loads

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ABSTRACT

Horizontal ground-couple heat pump (GCHP) system incurs lower installation cost compared with the vertical GCHP system. However, the shallow burial depth makes the heat transfer process susceptible to seasonal variations. This paper analyzes the short-term and annual performance of different geothermal heat exchangers' (GHEs) configurations and geological conditions by developing 3D finite element models. Field monitored data of ground temperature and thermal property are incorporated. Six common types of GHE configurations are analyzed, from which the most efficient patterns are identified. The annual performance of optimal GCHP pattern integrated with different types of building loads are analyzed. Major conclusions include (1) application of soil temperature harmonic function as commonly done in the current practice will lead to overestimation of thermal build-up effects underground; (2) utilization of local geological data (i.e., field measured ground temperature and soil thermal properties) helps improve the annual performance of horizontal GCHP system; (3) shift of ground temperature is less significant for GCHP operating in heating dominant areas due to balanced heat injection and extraction. This study indicates incorporating local geological data reduce the GHE design length by 25% to 60% and therefore is a viable strategy to achieve cost effectiveness.

KEYWORDS

Horizontal geothermal heat pump system, finite element model, building thermal load model, building integration, field monitoring data, geology

1. Introduction

The environment issue and fossil fuel crisis have greatly promoted the renewable energy revolution. Geothermal energy, as one type of renewable energy, has been widely explored worldwide. The direct utilization of geothermal energy has been reported to be the most promising renewable energy format, and the total installation capacity at the end of 2014 has increased around 45% compared with that in 2010 [1]. China, United States, Sweden, Turkey and Germany contributed to about 65.8% of the direct-use installed capacity [1]. With the growing awareness and remarkable development of geothermal heat pump system, the application of geothermal energy has opened a promising pathway to achieve sustainability.

The most typical and popular utilization of geothermal energy is the ground-coupled heat pump (GCHP) system, which utilizes the geothermal heat exchangers (GHEs) to extract/inject heat from/to the ground. Horizontal GCHP system, whose underground heat exchanger pipes are connected in series or parallel in a horizontal trench, is attractive due to its merits of low installation cost and easy maintenance, particularly for residential applications. Although many numerical [2-8] and experimental [6, 9-12] studies have been conducted to investigate the performance of GCHP system with vertical GHEs over recent years, only limited studies have been reported on GCHP system with horizontal GHEs [13-19]. Congedo et al. [13] conducted a simulation based comparison of GCHP system with horizontal GHEs in three configurations, i.e., linear, helical and slinky. Their results showed that the helical GHE arrangement is the most efficient, and thermal conductivity of the ground is the most influential factor for horizontal GCHP system. Naylor et al. [14] suggested it is necessary to consider the seasonal variations of soil thermal properties to optimize horizontal GCHP system design. Their results indicated using in-situ measured seasonal soil property data can decrease the design length of GHEs by 44-52% compared with applying standard industry practice to the estimate soil thermal properties. Naili et al. [15] carried out an experimental study to characterize the GHEs response and evaluate the optimal parameters of GCHP system with horizontal GHEs installed in a hot climate zone. The highly dependency of horizontal GCHP system on climate and building type in term of economic efficiency was also reported by Wiryadinata [16]. Benli [17] deployed experiments to compare the performance of GCHP system with horizontal and vertical GHEs for a greenhouse heating, which illustrated that although GCHP system with vertical GHEs achieved a higher Coefficient of Performance (COP) than the horizontal counter part, the significant higher installation cost of vertical GHE is a major implementation barrier. Sanaye [18] applied the Genetic Algorithm technique to conduct the thermal and economic simulation and optimization of horizontal GCHP system. Recently, an innovative bio-inspired model that integrated regression techniques and local models was proposed to investigate the ground temperature behavior after installing the horizonatal GHEs [19]. Overall, the existing study and knowledge on the behaviors of horizontal GCHP system is limited. Another major problem for GCHP system integration with building is that although many simulation tools (i.e., eQuest, TRNSYS) provide modules to conduct the integrated simulation with the GCHP system, the model of GHE is based on a number of simplifications and ignors the influence of geometry and transient behavior of soil thermal properties, which can be crucial for horizontal GCHP system. These lead to problems (i.e. overdesign) for GCHP system design and operation.

This study aims to study the horizontal GCHP system performance with respect to the seasonal variations of the ground conditions. A 3D numerical model is developed to simulate the heat exchange process associated with different horizontal GHE configurations. The seasonal soil parameters from a field monitoring program are used to populate the model parameters, which represent two contrast scenaries, i.e., one with significant variations of ground thermal properties and one maintains relative stable. The behaviors of horizontal GCHP system in meeting building loads requirements at different climate zones (i.e., seasonal balance, heating dominant, cooling dominant) are analyzed. The study demonstrates the importance of considering the seasonal ground properties variations in improving the design and achieving desired short-term and annual performance of horizontal GCHP system.

2. Numerical Model Development and Implementation

2.1 Finite Element Modeling

Han and Yu [2] presented a 3D coupled finite element model (FEM) to study the thermal behaviors of vertical GHE and to analyze factors affecting its performance. The model developed in this study refers to the theory described in [2] and therefore is not repeated here to avoid duplication. With this theory, a 3D FEM was developed for horizontal GHE via a commercial finite element software COMSOL® Multiphysics, in which, the heat exchange between the fluid and GHE pipe is simulated by non-isothermal pipe flow module while that between GHE pipe and adjacent ground can be simulated by heat transfer module.

In the non-isothermal pipe flow module, the pipe flow is simplified as one-dimensional flow that ignores the heat transfer in the cross section of fluid inside the pipe (i.e., temperature of the fluid in the cross section is assumed to be uniform) and improves the computational efficiency. The GHE pipe is assumed to be made of High-density Polyethylene (HDPE) pipe with an inner diameter of 36 mm and a wall thickness of 2 mm. In the heat transfer module, the computational domain or the ground is assumed to be a cuboid with dimension of 35 m (length) ×32 m (width) ×10 m (depth). The GHE pipes are assumed to be installed with the average depth of 1.5 m below the ground surface. The geometric parameters and material properties are summarized in Table 1.

The Dirichlet boundary condition is applied on the side and bottom boundaries of the computational domain with magnitude of temperature as a function of depth and time, *T*(z,t), which can be assigned with either soil temperatures harmonic function or the in-situ measured soil temperatures. The boundary condition of heat convection between the ground and atmosphere is described by applying the Robin boundary condition on the top surface of the ground, where the monitored air temperature is imposed and the convection coefficient *h* is assumed to be 0.53 W/m/K according to the literature [20]. In addition, free tetrahedral mesh method is adopted to generate the tetrahedral elements with the mesh refined near the GHE pipe to ensure the computational efficiency and accuracy.

Table 1. GHE properties

Item	Description
Average installation depth of GHE pipe	1.5 m
Pipe material	HDPE
Pipe diameter D	36 mm
Ground properties	Soil
Fluid in the pipe	Water + 10% ethyl alcohol
Fluid volumetric flow rate Q_v	1 L/s
Ground specific heat capacity Cp_{ground}	1175 J/kg/K
Fluid thermal conductivity k_{fluid}	0.56 W/m/K
Fluid specific heat capacity Cp_{fluid}	4190 J/kg/K
Pipe wall (HDPE) thermal conductivity k_{pipe}	0.46 W/m/K

Soil temperatures harmonic function

The soil temperature distribution is estimated as a function of depth and time [21] with associated parameters acquired from Ref. [22], Table.5.11 for Indianapolis, Indiana.

$$T(z,\mathrm{t}) = \mathrm{T}_m + T_a e^{-z\sqrt{\frac{\omega}{2a_s}}} \cos\left[\omega\left(\mathrm{t}-\mathrm{t}_0\right) - \mathrm{z}\sqrt{\frac{\omega}{2a_s}}\right] \quad (1)$$

where, T_m is the average ambient temperature at the ground surface, which is set as 12.78˚C (55 °F) for Indianapolis. T_a is the amplitude of temperature variation at the ground surface, which is -4.44˚C (24 °F). ω is the angular frequency of temperature variations, which is set as $2\pi/365$ d^{-1}. a_s is the solid thermal diffusivity, which is assumed to be $0.8*10^{-6}$ m^2/s. t_0 denotes to the time (in days) when the minimum surface temperature occurs, which is 34 days.

The soil temperature profiles at different depth based on Equation (1) are presented in Fig. 1 in dash lines.

In-situ monitored soil temperatures, air temperature, and soil properties

Naylor et al. [14] deployed a shallow monitoring network in Indiana to characterize the dynamic soil thermal properties under different geological conditions. Total six locations of different hydrogeological settings and near-surface glacial sediments were monitored. In-situ temperature data was continuously recorded via the temperature sensors installed at 0.3 m intervals below the ground surface, and in-situ thermal conductivity and diffusivity were determined via differential temperature sensor aiming to measure radial differential temperature around a heating wire at 1.2 m depth. The site meteorological data, such as air temperature, wind speed, relative humidity and precipitation, etc., were also recorded to determine the surface energy and water budgets, which drive fluxes of energy and moisture in the shallow subsurface.

In the study, two sites with/without significant seasonal thermal properties variations are analyzed to compare the influence of ground soil property variations on the horizontal GCHP system. One site is located at Bradford Woods with main soil as alluvium, while the other site is at Shelbyville Moraine with main soil as glacial till.

Fig. 1 displays the comparison of the temperature profiles obtained from soil temperature harmonic function (labeled as F) and in-situ experimentally measured soil temperatures at two sites in the State of Indiana, USA, i.e., Bradford Woods (labeled as B) and Shelbyville Moraine (labeled as S). The temperature at the shallow ground shows clear seasonal variations. The ground temperature at certain depth predicted by the harmonic function shows a similar trend as field monitored data, although they do not exactly match each other. The amplitude and the corresponding maximum and minimum occurring moments are somehow consistent, indicating the application of the soil temperature harmonic function is acceptable with proper calibrations to certain extent.

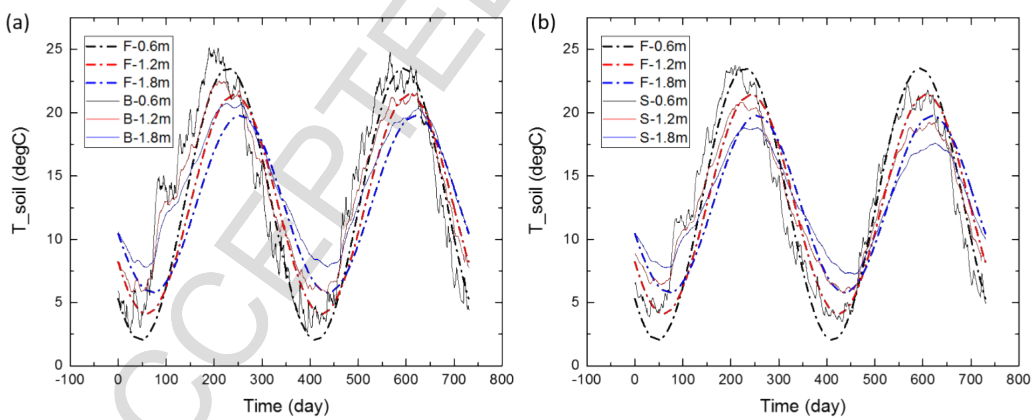

Fig. 1. Variation of soil temperatures at different depth (Bradford Woods (B) and Shelbyville Moraine (S))

Fig. 2 shows the variations of ambient air temperatures and soil thermal conductivities during 2012-2013. According to Fig. 2, the air temperatures in Bradford Woods and Shelbyville Moraine are similar, whereas their thermal conductivities exhibit very different seasonal behaviors. The spikes presented in Fig. 2(b) is caused due to malfunction of the temperature sensor, which recovers to the normal level after replacement. The thermal conductivity of Bradford Woods experienced appreciable amount of decreases during the 2012 water year (10/2011-09/2012) due to the decrease of soil moisture content in the drought season. [23]

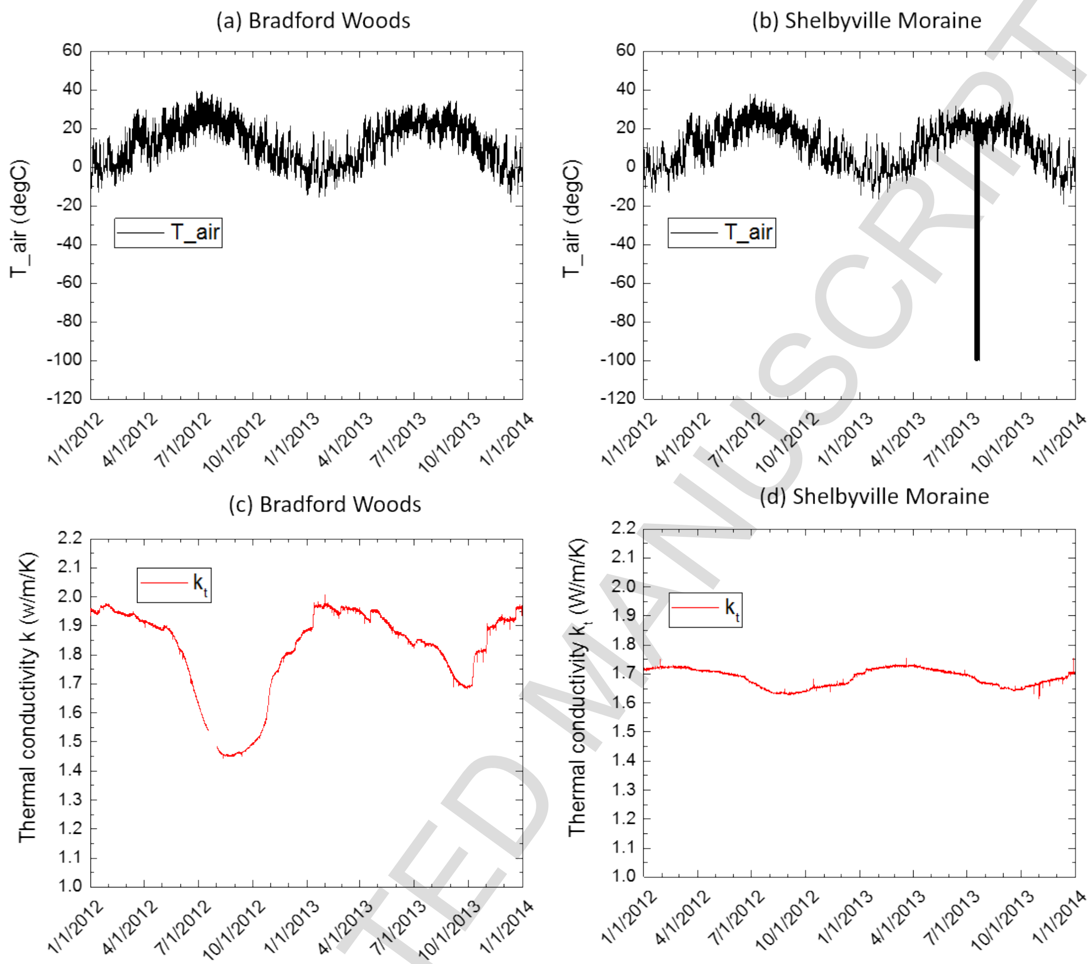

Fig. 2. In-situ measured parameters: air temperature (a) in Bradford Woods; (b) in Shelbyville Moraine and thermal conductivity (c) in Bradford Woods; (d) in Shelbyville Moraine

2.2 Behaviors of horizontal GCHP system

2.2.1 Short-term performance of horizontal GCHP system with different configurations and geological conditions

The short term performance of horizontal GCHP is evaluated based on its performance in ground heat extraction. The conceptual simplified model for comparison is shown in Fig. 3, the inlet temperature of the short-term performance simulation model is assigned to be a constant value of 0 ℃ and the corresponding outlet temperature is selected as an indicator of the horizontal GCHP system in ground heat extraction. Comparison analyses are conducted to evaluate the performance of horizontal GCHP system installed under six typical design configurations. Fig. 4 displays the geometry of those horizontal GHE configurations, which generally can be classified into three types: linear GHE (A-D), slinky GHE (E) and helical GHE (F) [13]. For linear GHE, total four patterns with either two pipes per trench (A, B) or four pipes per trench (C, D) are studied, and all of them follow the recommendation proposed by ASHRAE [24].

Fig. 3. Flow chart for the short-term performance of horizontal GCHP model

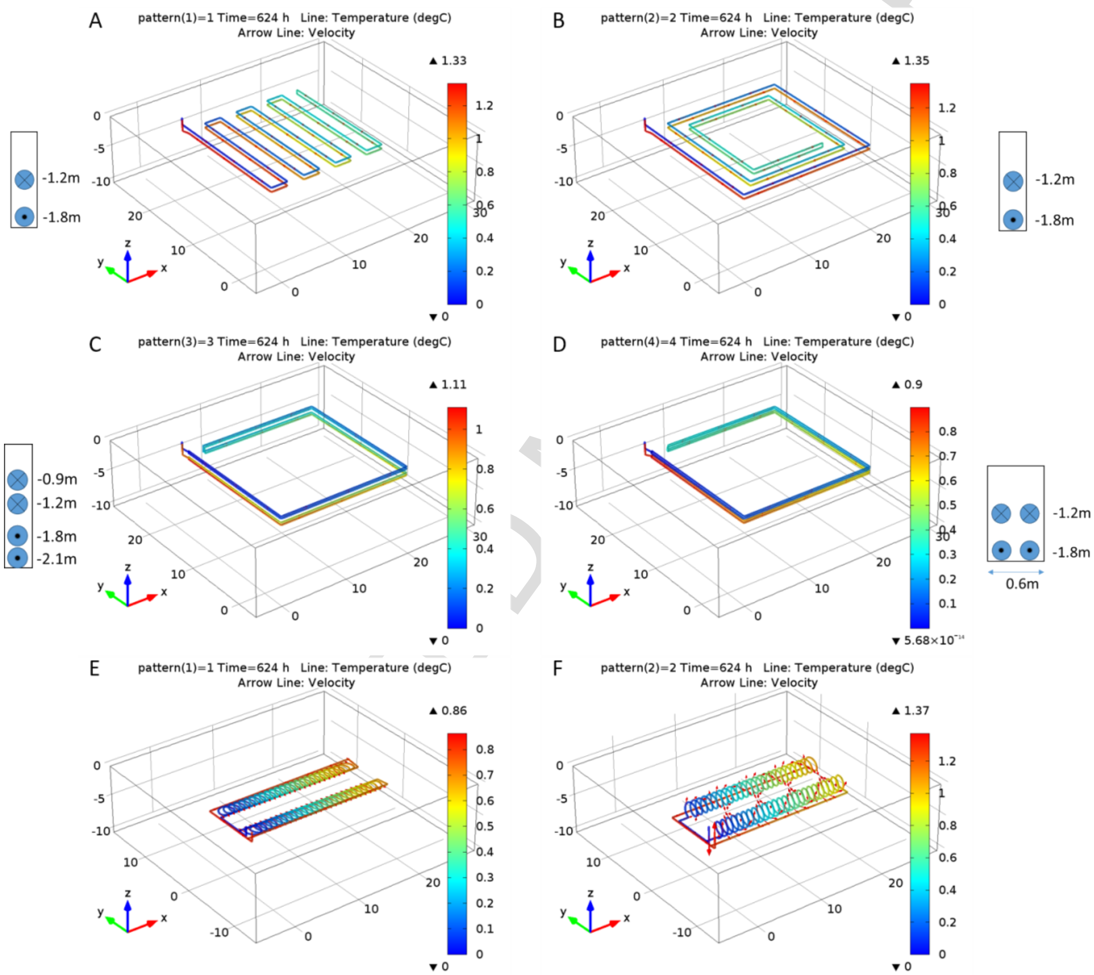

Fig. 4. Geometry of different horizontal GHE design with illustration of the temperature variation along the heat exchanger pipe in heating mode

2.2.2 Annual performance of horizontal GCHP system under different geological design conditions

The annual performance of the horizontal GCHP system is evaluated based on its behaviors with integration of the building loads. Three typical building load scenarios are considered including seasonal balance, heating dominant, and cooling dominant. It is assumed that the horizontal GCHP system provides sufficient capacity for building heating and cooling demand, which is estimated with a simplified building load model and heat pump operating performance curve. The annual performance of horizontal GCHP system is described by the shift of ground baseline temperature due to the annual operation of GCHP system. Different geological conditions are considered including those with relatively constant ground thermal properties versus those vary through the seasons, which are determined based on field monitoring data. Fig. 5 presents the detailed flow chart for the evaluation of the annual performance of horizontal GCHP model.

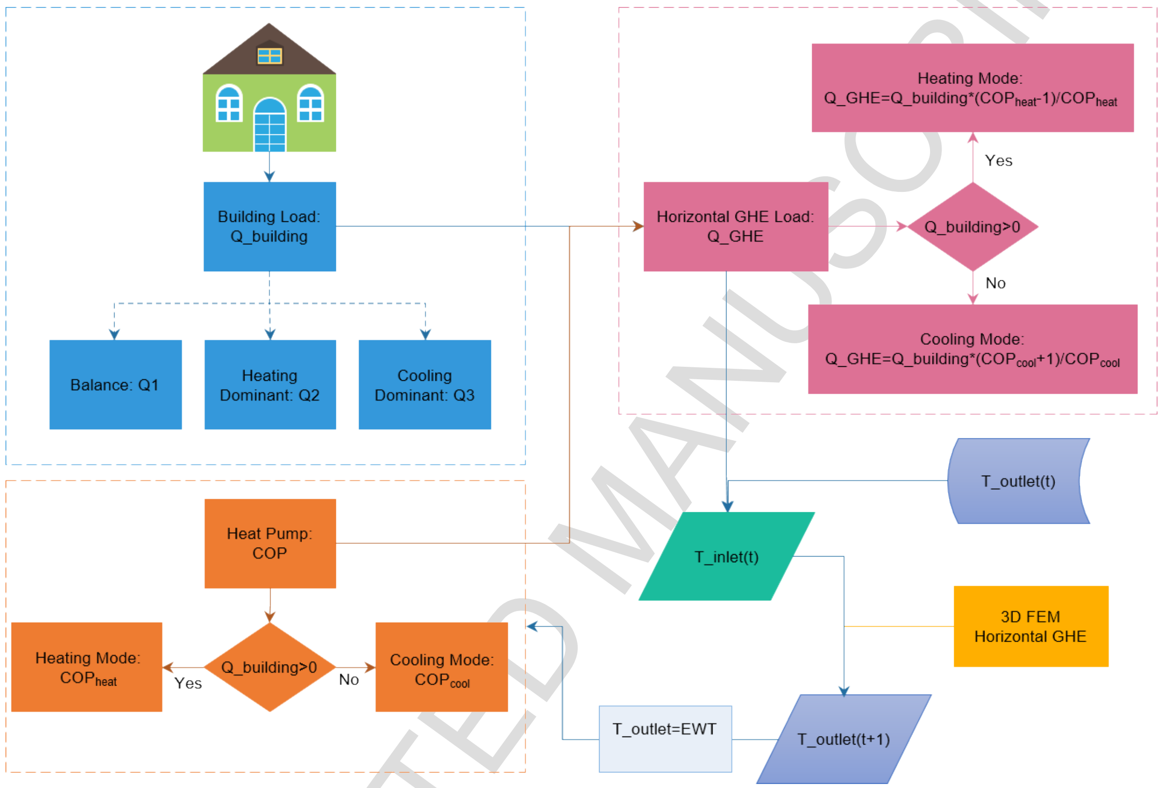

Fig. 3. Flow chart for the annual performance of horizontal GCHP model

Accurate description of building load can be estimated via verified code. For example, Fig.6 presents an example of the typical building load process over one-year period simulated by eQuest for a typical residential building located in Indiana with 2500 m^2 occupancy area. Overall, the trend of building thermal load variation can be described by a sinusoidal process, with the exception of a few periods during winter with abnormal weather conditions. The average magnitude of the sinusoidal process is close to zero, which means that the type of building load demand achieves seasonal balance approximately.

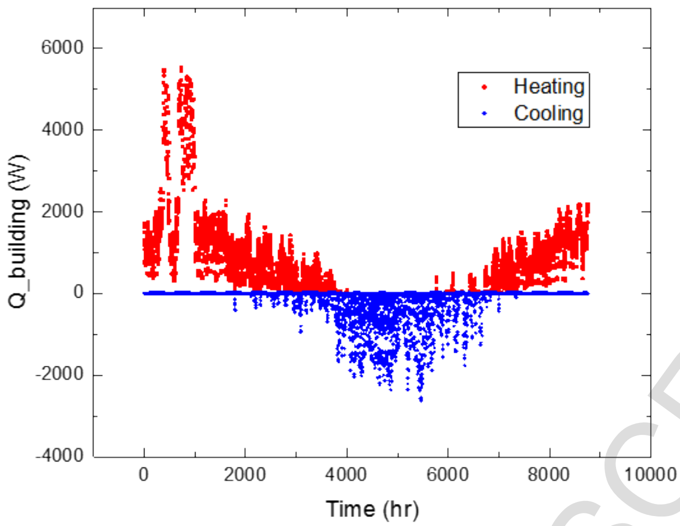

Fig. 6. Simulated building load process for a residential building in Indiana by eQuest (from the beginning of year)

To simplify the analyses without incurring significant error, the building load is approximated with sinusoidal model based on the observed trend of eQuest model. The advantage of the simplified model is to make it easy to consider different building load scenarios, including seasonal balance, heating dominant, and cooling dominant. Without losing the generality, three different building loads are assumed to follow the following modified sinusoidal functions [25]:

Seasonal balance: $$Q_1 = A * \sin(wt) \quad (2)$$

Heating dominant: $$Q_2 = 0.75A * \sin(\omega t) + 0.25A * |\sin(\omega t)| \quad (3)$$

Cooling dominant: $$Q_3 = 0.75A * \sin(\omega t) - 0.25A * |\sin(\omega t)| \quad (4)$$

where, ω is the angular frequency, and it can be obtained by: 2π/T (T=1 year=31,536,000 s). *A* denotes to the peak building load which is assumed to be 10 kW in this analyses.

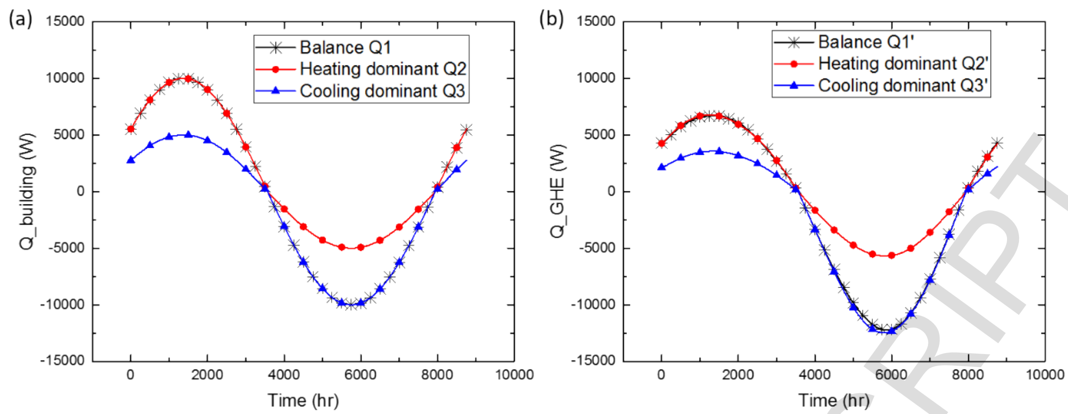

Fig. 7. (a) Building load profiles; (b) Source (ground) load profiles.

Fig. 7(a) shows the graphs of corresponding building loads. This simplified building load model is on the basis of two assumptions: (1) heating season (Q_building >0) occurs before cooling season (Q_building <0); (2) heating and cooling periods are equal throughout the year, which ignores the transition seasons (i.e., spring, autumn) with typical Q_building =0.

The performance of heat pump is typically estimated via its COP that is defined as the ratio of utilized thermal energy to electricity energy consumed for heat pump operation. The required heat injection or extraction by the GHE to meet the required building load can therefore be calculated by:

$$Q\_GHE = \begin{cases} Q\_building * \dfrac{COP_{heat} - 1}{COP_{heat}}, Q\_building > 0 \\ Q\_building * \dfrac{COP_{cool} + 1}{COP_{cool}}, Q\_building \leq 0 \end{cases} \quad (5)$$

The COP is related to the Entering Water Temperature (EWT) from heat source. The dependency of COP on EWT has been documented by Shiba et al. [26], accordingly, Nam et al.[27] proposed the COP as function of EWT (in Fig. 8) when the typical design of the heat pump outlet temperature to room is 45 ˚C in heating mode and 7 ˚C in cooling mode.

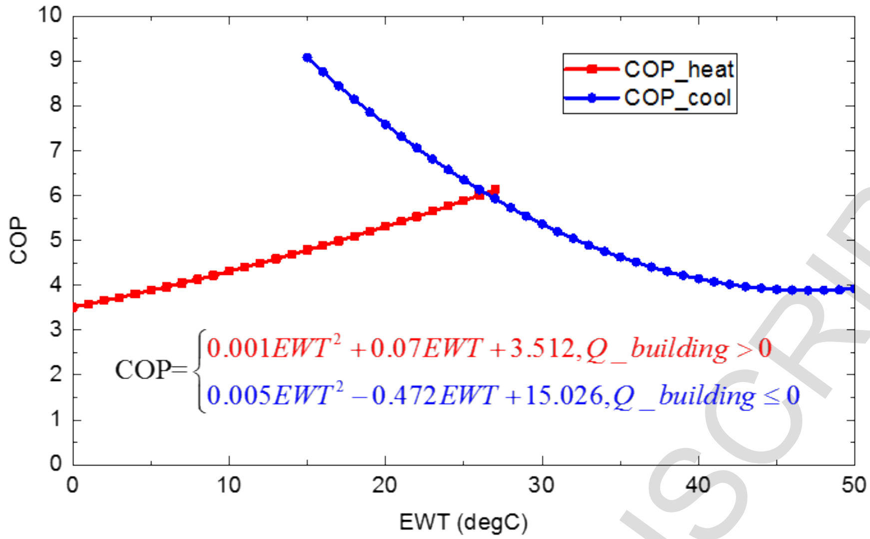

Fig. 4. Performance of Heat pump versus EWT

The inlet temperature of GHE can be calculated by:

$$T\_inlet(t) = T\_outlet(t) - \frac{Q\_GHE}{Cp_{fluid} * \rho_{fluid} * Q_v} \qquad (6)$$

where the *T_outlet* is assigned to be soil temperature at t=0. Regardless of the heat loss between GHE outlet and heat pump inlet, the outlet temperature of GHE should be same as EWT. Then for a specific inlet temperature, the 3D FEM model for the horizontal GCHP will compute the corresponding outlet temperature at the next time step, which is then used to calculate the inlet temperature as well as the new COP at the next time step. This closed loop procedure integrates building load model with 3D FEM model for the horizontal GCHP. From these, it determines the annual performance of horizontal GCHP system.

3. Results and discussions

3.1 Comparison of the short-term heat extraction performance of horizontal GCHP with different design configurations

The short-term performance of GCHP in different design configurations in heat extraction are simulated and discussed in this section. Fig. 9 compares the total length of GHE in different configurations, which gives an average length of 313 m. The maximum difference in the length of GHE is 9 m or around 3% of the average length. Therefore, it is assumed that the performance of GCHP design configurations are comparable based on similar total lengths. As illustrated in Fig. 4, temperature of circulation fluid increases along the heat exchange pipe for all configurations due to the thermal energy absorption from ground in heating mode. Simulations are conducted to determine the outlet temperature from GHE over 48 hours' continuous operation during the coolest period of the year (Jan. 24th to Jan. 26th, 2012). The resultant temperature at the outlet after different operational times are shown in Fig. 10. The differences in the circulation fluid at the outlet shows the different performance of the GHE configuration in thermal energy extraction.

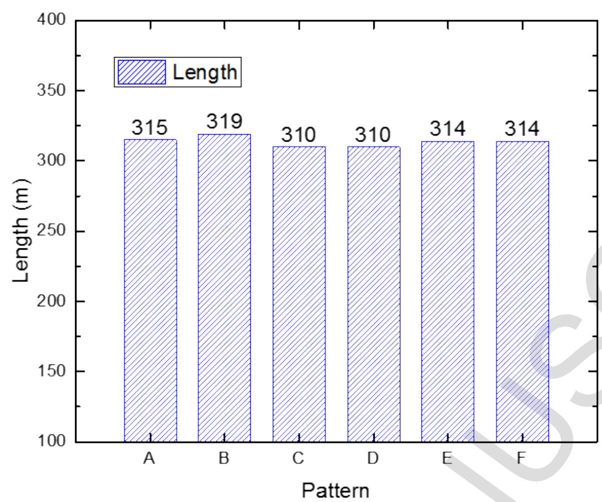

Fig. 9. Total installation GHE length in different configurations

The linear GHEs with two pipes per trench (A, B) and helical GHE (F) appear to achieve higher outlet temperature, followed by design with four pipes per trench (C, D) (Fig. 10(a)). To consider the effects of GHE length, the extracted thermal energy per length (q) is calcualted as:

$$q=\frac{Q\_GHE}{L}=\frac{\mathrm{Cp}_{fluid}\cdot \mathrm{u}\cdot \mathrm{A}\cdot \rho_{fluid}\cdot (T\_outlet\text{-}\mathrm{T}\_inlet)}{L} \quad (7)$$

in which, *Q_GHE* denotes to the total extracted thermal energy that only depends upon the outlet temperature. The results of relative performance by the per unit length thermal energy extraction showed in Fig. 10(b) are consistence with that in Fig. 10(a). In general, the GHE in configurations of A, B and F perform better in thermal energy extraction for the same installation area and similar total length. The configurations of C, D perform slightly better than E. Overall, the GHE pipe patterned in two per trench and helical shape achieved better performance in thermal energy extraction. This observation implies that the separation distance of GHE pipes has predominant effects on the efficiency of horizontal GCHP system. Smaller separation distance will lead to the less amount of energy extraction. Therefore, it is important to optimize GHE configuration to ensure the horizontal GCHP system performance, which might also need to consider factors such as installation cost. Gradual drop of thermal energy extraction is observed as the operation time goes on, which is caused by the thermal buildup effects of the adjacent ground. For example, the per unit length energy extraction, q (A), is reduced by around 40% between 6 hour of operation to 48 hour of operation. This observation is consistent with the field observation that the continuous operation negatively affects the energy extraction efficiency. Therefore, operational strategies, such as the use of intermittent operation mode, could improve the soil thermal recovery to achieve better GCHP performance.

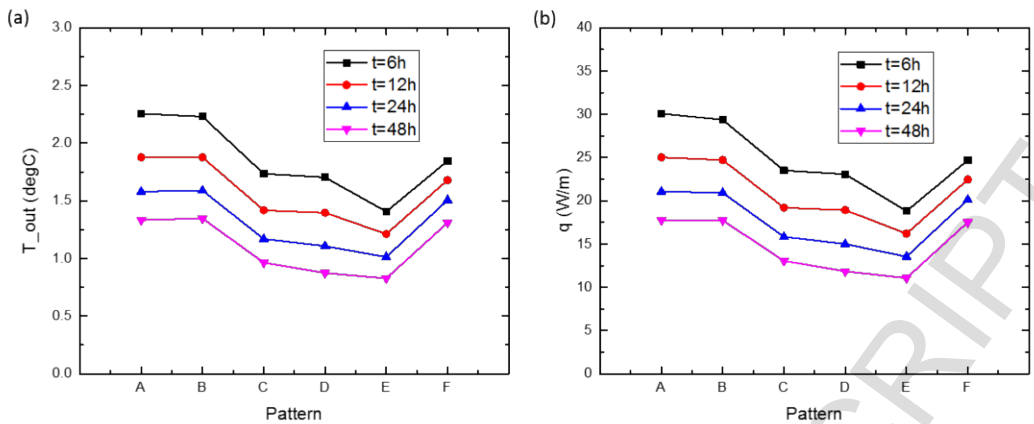

Fig. 10. Comparation of heat extraction performance of different GHE configurations after different time of operation (a) the outlet temperature and (b) the energy extraction per length (GHE type A: linear zigzag with two pipes per trench, type B: linear spiral with two pipes per trench, type C: linear with four pipes per trench that are in one vertical line, type D: linear with four pipes per trench that are in two vertical lines, type E: slinky GHE and type F: helical)

3.2 Influence of local geological conditions on the short-term performance of horizontal GCHP system

The design of horizontal GCHP system requires the information about ground subsurface temperature and thermal properties of soils. The conventional design method for horizontal GCHP system generally uses the soil temperature harmonic function to describe the temperature process underground and assumes constant underground soil thermal properties. However, the influence of local geological conditions, including the seasonal variations of soil thermal properties may have significant effects on the performance of the horizontal GCHP system. To elucidate the influence of local geological conditions, analyses are conducted based on modeling each type of horizontal GCHP system subjected to three different situations: (a) underground temperature described with soil harmonic function, and soil properties are assumed to be constant at the values of the monitored average soil thermal parameters; (b) underground temperature based on in-situ measurement and use soil thermal parameters with significant seasonal variation as measured at Bradford Woods site; (c) underground temperature based on in-situ measured soil temperatures and soil thermal parameters do not show significant seasonal variations as observed in Shelbyville Moraine site.

The results of outlet temperature and per unit length heat extraction by different horizontal GCHP designs after 48 hours of continuous operation are summarized in Fig. 11. Evidently, the GCHPs are predicted to achieve better performance by use of field measured data compared with simplified assumptions commonly used in the current horizontal GCHP design (estimate the ground temperature for a certain region and use estimated thermal properties for soils), and the observation is true for all GCHP design configurations. This suggests that use of field data might help to mitigate the overdesign commonly found with the current horizontal GCHP system. This is a veridiction that accurate site thermal characterization can lead to cost saving for horizontal GCHP, which helps to overcome a major barrier for the use of horizontal GCHP in practice.

Another observation is that the performance of GCHP is only slightly better at Bradford Woods site, which has significant season variations, than that at the Shelbyville Moraine site, which has relatively stable subsurface soil properties. This might be due to the fact that the model prediction is only for short term 48 hours' continuous operation period, where the temporal variations in the subsurface temperature and thermal properties are insignificant. It is expected that the influence of local geological characteristics, i.e., subsurface temperature and seasonal variations of soil thermal properties, can have a major influence on the performance of horizontal GCHP system. By applying in-situ measured soil properties, the design length of horizontal GHE can be reduced by 25% to 60% for different configurations. To this end, efforts in collecting field data should help to institute more economic design of horizontal GCHP system.

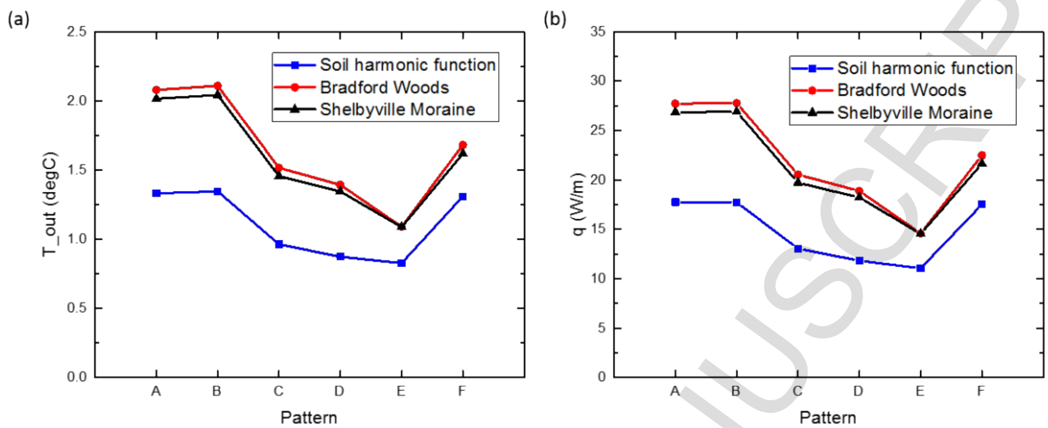

Fig. 11. (a) The outlet temperature and (b) energy extraction rate per length of horizontal GCHP system with different installation configurations at t=48h

3.3 Influence of local geological conditions on the annual performance of horizontal GCHP system for building with balanced load

The influence of local geological conditions, i.e, the subsurface soil temperatures and thermal properties' seasonal variations, on the long term performance of horizontal GCHP system design is analyzed using the computational model and field data. The model considers the type B GHE design integrated with building loads as describe in section 2.2.2, and only building with seasonal balance load scenario is discussed in this part. Keep in mind, however, that for building with seasonal balanced load, due to differences in the COP of horizontal GCHP system working at heat injection or extraction modes, horizontal GCHP system injects more heat into the ground than the heat it extracts from the ground over one-year period (Fig. 7b). This could lead to thermal built-up and shift of underground baseline temperature.

Community scale implementation of horizontal GCHP system has shown that the shift of ground baseline temperature deteriorates its annual performance. Therefore, the shift of subsurface temperature due to GCHP system operation is used as the criteria to assess the annual performance of horizontal GCHP system. For this purpose, two locations in the ground outside the GHE pipe are selected to evaluate on the effects of GCHP system operation based on their temperature variations after one year's operation. The two selected locations are both located at the average installation depth of GHE, the coordinates of these two locations are showed in Fig. 12. Different scenarios are considered based on different extent of incorporating field monitoring data.

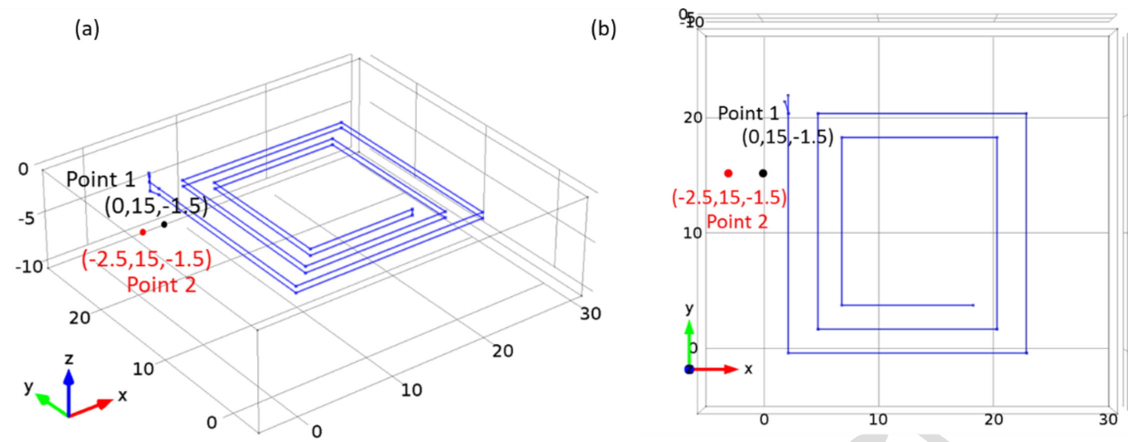

Fig. 12. The locations of the selected two points with (a) 3D view and (b) 2D view

Scenary 1: the effects of incorporating field monitored soil thermal properties

To elucidate the influence of soil thermal properties' seasonal variation on the GCHP system performance, comparison simulations are conducted where the same soil temperature boundary conditions based on soil harmonic function are applied. Soil thermal properties are based on in-situ monitored Bradford Woods' soil thermal properties or those using yearly average soil thermal properties. The initial inlet temperature is set to be the same and the initial soil temperature is set to be 6°C. The results of ground temperature shift at selected points 1 and 2 are shown in Fig. 13. Overall after one year's operation, the temperatures of point 1 and point 2 increase for GCHP system integrated to a building with balanced load. This is consistent with the fact that more heat is injected to the ground than that extracted due to differences in the COP of GCHP system. Compared with using an average soil thermal conductivity, the use of measured soil thermal conductivity that considers its seasonal variations leads to larger shift of ground baseline temperature. This implies that the use of field monitored site specific soil thermal properties data could help to predict and therefore prevent potential problems of ground temperature shift which compromises its efficiency.

The results after the total GHE length is decreased from 319 m to 269 m, or around 15% reduction in length, are also shown in Fig. 13. By decreasing 50 m design length, the application of in-situ measured soil data shows the nearly same temperature shift as using yearly average soil data. This is sufficient to demonstrate the importance of the in-situ soil parameter measurement. With the accurate in-situ measured soil data, the optimal design of horizontal could be achieved.

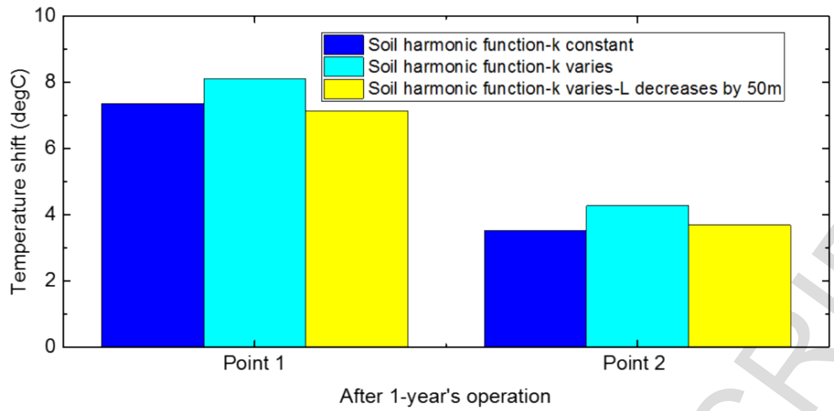

Fig. 13. Temperature shift of point 1 and point 2 by using in-situ measured and yearly average thermal properties for building load seasonal balance scenario

Scenary 2: the effects of incorporating both field monitored subsurface temperature and soil thermal properties

Simulation are conducted for the GCHP system after one year of service under the following design conditions: (1) underground temperature based on in-situ measurement and soil thermal parameters with significant seasonal variation as measured at Bradford Woods site; (2) underground temperature based on in-situ measured soil temperatures and soil thermal parameters do not show significant seasonal variations as observed in Shelbyville Moraine site; and (3) underground temperature described with soil harmonic function and soil properties are assumed to be constants that equal to the average value of monitored soil thermal parameters. The results of computational simulation are shown in Fig. 14. In general, the ground temperatures at both point 1 and point 2 increase after one year's operation for GCHP system integrated with a building with balanced thermal load, due to the thermal build-up effects discussed previously. Besides, a few interesting observations can be made:

(1) The shifts of ground temperature predicted by applying ground temperature harmonic function and constant soil thermal properties are significantly larger (around 70% increase for point 1) than those using in-situ measured ground temperature and soil thermal parameters. This implies that the application of ground temperature harmonic function as commonly used in current design will lead to overestimation of the thermal build-up effects.

(2) The shifts of baseline ground temperature are similar for Shelbyville, with insignificant seasonal soil thermal properties' variations, and Bradford Woods, with significant soil thermal properties' variations (Fig. 14). This implies that seasonal variation of in-situ soil thermal properties does not significant affect the shift of ground temperature.

Incorporating the site specific subsurface temperature helps to reduce the over prediction of ground temperature shift due to imbalanced heat injection/extraction associated with GCHP system operation.

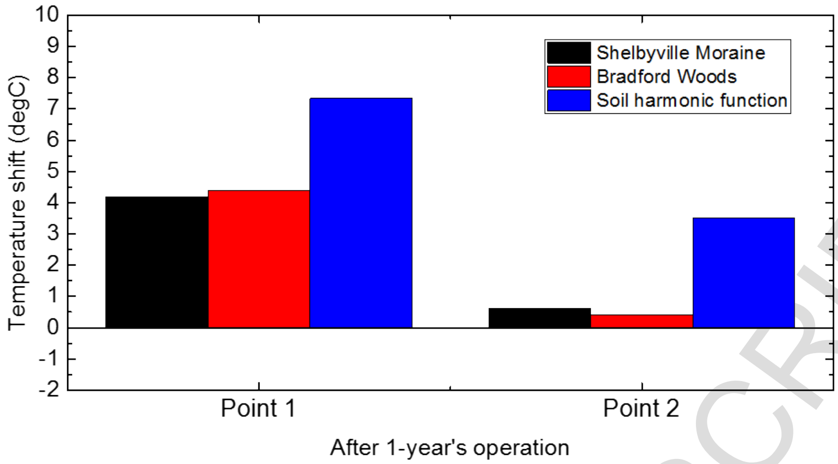

Fig. 14. Temperature shift of point 1 and point 2 after one year's operation under different geological design conditions for building load seasonal balance scenario

3.4 Influence of integrated building thermal load senarios (i.e., heating dominant or cooling dominant) on the annual performance of horizontal GCHP system

The behaviors of GCHP system integrated with the other two types of building load senarios, i.e., heating or cooling dominant, are also investigated. The influence of field temperature and soil thermal properties data on GCHP performance are analyzed. The results are summarized in Figs. 15-18. Fig. 15 and Fig. 16 show the change of ground temperatures at selected Points 1 and 2 underground after one year of GCHP operation with integrated building that is cooling or heating dominant. The use of field monitored soil thermal properties data leads to smaller shifts of ground baseline temperature under both conditions. Fig. 17 and Fig. 18 summarize the ground temperature build-up effects when both subsurface temperature and soil thermal properties are incorporated for GCHP system analyses. The comparison shows that the shift of ground temperature is less significant when GCHP system is integrated with a building that is heating dominant (i.e., in cold region). This phenomenon can be illustrated by use of Fig. 7. This is to certain extent due to the higher efficiency of heat pump working in the heating mode compared with the cooling mode. (Conceptually, the heat produced due to operation of heat pump also contributes the overall heat produced for building heating purpose.) Therefore, in the heating dominant area, although it requires providing larger amount of heat into building in the winter season than the amount of heat extracted from the building during summer season, the amount of heat actually extracted from the ground by the GHE during winter season is approximately in balance with the amount of heat injected into the ground by the GHE during the summer season. This helps to maintain balance in the heat injection and extraction. Therefore, for building load that is heating dominant, the source load (ground thermal extraction and injection) by GHE is closer to balanced heat injection/extraction from the ground. This leads to smaller thermal build-up effects under the ground. This observation indicates that stable ground temperature is more easily achieved with GCHP integrated with building that is heating dominant (or cold region). This is consistent with the documented case studies, such as a GCHP system used for residential application in heating dominant region [9], where the GCHP system did not show performance deterioration after 4 years' operation.

The analyses also show that incorporation of field monitored subsurface temperature in addition to the seasonal variation of in-situ soil properties reduces the ground temperature shift for GCHP system working with building that is both heating and cooling dominant. These again validated the potential benefits of monitoring the field subsurface thermal conditions in improving the design and annual performance of GCHP system.

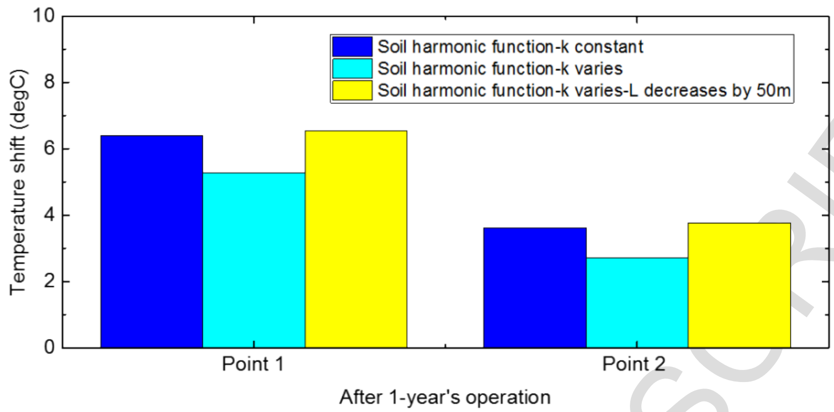

Fig. 15. Shift of ground temperature at point 1 and point 2 by use of in-situ measured thermal properties versus constant thermal property for GCHP integrated with a building that is heating dominant

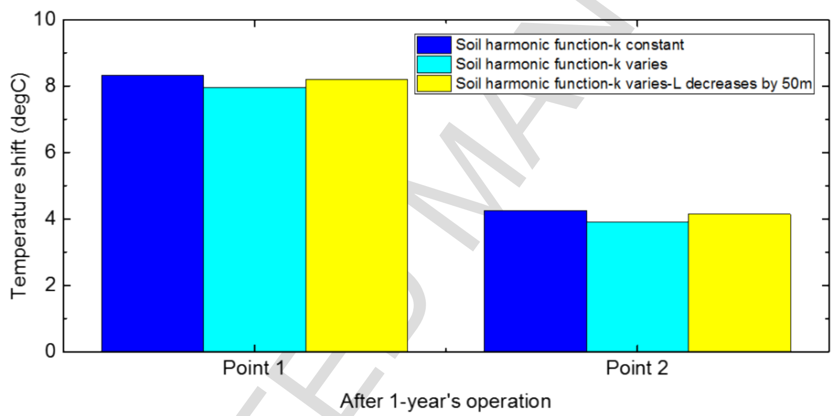

Fig. 16. Shift of ground temperature at point 1 and point 2 by use of in-situ measured thermal properties versus constant thermal property for GCHP integrated with a building that is cooling dominant

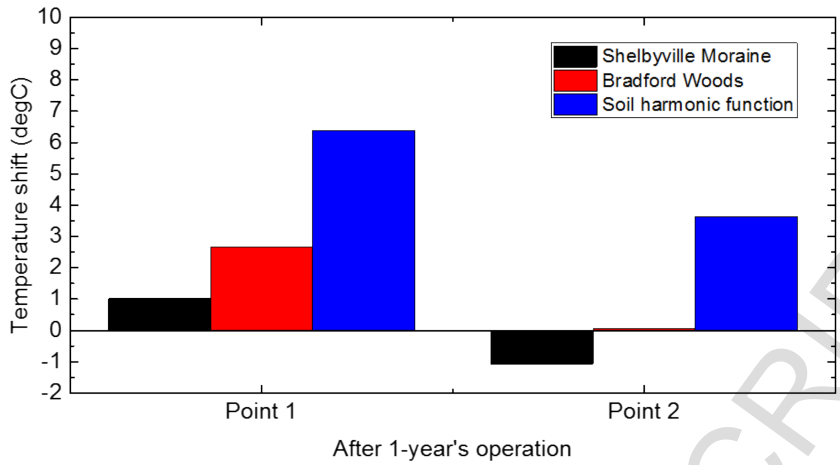

Fig. 17. Shift of ground temperature at point 1 and point 2 by use of in-situ measured ground temperature and soil thermal properties versus that assuming soil temperature harmonic function for GCHP integrated with a building that is heating dominant

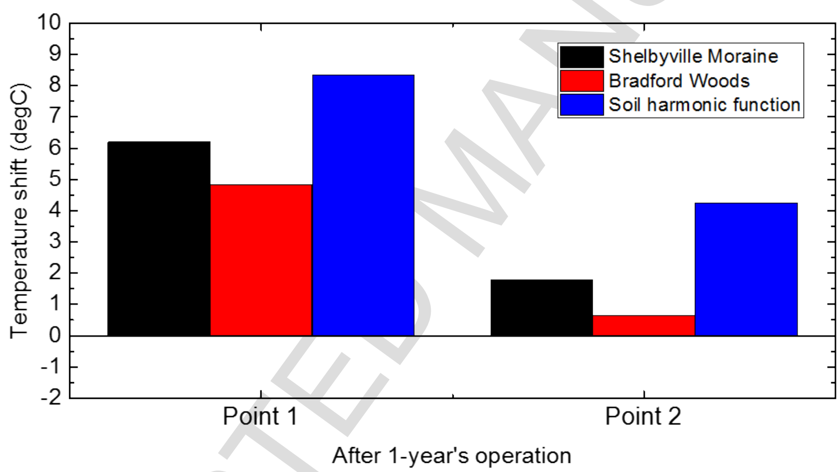

Fig. 18. Shift of ground temperature at point 1 and point 2 by use of in-situ measured ground temperature and soil thermal properties versus that assuming soil temperature harmonic function for GCHP integrated with a building that is cooling dominant

4. Conclusions

Computational model is developed to analyze the short-term and annual performance of horizontal GCHP system. The model simulates 3D heat transfer between ground heat exchanger (GHE) and shallow ground integrated with building with different thermal loads. Major influential factors, i.e., GHE pipe patterns, geological design conditions and building load scenarios, are analyzed.

The short term performance of six different GHE configurations are firstly analyzed with the computational model. From these patterns of GHE layout that achieved better thermal energy exchange per unit length are identified. The model predicts higher GHE performance can be achieved by using field monitored temperature and thermal properties data than using estimated soil parameters as commonly done in the current industry practice. It is also found that continuous operation of GCHP compromises its energy extraction efficiency, which implies allowing soil thermal recovery such as by intermittent operation will help the GCHP to achieve improved performance.

The annual performance of GCHP is evaluated by developing a model that integrates building thermal load model with 3D FEM model for horizontal GHEs. With this model, three different geological design conditions under three building load scenarios (i.e., balanced, heating dominant, or cooling dominant) are analyzed. The shift of ground temperature is used as the indicator to compare the long term performance under the assumption that the building heating/cooling demand is fully met with the GCHP system. A few salient observations include:

1) The application of soil temperature harmonic function as design inputs will lead to the overestimation of thermal build-up effects. The horizontal GCHP system is projected to achieve 25% to 60% higher performance with accurate in-situ measured soil temperature data.

2) The seasonal variations of in-situ soil thermal properties do not show significant effects on the performance of horizontal GCHP system for building with balanced thermal loads (i.e., only 0.2°C difference between Shelbyville Moraine site which shows significant seasonable variation versus Bradford Woods site which is relatively stable). They, however, have more appreciable effects when working with building that is heating or cooling dominant (the differences between these two sites are 1.19°C and 1.37°C respectively under such conditions).

3) Less thermal built-up occurs for horizontal GCHP system working with the building that is heating dominant (or in cold region). For example, the predicted yearly temperature shift was 1.01°C for Shelbyville Moraine and 2.2°C for Bradford Woods. This is possibly due to heat injection to /extraction from the ground are balanced under such conditions.

Horizontal GCHP system features the advantages of incurring lower installation cost compared with the vertical GCHP counterpart. Results of this study show that collection of field data such as subsurface temperature and soil thermal properties will help to improve the prediction of its short term as well as long term performance when integrated with building. This potentially will lead to 25% to 60% reduction of the GHE design length, which presents an opportunity to improve the current design method in terms of cost effectiveness.

5. Acknowledgements

This research is partly supported by the US National Science Foundation and China Scholarship Council.

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Highlights

- Developed a 3D Finite Element Model (FEM) of horizontal GCHP system integrated with building thermal loads.
- Analyzed the short term performance of different GHE configurations considering site specific geological data.
- Evaluated the long term performance of GHE integrated with different building load scenarios with consideration of monitored thermal geological data.
- Assessed the potential benefits of characterizing thermal conditions at design site to refine the design of horizontal GGHP.