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Impacts of Prospective LEED Building's Energy Loads on a Borehole Heat Exchanger: A Case Study in Central Illinois

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ABSTRACT

Assessing the thermal behavior in the subsurface surroundings of a borehole heat exchanger (BHE) is necessary for evaluating the performance of GSHP systems. In this study we undertook a preliminary thermal analysis on a constructed GSHP system that is coupled to a LEED-certified building, the Campus Instructional Facility (CIF), at the University of Illinois at Urbana-Champaign, The building is designed to utilize multiple energy-saving technologies that achieve a building performance of LEED-Gold certification. Energy modeling of the entire building was performed in DesignBuilder software by considering all of the high efficiency thermal-insulated features, and the building energy load was obtained and used in the iterations of the ground thermal response model. An analytical model (Erol & François 2018) was applied to evaluate the thermal response from a single BHE within a multilayer geology considering the annual energy extraction/rejection from the building. A parallel scenario was considered for comparison when the GSHP was coupled to a building with a typical heating-dominated load profile in central Illinois. The difference in the development of isotherms around the BHE are simulated to demonstrate the benefits of coupling green buildings and GSHP. This research may facilitate the wider implementations of GSHP systems with energy-efficient buildings.

INTRODUCTION

Ground source heat pumps (GSHPs) have been widely adopted to exchange thermal energy between buildings and the underground. However, the high-upfront cost and system degradation over their lifespan has prohibited their further penetration in the current heating and cooling marketplace. System degradation and lower efficiencies may result from the lack of knowledge of the local ground thermal properties, the mismatch between building heating and cooling loads, the over-conservative design in the borefields, etc. (Zanchini et al., 2012; Zhao et al., 2021). Recent research has revealed that a multilayered geology and the presence of groundwater have significant impacts on the performance of GSHP (Stylianou et al., 2019; Zhao et al., 2022). When it comes to simulating GSHP long-term operations (At least for 1 year, including all the seasonal effects), the observed ground thermal behaviors may provide strategies to optimize their design and operation.

Across the globe, buildings energy systems account for approximately 40% of their total energy consumptions and 36% of their carbon emissions (Al Shargabi et al., 2022). LEED (Leadership in Energy and Environmental Design) developed a rating systems for confirming the sustainability of buildings (U.S. Green Building Council, 2022). Compared to other buildings with traditional heating and cooling systems, a LEED-certified building provides substantial benefits from a multitude of aspects, among which the low heating-cooling loads are a requirement that reduce the electricity usage for air conditioning. Therefore, these measures allow GSHP systems to be implemented with a lower temperature heat extraction/rejection when connected to the ground avoiding long-term overheating. However, significantly increase in the installation of GSHP was not observed in green buildings. The high upfront cost of GSHP prohibits the designers from including the shallow geothermal into system integration during the budgeting process. Yet, it was still found that in many cases, the long-term energy cost constitutes a significant weight of the life cycle budget for green buildings

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(Dwaikat et al., 2018; Filippini et al., 2022). Therefore, this paper presents the preliminary results of a case study in central Illinois, where a LEED-certified instructional facility was conditioned by GSHP, to evaluate the feasibility and economics of GSHP on green buildings. The in-situ information of the building and the energy modeling were first introduced, then followed by the explanation of the analytical thermal response model, and finally the results of the simulation were delivered.

IN-SITU BUILDING INFORMATION AND MODELING

Campus Instructional Facility (CIF) is a four-story building dedicated to academic and classroom use, located on the campus of The University of Illinois at Urbana-Champaign (UIUC). At the southeastern side of the building, a 40-well geothermal borefield of 137.5-m depth is completed and expected to cover 65% of the entire heating-cooling demand of the building. Besides a GSHP system, the building is innovatively designed by incorporating multiple sustainable elements, such as daylighting, radiant panels, and air ventilation, etc. which makes it a unique case study associated with GSHP implementation. To model the energy consumption of the building, a 3D building model was established and simulated using a commercial software, DesignBuilder. The simulation engine of DesignBuilder is the EnergyPlus software, which was developed by the American Energy Association in 2011 (See et al., 2011). To obtain the dynamic seasonal load of CIF, the thermal properties of the building envelopes, the personnel and lighting loads, and the indoor temperature settings within different zones, etc. were applied as inputs. Table 1 lists the input parameters in the building energy model. Figure 1 shows the location of the building and its exterior appearance in both in-situ view and model view. Figure 1 d) presents the simulation results in DesignBuilder, where the variation of annual ambient temperature profile for the entire building was provided. Since the aim of this study is to show the thermal response of the ground around a single borehole, the borehole load is simply computed as the total load divided by the number of boreholes. To compare the performance between the studied building (CIF) and the conventional one (Control), a parallel set of thermal properties was applied to external wall, roof and fenestrations, as indicated by the bracket values in Table 1, and the daily load for a single borehole was plotted in Figure 1 e). As observed, the heating and cooling loads in the CIF are generally lower compared to the "control". To be more specific, the average heating loads in the worst month (Jan) are 17.33 kW (Control) and 7.27 kW (CIF), respectively. In summer, the applied high-performance insulation technologies and the intense educational activities in CIF increase its cooling demand, thus making it a slightly cooling-dominated profile (490.7 kW for cooling and 418.4 kW for heating as total building loads). In contrast, the cooling load in the "control" profile is lower than heating load (578.3 kW for cooling and 737.3 kW for heating as total building loads). To simplify the model, the impacts of COP's annual variations on the discrepancy of borehole loads and building loads were neglected. Instead, the COP was considered as a constant value (4) in both cases. Thus, the building loads (For a single borehole) were then simply ratioed by COP to be converted as borehole loads and the direct inputs in the ground thermal response model, as shown in Figure 1 e).

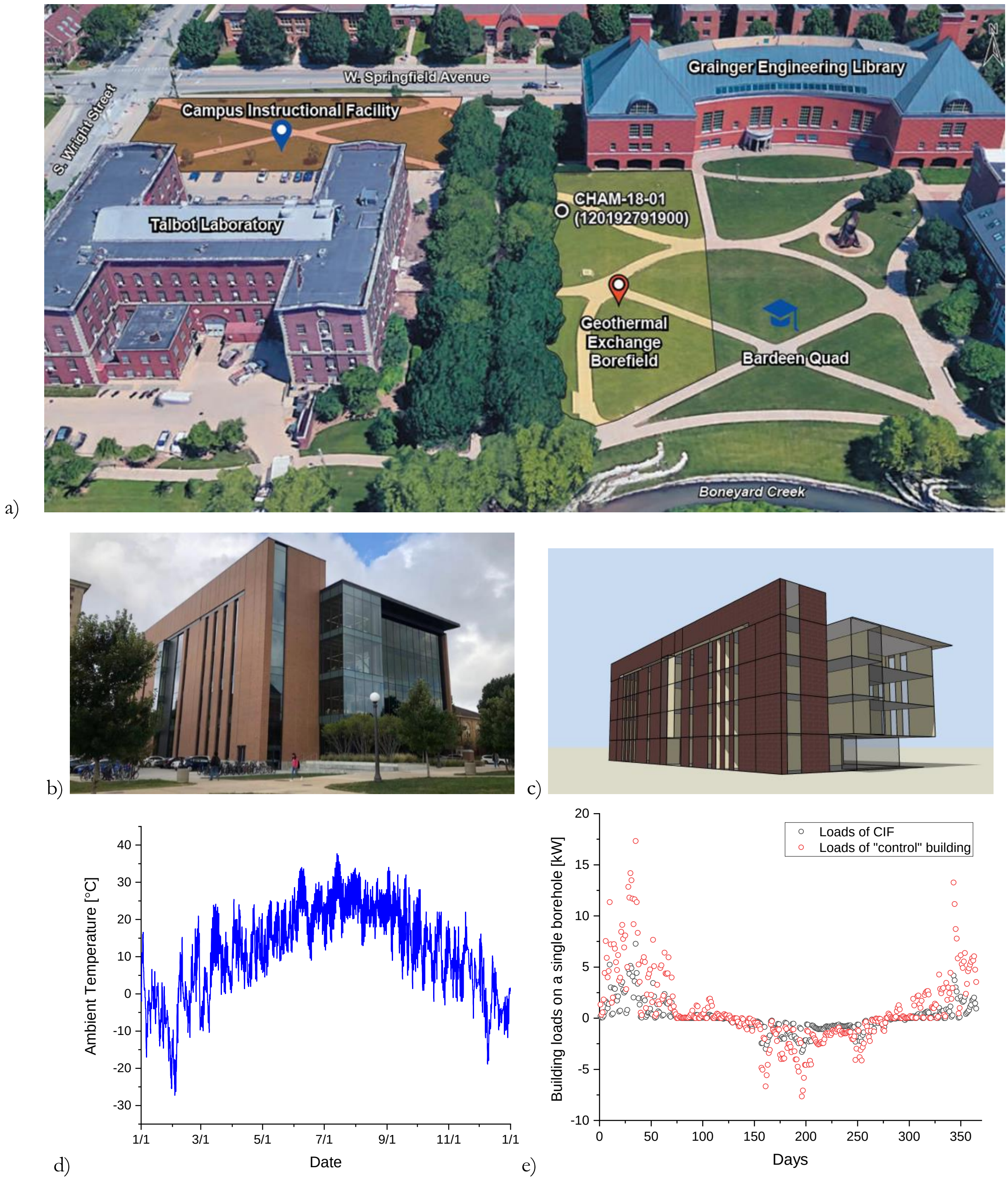


Figure 1 Modeling of Campus Instructional Facility (CIF). (a) Location of the CIF viewed in Google Earth with 3D buildings layer (Google Earth, 2022; Stumpf et al., 2021). (b) In-situ view. (c) Model view in DesignBuilder. (d) Variations of annual ambient temperature. e) Variations of annual building thermal loads on a single borehole. Negative and positive values denote the cooling and heating loads respectively.

Table 1 Model input parameters in DesignBuilder for the LEED building and the "control" building

Item	Value/Description
U-value of external wall	0.055 (0.35) W/m²-K
U-value of roof	0.03 (0.25) W/m²-K
U-value of fenestration	0.35 (2.76) W/m²-K
Window-to-wall ratio	38%
Fenestration SC	0.44 (0.135)
Fenestration transmittance	0.78 (0.73)
Lighting	4.62 W/m²
Personnel	40 W/person
Temperature settings	Heating: 21.1 °C 35% RH Cooling: 23.9 °C 50% RH
Outdoor design conditions	Summer: 35 °C Winter: -24.4 °C
Weather file	University of Illinois, Willard

ANALYTICAL MODEL FOR MULTILAYER GROUND THERMAL RESPONSE

To evaluate the transient temperature variation surrounding the borehole, an analytical model was implemented in this study to integrate the building energy load profiles measurements. Erol and François (2018) developed a multilayer model for effectively calculating the temperature change from any observation point. The model mainly consists of two segments—the thermal response in the specified layer (denoted by subscript "1"), and the thermal response from adjacent layers (denoted by subscript "2…n"). In their original study, the heterogeneity of the subsurface physical properties within the same geologic layer was even considered, with assigning different values to the longitudinal and transversal changes in thermal diffusivity and conductivity. Nevertheless, the current field study on campus of UIUC did not consider differences in material properties in 3 dimensions. The analytical model has thus been simplified from the computations represented by the following equations, where x, y, z denote the spatial coordinates, r is the radial distance, and t time. Further, q denotes the heat flux per unit length of borehole; v and α denote the thermal transport velocity and thermal diffusivity, respectively.

$$\Delta T(x,y,z,t) = \Delta T_1 + \Delta T_2 + \ldots + \Delta T_n \tag{1}$$

$$\Delta T_1(x,y,z,t) = \frac{q}{2\pi k_1}\exp(\frac{xv_1}{2\alpha_1})\left\{\int_0^{z_1} f_1(x,y,z,t)dz' - \int_{-z_1}^{0} f_1(x,y,z,t)dz'\right\} \tag{2}$$

$$\Delta T_n(x,y,z,t) = \frac{q}{2\pi k_n}\exp(\frac{xv_n}{2\alpha_n})\left\{\int_{z_{n-1}}^{z_n} f_n(x,y,z,t)dz' - \int_{-z_n}^{-z_{n-1}} f_n(x,y,z,t)dz'\right\} \tag{3}$$

$$f_n(x,y,z,t) = \frac{1}{4r}\left[\exp(\frac{-rv_n}{2\alpha_n})erfc(\frac{r-v_n t}{2\sqrt{\alpha_n t}}) + \exp(\frac{rv_n}{2\alpha_n})erfc(\frac{r+v_n t}{2\sqrt{\alpha_n t}})\right] \tag{4}$$

To analyze the seasonal effects on the extent and migration of thermal plumes, one-year and three-year building load profiles were integrated into the model, and the iteration code was run in MATLAB. The initial ground temperature was set as 11°C as the in-situ thermal response tests indicated. To include the effects of adjacent geologic layers, the subsurface environment beneath CIF was divided into three lithologies with different hydrological and thermal properties measured by Burch et al (1999) and Stumpf et al. (2021), respectively, as shown in Table 2. The main groundwater flow exists in the second layer, while an extremely low velocity was assigned to the other two layers. The temperature of groundwater was set to be the same as initial ground temperature, 11°C.

Table 2 Geological layered properties

Lithologies	Depth range (m bgs)	Thermal diffusivity (mm^2/s)	Groundwater velocity (m/s)
Till	0~22.4	1.01	1×10^{-8}
Sand and gravel	22.4~85.5	1.47	2.07×10^{-7}
Clay and bedrocks	85.5~137	1.20	1×10^{-8}

RESULTS AND DISCUSSION

The graphs by the end of December obtained from the one-year and three-year simulation results are shown in this section, where both vertical and horizontal temperature profiles are presented. The horizontal domain (X-Y) was divided into 41 × 41 grids and the length of each grid was set as 0.5 m to better visualize the far field temperature. The vertical domain (X-Z) was divided into 81 × 41 grids and the length of grid in radial direction was set as 9.375×10^{-3} m to show the temperature gradient near the borehole. The sectional X-Y planes were selected at the depths of 55 m and 110 m below ground surface (bgs), which are the lithologies with the maximum and minimum groundwater flow velocities. The groundwater was set to flow towards the increasing values of direction-X. As observed in Figure *2*, at the depth of 110 m, within the deepest lithology, the isotherms are dispersed symmetrically from the center of BHE. While for the sand and gravel where the groundwater flow is 2.07×10^{-7} m/s, the rejected heat in summer slightly migrates along the downstream of groundwater. The modeling results indicated very minor temperature change in the surroundings of the BHE, as the temperature at the majority of the grids fell into the range of 10.3 °C ~ 11.2 °C. Also, negligible difference was observed between the temperature contours by the end of first year and third year, indicating the thermal steady state was reached early in the first year. Furthermore, the migration of heat plume was not significant, partially because groundwater flow is relatively slow. It also indicates that the rejected heat from CIF was sufficiently mild to be offset by the surrounding environment before it further developed in the x direction.

The simulation results for BHE coupled to a building with a traditional heating and cooling system, referred as the "control", are presented in Figure 3, where a heating-dominated profile is observed. In the lowest lithology, the minimum temperature simulated near the wall of borehole (x = 0.5 m) reached 7.89 °C and 7.76 °C by the end of first and third year, respectively. With the presence of groundwater flow, the overcooling was slightly mitigated. As the cold center migrates in the x direction, the heat extraction near BHE becomes effective. At the same radial distance (x = 0.5 m), the temperature decreased from 8.64 °C to 8.57 °C as time marched from one year to three years. The severeness of overcooling in the scenario of "control" and CIF was further visualized in Figure 4. As one can observe, as it approaches from far field to the borehole wall, the difference between the magnitudes of temperature drops in "control" and CIF increases. Also, the presence of groundwater may narrow this gap in the upstream as it may refresh the local ground temperature.

The comparison between the vertical temperature profiles of the CIF and control is shown in Figure 5. To better visualize the temperature difference between the different lithologies and scenarios, a depth of 40-137 m was chosen to generate the isotherms. As demonstrated, much milder temperature drop was found in the CIF scenario when compared to the "control". In the "control" scenario, the maximum temperature decrease at the borehole wall was 10.55 °C, while when it comes to CIF, it was 2.73 °C, which reduced 74.1% of the thermal anomaly. Furthermore, the presence of groundwater may reduce the effects of either heating or cooling, introducing benefits to the performance of BHE.

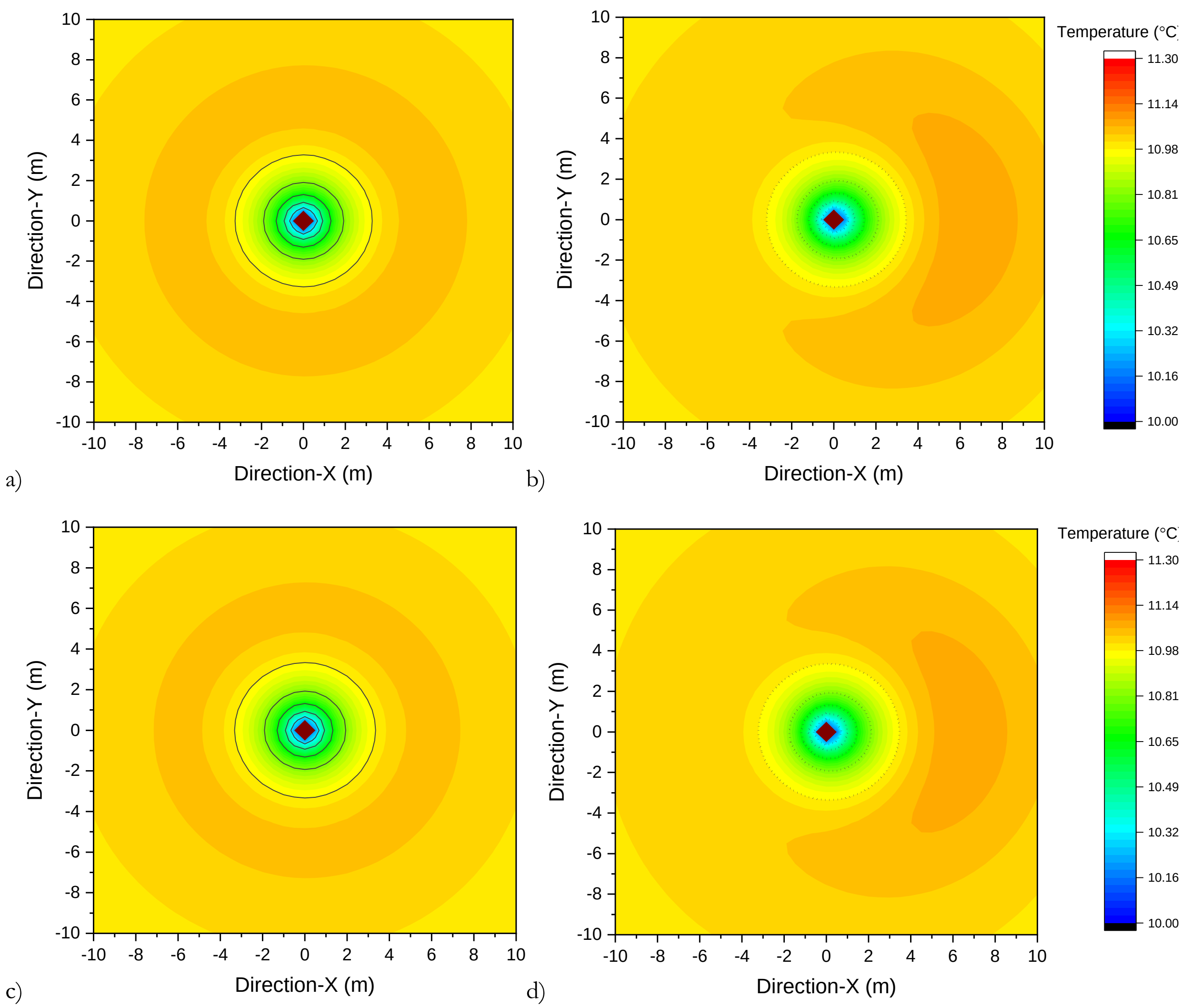
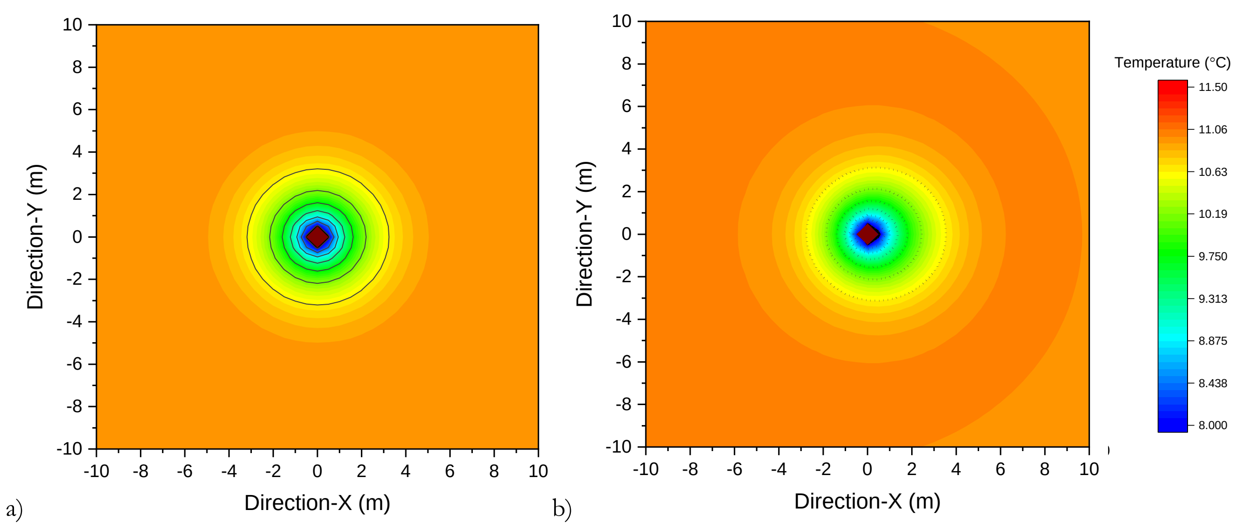


Figure 2 Isotherms around the BHE coupled at the CIF by the end of first year (Dec 31st) at a) depth of 110 m (with minimum groundwater flow). b) depth of 55 m (with 2.07×10^{-7} m/s groundwater flow). Temperatures at the end of third year (Dec 31st) in the lithologies at c) depth of 110 m and d) depth of 55 m.



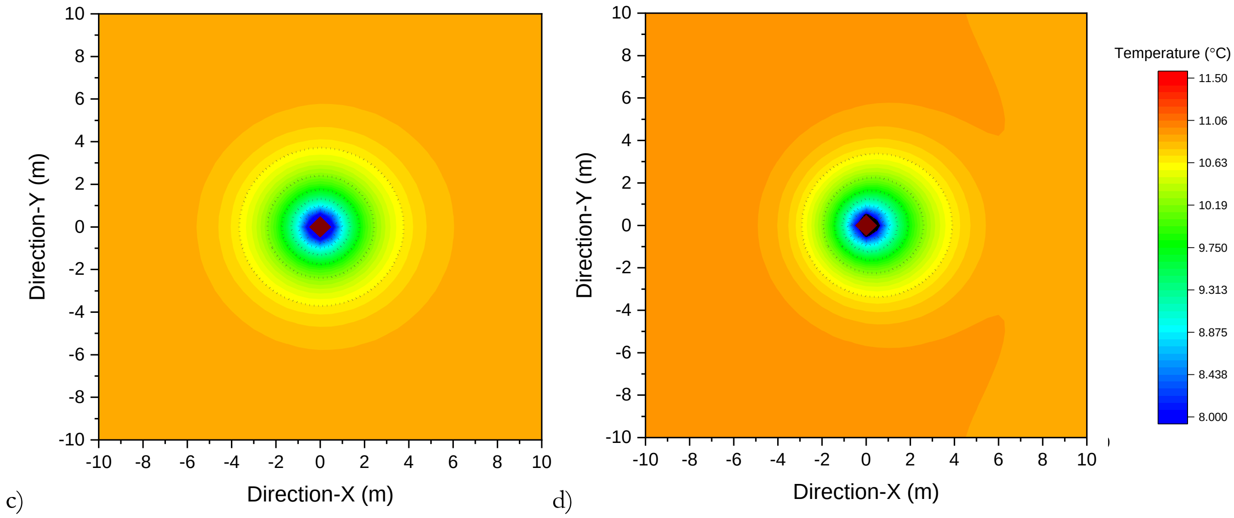


Figure 3 Isotherms around the BHE coupled with the "control" building at the end of first year (Dec 31st) at depths of a) 110 m (with near-zero groundwater flow) and b) 55 m (with 2.07×10^{-7} m/s groundwater flow). By the end of third year (Dec 31st), the temperature decrease, and isotherms are shown at depths of c) 110 m and d) 55 m.

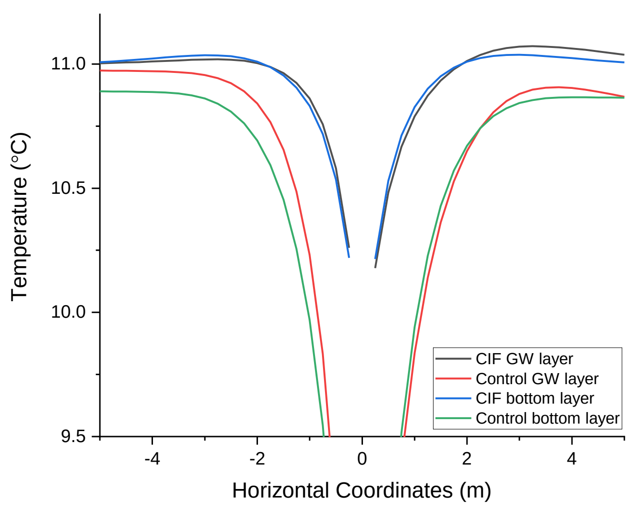


Figure 4 The one-dimensional temperature profiles along the direction-X at horizontal sectional planes with/without groundwater abundance in the scenario of CIF and "control" by the end of third year (Dec 31st). GW denotes the layer with highest groundwater velocity.

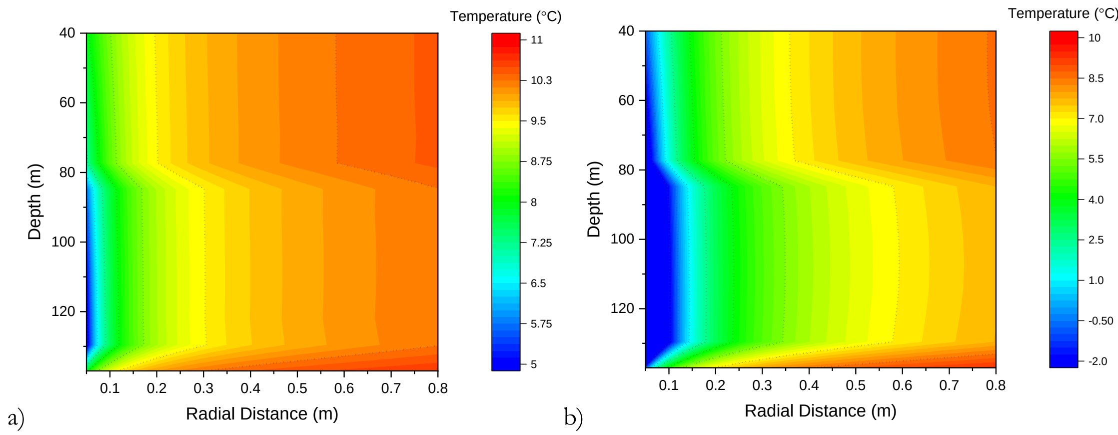


Figure 5 The vertical temperature profile along the BHE between 40-137 m bgs by the end of the third year (Dec 31[st]) for a) BHE coupled with CIF. b) BHE coupled with "control" building.

CONCLUSION

This study investigated the ground thermal response from a single BHE for two buildings with different energy loads—the CIF building which is seeking LEED certification and the "control" with a traditional energy system. As the two buildings were simulated with the same borehole length, the results showed that the prospective LEED building may significantly reduce the possibility of overheating and overcooling the ground. By the end of the third year of operation, the simulation for the BHE coupled with the CIF suggests there would be a 74.1% lower temperature drop at the borehole wall compared to the "control" building in central Illinois. The groundwater flow in this lithology was observed to be very slow, though flowing groundwater had beneficial impacts on dissipating thermal anomalies. This study provide evidence on the necessity of climate-adaptive building envelopes when a GSHP is implemented. Nevertheless, the LEED buildings require higher constructional cost compared with others. Therefore, future efforts should be put on the life-span economic analysis of GSHP to evaluate its financial feasibility in practice.

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NOMENCLATURE

α = Thermal diffusivity (m^2/s)
β = Thermal expansion coefficient (1/K)
q = Specific heat load (W/m)
r = Radial distance from the line source (m)
ν = Kinematic viscosity (m^2/s)
t = Time (s)
x, y, z = Spatial coordinates (m)
z' = Integrating factor (-)

T = Temperature of the ground (°C)

Subscripts

n = Number of ground layers

Special

Control = The building with envelopes using traditional thermal properties

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