Thermohydraulic Comparison of Horizontal Geo-Exchange Pipes Versus Traditional Boreholes

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Abstract

Ground Source Heat Pump (GSHP) systems provide efficient, low-emission heating and cooling but remain constrained by the high drilling costs associated with deep vertical boreholes. This study evaluates a shallow, cost-effective alternative: Horizontal Plastic Geo-Exchange Pipes (PGEPs) installed using Horizontal Directional Drilling (HDD), and compares their thermal performance to a conventional vertical U-tube borehole. A thermohydraulic PGEP model was developed and experimentally validated, while the borehole model was benchmarked against a finite line-source analytical solution. A full-year simulation incorporating hourly school building loads and a Toronto-based ground temperature model was conducted for both systems. The horizontal PGEP delivered a maximum capacity of 1.5 tons and an annual average COP of 3.7, outperforming the vertical borehole, which achieved only 1.0 ton under identical constraints. PGEP performance advantages stem from its larger heat-exchange surface area, laminar-flow-enhanced residence time, and installation depth benefiting from seasonal thermal recharge.

Keywords: Geothermal; Ground Source Heat Pump; Numerical Modelling; Energy Efficiency; Sustainability

1. Introduction

Ground Source Heat Pump (GSHP) systems are effective clean energy technologies, capable of providing both heating and cooling without burning fossil fuels. They require considerably less electrical input than traditional systems, making them a sustainable and energy-efficient alternative for residential, commercial, and industrial applications. These systems operate by exploiting the earth's naturally stable subsurface temperatures as a renewable thermal reservoir. Ground source heat refers to the low-enthalpy thermal energy stored in the earth's shallow layers as a result of absorbed solar radiation [1]. The thermal energy contained within the top 1–200 m of the ground acts as a heat sink or source that can be used to absorb or emit heat to meet building thermal demands [2]. This environmentally friendly approach significantly reduces greenhouse gas emissions and energy consumption—up to 75 % less than electric resistance heating [3].

Despite their environmental and operational advantages, GSHP systems face challenges related to high initial capital costs and longer payback periods compared to conventional HVAC systems. The main contributor to this drawback is the elevated expense of drilling and installing vertical boreholes, which can reach depths of up to 250 m [4]. As a practical alternative, steel helical piles (HSPs) have gained widespread use as structural foundation elements in low- to mid-rise buildings. These piles are typically installed through direct insertion without the need for pre-drilling, reaching shallower depths between 6 m and 30 m [5]. Beyond their conventional structural function, HSPs also exhibit strong potential as shallow in-ground heat exchangers, allowing their integration into GSHP systems. This dual-purpose functionality not only reduces installation costs and spatial requirements but also enhances the overall feasibility of geothermal systems compared to conventional deep-borehole configurations.

The operational principle is analogous to that of traditional borehole heat exchangers: a working fluid is circulated through plastic tubing fitted within the hollow steel pile. Heat transfer occurs through forced convection between the working fluid, the steel wall, and the surrounding soil. During the cooling season, the warm fluid transfers heat to the pile and the ground, lowering indoor temperatures, whereas during the heating season, the cooler fluid absorbs heat from the surrounding soil to warm the building interior. Addressing the limitations of traditional GSHP systems, this research focuses on advancements within the GSHP industry aimed at reducing installation costs. The following sections review prior studies involving the use of steel helical piles (HSPs) as geothermal heat exchangers and introduce an innovative horizontal GSHP technology designed to overcome existing limitations of HSP-based systems while further lowering overall installation costs.

2. Background Information

A study by Attard et al. [4] investigated the performance of helical steel piles (HSPs) as geothermal heat exchangers, highlighting their potential for improved efficiency and reduced installation costs. The experimental system was installed at the Eby Rush Power Station in Waterloo, Canada, where both heating and cooling tests were conducted to evaluate the thermal capacity, power consumption, and coefficient of performance (COP) of the novel HSP configuration. In the setup, a conventional ground loop array operated with a 30% propylene glycol solution, while the helical pile array utilized plain water as the working fluid. A three-way electronic valve regulated flow between the ground and pile loops, determining whether the heat pump discharged fluid to the ground loop, the pile loop, or both simultaneously. The pile array itself was divided into two independent loops, each controlled by separate two-way valves, allowing either loop—or both—to be activated as needed. Through this flexible valve control and remote monitoring system, three steady-state performance tests were conducted to assess the system's operational characteristics under varying conditions.

Peak Cooling Capacity Test: The inlet temperature of the water circulating through the steel piles rose sharply during the initial operation of the heat pump, followed by a gradual increase once steady-state conditions were achieved. Both inlet and outlet temperature trends were similar throughout the test. The temperature across the eight piles increased from 13.9 °C to 20.5 °C, yielding a COP of 2.13. This relatively low value was attributed to system losses and the influence of a secondary heat exchanger.

Cooling Steady-State Capacity Test: Increasing the flow rate on the heat exchanger side resulted in a greater temperature difference between the inlet and outlet of the piles. Under full load, a temperature change of 14.8 °C was observed with a COP of 3.4. Across all steady-state cooling tests, the COP ranged between 3.2 and 4.5.

Heating Steady-State Capacity Test: During the heating tests, the inlet temperature of the pile loop initially dropped as flow through the heat exchanger increased. Both inlet and outlet temperatures continued to decrease gradually until steady operation was achieved. Increasing the flow rate from 2.76 l/min to 6.1 l/min led to higher temperature differences across the piles. At a flow rate of 1.46×10^{-4} m^3/s, the maximum temperature difference of 5.5 K was recorded, slightly higher than those observed in the previous tests (2.82 °C and 4.87 °C). Overall, results confirmed that higher flow rates produced greater temperature differentials, with the average COP across all heating tests determined to be 3.35.

The analysis of Ground Source Heat Pump (GSHP) systems can be performed using either analytical methods or numerical modeling approaches. Analytical models are based on simplified physical formulations that are intuitive and straightforward to apply; however, they are generally unsuitable for representing complex geometries or implementing realistic boundary conditions. In contrast, numerical modeling enables the simulation of GSHP systems with intricate configurations and diverse soil or boundary conditions, making it a widely adopted method among researchers [6]. A key advantage of numerical modeling is its ability to simulate system performance without the spatial and financial constraints associated with experimental setups. In particular, Computational Fluid Dynamics (CFD) combined with Finite Element Analysis (FEA) provides a powerful framework for investigating GSHP performance. CFD focuses on the analysis of fluid flow and heat transfer phenomena by solving the fundamental governing equations of mass, momentum, and energy conservation. For GSHP applications, these equations are solved to describe the coupled thermal and hydraulic behavior of the working fluid, pipe walls, grout, and surrounding ground [7].

Bayomy et al. [8] conducted a numerical and analytical study of a vertical geo-exchange borehole using both conventional grout and bentonite-based backfilling materials enhanced with graphite. Their research combined a finite element model (FEM) developed in COMSOL Multiphysics with an analytical finite line-source (FLS) model to simulate transient heat transfer and validate numerical results. The FEM considered turbulent flow within the U-tube, real building heating and cooling loads, and variable heat-pump performance, while solving the mass, momentum, and energy conservation equations for the fluid, grout, and surrounding soil domains. The results demonstrated strong agreement between the analytical and numerical approaches, with small absolute temperature differences observed throughout the simulation period. The conventional borehole exhibited ground-temperature fluctuations between 6 °C and 13 °C and an average temperature rise of approximately 1.1 °C over four years of cooling-dominant operation. The system's coefficient of performance (COP) decreased from about 5.7 to 3.2 during the cooling season and to 2.7 during the heating season. When the grout was replaced by graphite-enhanced bentonite, the effective thermal conductivity increased to about 5 W/m·K, enabling a 40 m borehole to achieve similar or better performance than a conventional 80 m borehole. Monthly average COPs improved by 5–13 %, confirming the material's ability to enhance heat-exchange efficiency and reduce drilling depth requirements.

Nicholson et al. [9] developed and validated a detailed numerical model of a ground heat exchanger (GHE) using CFD and Finite Element Analysis (FEA). The simulations, conducted in COMSOL Multiphysics, were aimed at optimizing the thermal and hydraulic performance of Ground Source Heat Pump (GSHP) systems and evaluating their hydrothermal characteristics. Although laminar flow is not typically employed in conventional GHEs, the study intentionally utilized it to extend the residence time of the working fluid—plain water—within the helical pile. This approach promoted near-thermal equilibrium between the fluid and the surrounding soil, enhancing heat transfer while minimizing pumping power and pressure losses. Simulations were performed at flow rates of 1, 2, and 4 l/min, using helical steel casings with nominal API (American Petroleum Institute) sizes of 13.5, 23, 29, 53, 60, and 68, and plastic inlet/outlet pipes ranging from 1 cm to 5.1 cm diameter. The reference configuration employed an API 23 steel casing with an 11.9 cm inner diameter and 2.5 cm nominal plastic pipes. Increasing the flow rate from 1 to 2 l/min resulted in an average heat exchange gain of 383.98 W and 398.70 W for the regular and double-sized pipe configurations, respectively. These results indicated that there exists an optimal combination of pile and pipe diameters that maximizes heat exchange under laminar flow conditions. Interestingly, in the enlarged double-sized piles, larger diameters produced lower heat exchange rates and broader temperature distributions, attributed to a greater thermal mass radius within the soil. In contrast, increasing inlet-pipe diameter raised the Reynolds number and improved convective potential, confirming that both pipe diameter ratio and water volume are critical to performance. The study also observed that variations in pipe geometry had a stronger effect on fluid temperature than on soil temperature distribution, suggesting potential guidelines for array spacing and pile sizing in future designs. Pipe length was another influential factor: each 1 m increase in the inner plastic pipe length enhanced heat exchange by approximately 21.7 W, largely independent of soil conductivity variations. However, the outlet pipe length was sensitive to stratified soil properties, implying that optimal lengths should correspond to soil layers with higher thermal conductivity. Overall, while laminar flow yields lower heat transfer rates than turbulent flow in conventional boreholes, it provides reasonable thermal performance at significantly lower pumping power and installation cost. Thus, laminar operation in shallow helical systems may offer a practical and cost-effective solution for small-scale installations, retrofits, hybrid systems, and domestic hot water applications.

Horizontal ground heat exchangers have also been investigated for their simpler installation and lower cost. Tarnawski et al. [10] found diminishing COP gains beyond 350 m loop length, while Gan [11] demonstrated that soil composition and depth significantly influence performance—sandy soils and burial depths of 1–2 m enhance heat transfer by up to 17 %. Such studies established that moisture-coupled, transient modeling is essential for accurate horizontal GSHP analysis.

Building on these foundations, Ghalayini et al. [12] introduced Plastic Geo-Exchange Pipes (PGEPs)—ground heat exchangers that maintain the same geometric configuration as Helical Steel Piles (HSPs) but are constructed from High-Density Polyethylene (HDPE) and installed horizontally using Horizontal Directional Drilling (HDD) techniques. Numerical simulations conducted in COMSOL Multiphysics analyzed 61 m-long PGEPs installed at depths of 4.6 m, 5.5 m, and 6.4 m, and compared their performance with a 15.2 m vertical configuration of similar geometry. These depth levels were selected to represent the typical installation range of HDD practices used in underground utility applications. The results indicated that ground temperature stabilizes near 6.4 m, where the influence of solar radiation and atmospheric variations becomes minimal. Each 0.9 m increase in burial depth from 4.6 m produced an additional 0.5 tons of heating capacity per 61 m pipe, attributed to the more stable soil temperature domain at greater depths. Among all configurations, the 5.5 m installation provided the best balance between thermal efficiency and installation cost, achieving an average annual COP of approximately 3.7 (heating $\approx$ 3.5, cooling $\approx$ 7.3). However, while these studies established the thermal potential of horizontal PGEPs, no work to date has directly compared their performance to a conventional vertical borehole under identical load and ground conditions—leaving a critical gap in evaluating whether shallow HDD-installed systems can serve as practical, cost-effective replacements for traditional GSHP configurations.

3. System Description

This study examines the thermohydraulic performance of a horizontal PGEP and traditional borehole systems through numerical modeling and CFD simulations carried out in ANSYS Fluent [13] and COMSOL Multiphysics [14] respectively. As shown in Figure 1, the PGEP features an outer HDPE casing with an approximate diameter of 14.7 cm, along with inlet and outlet PEX (cross-linked polyethylene) pipes each measuring 2.1 cm in diameter. The horizontal section of the system spans 61 m and incorporates a curved bend extending approximately 2.6 m horizontally and 1.8 m vertically. In this configuration, the inlet pipe runs the full length of the outer casing, ending 10.1 cm before the pipe's termination point, while the outlet pipe extends 30.5 cm into the bend. The PGEP is installed at a burial depth of 6.1 m, where subsurface temperature conditions are more stable and suitable for ground heat exchange.

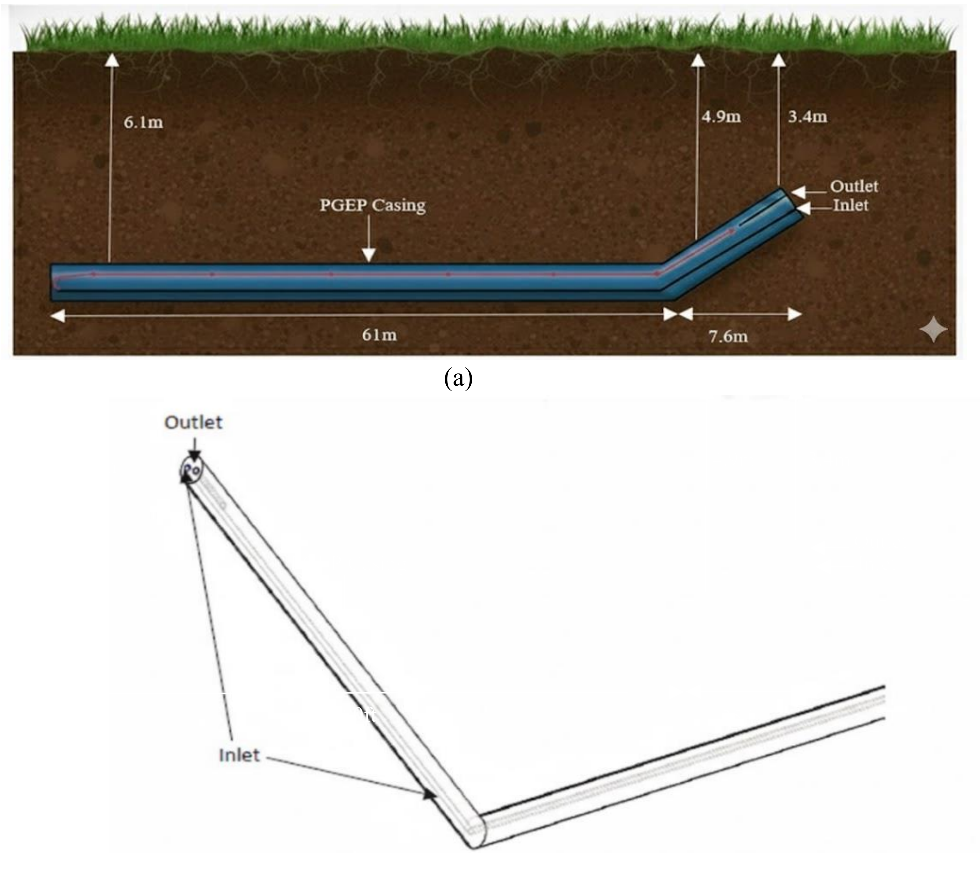
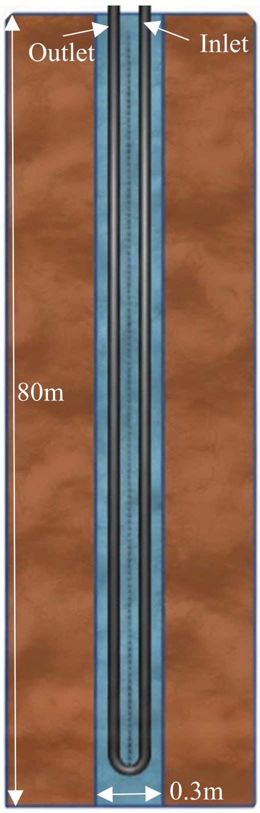


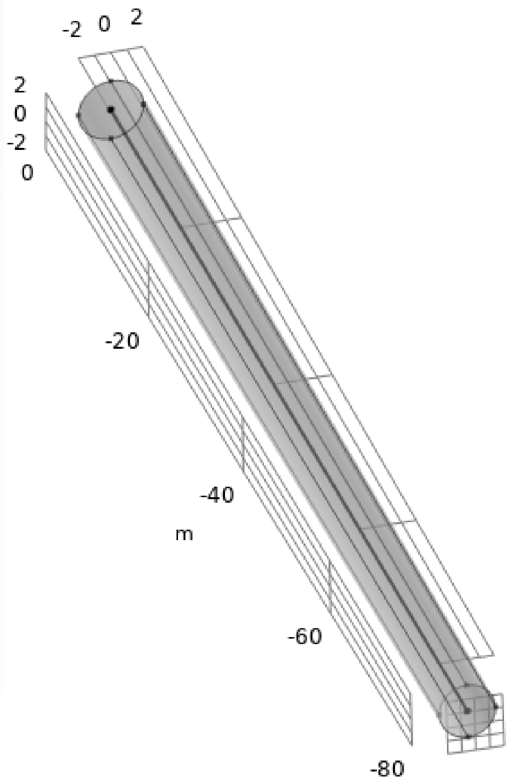
Figure 1. Horizontal PGEP Model (a) Conceptual Layout (b) Transparent Geometry

This configuration facilitates the filling of the outer casing with the working fluid (20 wt% ethanol–water), enabling heat exchange between the GHE casing and the surrounding soil. Previous work by Ghalayini et al. [12] demonstrated that laminar flow at 3 l/min provided reasonable thermal performance; however, system performance improved significantly when the flow rate was increased to 11 l/min. This flow rate was selected because it represented the maximum allowable capacity of the circulation pump in the horizontal PGEP pilot project. It was determined through both experimentation and modelling that higher flowrates yielded higher heat transfer rates and COPs.

At 11 l/min, the Reynolds number within the inlet and outlet pipes is approximately 10,000, indicating turbulent flow. In contrast, the larger diameter of the outer casing results in a Reynolds number of about 1400, which remains within the laminar flow regime. Therefore, even though turbulence occurs within the inner piping, the fluid within the outer casing—where the majority of heat exchange occurs—continues to behave laminarly. This confirms that the dominant mechanism enhancing heat transfer in the PGEP is the increased residence time of the working fluid rather than turbulence-driven convection.

The borehole system shown in Figure 2 serves as the reference configuration against which the thermal performance of the horizontal PGEP is evaluated. In this system, a traditional U-tube assembly is installed inside an 80 m deep vertical borehole. The U-tube is constructed from PVC plastic with a diameter of 2.1 cm, and the two legs of the loop are spaced 6.6 cm apart. The surrounding annulus is filled with thermally conductive grout, producing a final borehole diameter of 15.2 cm. Unlike HSPs and PGEPs—which rely on laminar flow to increase fluid residence time and promote heat transfer primarily through conduction—conventional borehole heat exchangers typically operate under turbulent flow conditions within the U-tube. Turbulence enhances the internal convective heat transfer coefficient, allowing more efficient thermal exchange between the circulating fluid, the pipe wall, and the surrounding grout–soil matrix. Properties of all materials can be found in Table 1.





(a) (b)

Figure 2. Borehole Model (a) Conceptual Model (b) Finite Element Model

Table 1. Thermophysical Properties of Materials

Material	Thermal Conductivity (W/(m.K))	Density (kg/m^3)	Heat Capacity (J/(kg.K))
HDPE	0.45	950	1930

PEX Plastic	0.41	1190	450
PVC Plastic	0.40	1350	1200
Soil	2.2	1700	1800
Grout	1.9	1500	1647

4. Methodology and Governing Equations

This study was carried out in three stages: (a) development of numerical models for both the horizontal PGEP and the vertical borehole system, (b) validation of the numerical model for the horizontal PGEP, and (c) thermal performance comparison between the two systems. Model validation was performed using experimental data collected from the PGEP pilot installation. In the experiment, the system operated under a constant thermal load and constant flow rate for a duration of 9 hours. The measured inlet temperatures from the field experiment were imposed as boundary conditions in the numerical model for the same operating period. The resulting numerical outlet temperatures were then compared with the experimental outlet temperatures, showing strong agreement with a maximum deviation of less than $\leqslant$ 0.5 ℃. This confirmed that the horizontal PGEP model developed in ANSYS Fluent accurately captured the thermal behavior observed in the pilot test. The borehole system on the other hand was validated against an analytical Finite Line Source (FLS) model and was found to be in good agreement with the numerical data at different times throughout the year within a maximum relative error of 0.5 ℃ [8].

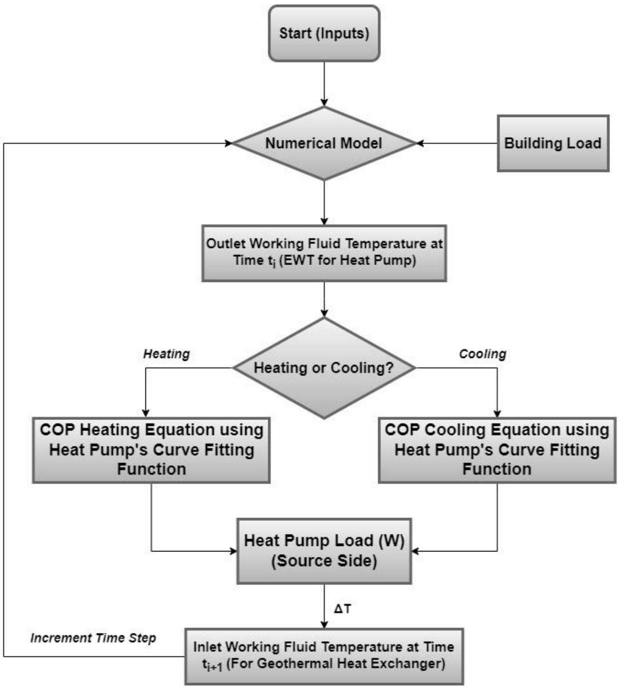


Figure 3. Numerical Computational Procedure for GSHPs

Figure 3 presents the computational workflow used to model the ground source heat pump system numerically. The procedure begins with defining the environmental inputs that govern subsurface heat transfer, including the depth-dependent thermal conductivity of the soil and, critically, the soil temperature distribution as a function of both depth and time. The soil temperature profile, $T_{(z,t)}$, is computed using the following expression [16]:

$$T_s(z,t) = T_{s,avg} + T_{s,amp1}e^{z\sqrt{\frac{\pi}{\alpha*365}}}\cos\left(\frac{2\pi}{365}(t-P_{11}) + z\sqrt{\frac{\pi}{\alpha*365}}\right) - T_{s,amp2}e^{z\sqrt{\frac{2\pi}{\alpha*365}}}\cos\left(\frac{4\pi}{365}(t-P_{12}) + z\sqrt{\frac{2\pi}{\alpha*365}}\right) \quad (1)$$

Where $T_{s,avg}$ is the annual average ground temperature, $T_{s,amp1}$ and $T_{s,amp2}$ are the amplitudes of the first and second harmonic surface-temperature variations, P_{11} and P_{12} are the corresponding phase lags (days), and α is the soil thermal diffusivity. The exponential damping terms $e^{z\sqrt{(\pi/(\alpha*365))}}$ and $e^{z\sqrt{(2\pi/(\alpha*365))}}$ capture the attenuation of temperature oscillations with depth. Here, z represents the depth below the ground surface, and t denotes the day of the year. Figure 4 illustrates the resulting ground-temperature model for Toronto, Ontario, Canada based on these parameters.

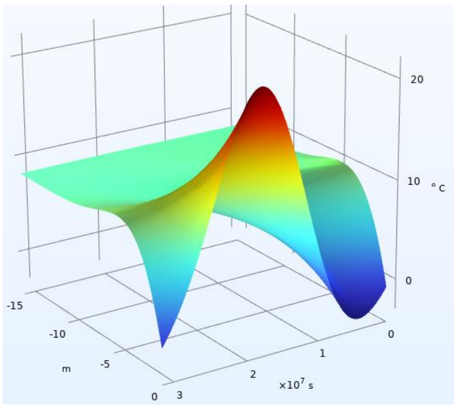


Figure 4. Ground Temperature Model for Toronto, Ontario, Canada

With the ground temperature model and the normalized building load applied to the numerical domain, the outlet temperature of the geothermal heat exchanger is computed at each time step t_i. Depending on the building load—whether the system is operating in cooling or heating mode—the outlet temperature and the corresponding Coefficient of Performance (COP) will vary accordingly. The COP correlations adopted in this study, obtained from the work of Li et al. [17], are provided below:

$$COP_{Heat}(T) = HA * (T_{out})^2 + HB * T_{out} + HC \tag{2}$$

$$COP_{Cool}(T) = CA * (T_{out})^2 + CB * T_{out} + CC \tag{3}$$

The COP correlations adopted from Li et al. [17] were derived under fixed heat-pump sink-side operating conditions. In heating mode, the building-side supply and return temperatures were maintained at constant values, while in cooling mode the corresponding sink temperatures were likewise assumed constant. As a result, variations in COP are primarily governed by the geothermal loop outlet temperature, allowing the COP to be expressed solely as a function of T_{out}. Where T_{out} is the outlet temperature of the geothermal heat exchanger. The coefficients used in the COP correlations $(H_A, H_B, H_C, C_A, C_B, C_C)$ were derived through curve fitting based on the experimental heat pump configuration from the pilot project for the horizontal PGEP. Once the heat pump load is computed, the final step in the iterative process is to determine the inlet temperature for the subsequent time step [17].

$$T_{in} = T_{\text{out}} + \frac{Q_{Building}}{\rho(T)*Cp(T)*V} * \left[\left[\left(1 - \frac{1}{COP_{Heat(T)}}\right) * A(t) * \left(1 - B(t)\right)\right] + \left[\left(1 + \frac{1}{COP_{Cool(T)}}\right) * B(t) * \left(1 - A(t)\right)\right]\right] \tag{4}$$

Here, T_{in} denotes the inlet temperature for the next time step in the simulation. Q_{Building} represents the building load, while $\rho(T)$ and $C_p(T)$ are the temperature-dependent density and specific heat capacity of the working fluid. V is the volumetric flow rate, and $A(t)$ and $B(t)$ indicate the operational mode of the building at a given time, corresponding to heating and cooling, respectively. Lastly the turbulent Nusselt number inside the U-tube borehole is given by the following equation:

$$Nu = 0.027 * Re^{0.8} * Pr^n \tag{5}$$

In this expression, Nu denotes the Nusselt number, Re is the Reynolds number, and Pr represents the Prandtl number. The exponent n takes a value of 0.4 for cooling operation and 0.3 for heating operation [8].

5. Results and Discussion

Figure 5 shows the hourly heating and cooling load profile for a secondary school located in Southwestern Ontario over a full year (8760 hours). Heating loads (shown in blue) dominate the colder months, with frequent peak demands between –1500 kW and –2000 kW, reflecting the high winter heating requirements of the building. Cooling loads (shown in orange) occur primarily during the late spring and summer months, reaching peak values of approximately 1000–1200 kW. The seasonal pattern is clearly visible: large negative (heating) loads in winter, a transition period in spring and fall, and significant positive (cooling) loads during mid-summer. This building load profile is used as the boundary condition for evaluating both the Horizontal PGEP and borehole's performance and annual energy balance.

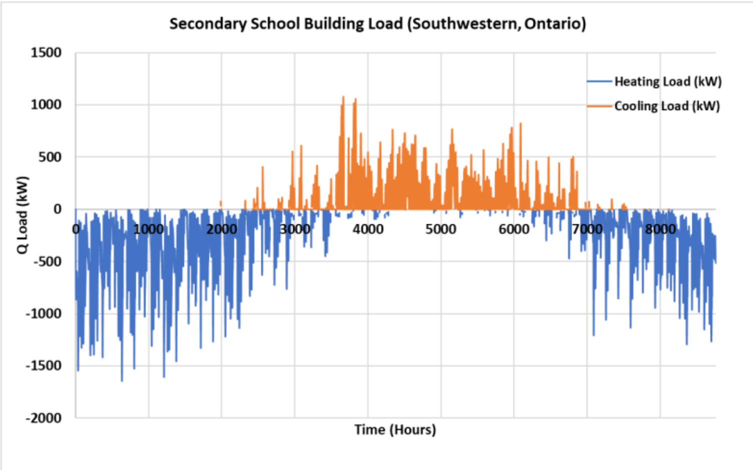


Figure 5. Building Load Profile of Secondary School

The ground temperature data used in this simulation reflect the climatic conditions of the City of Toronto, where shallow subsurface temperatures exhibit strong seasonal variation. The aim of the analysis was to estimate the required sizing and performance of a horizontal PGEP array capable of meeting 100% of the secondary school's annual heating and cooling demand. This was achieved by applying a normalized hourly building load profile to the numerical model. Closed-loop geothermal systems are conventionally designed to maintain outlet temperatures in the range of 0–25 °C, which corresponds to the allowable entering water temperature (EWT) for most commercial heat pumps. However, for the PGEP pilot installation, the working fluid consisted of a 20 wt% ethanol–water mixture, extending the operational EWT range to –3–40 °C due to its lower freezing point and enhanced thermal stability. This wider temperature tolerance is particularly important for shallow horizontal systems, where seasonal ground temperature swings are more pronounced than in deep boreholes. Figure 6 illustrates the simulated inlet and outlet temperatures of the PGEP over one full year under the school's load profile.

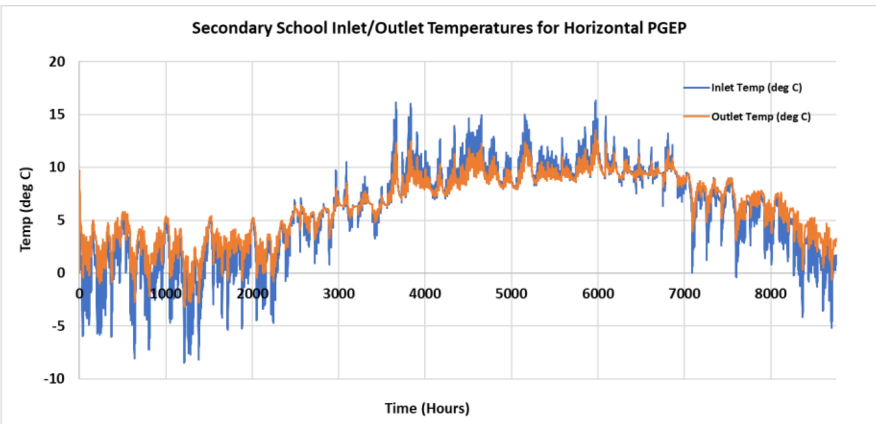


Figure 6. Horizontal PGEP Inlet and Outlet Temperatures for the Secondary School

The temporal variation of these temperatures is driven by the seasonal ground temperature cycle, which is more pronounced at the shallow burial depth of the horizontal PGEP due to its greater exposure to atmospheric conditions and solar radiation, as well as by the dynamic fluctuations in the building's heating and cooling loads. The minimum and maximum PGEP outlet temperatures—equivalent to the entering water temperatures delivered to the heat pump—were used to determine the system's maximum heating and cooling capacity. For this specific load profile, the horizontal PGEP configuration delivered an effective capacity of approximately 1.5 tons, demonstrating its suitability for small-to-medium-scale building loads. Beyond capacity estimation, the simulated outlet temperature data enabled further evaluation of system performance metrics. Using the instantaneous fluid temperatures and load profile, the coefficient of performance (COP) as seen in Figure 7, seasonal performance trends, and electrical energy consumption were computed.

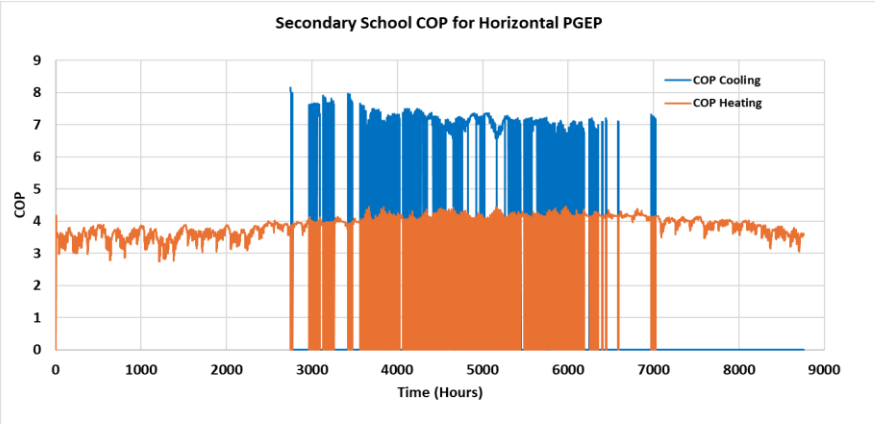


Figure 7. Horizontal PGEP COP for the Secondary School

The same design methodology used for sizing the horizontal PGEP system was applied to the borehole configuration. A normalized building load was imposed, and the borehole model was tested to determine the maximum heating and cooling capacity achievable while ensuring that the outlet temperature remained within the allowable entering water temperature (EWT) limits of the heat pump. As shown in Figure 8, the inlet and outlet temperature profiles for the borehole remain far more stable and exhibit significantly less seasonal fluctuation compared to the horizontal PGEP results in Figure 6.

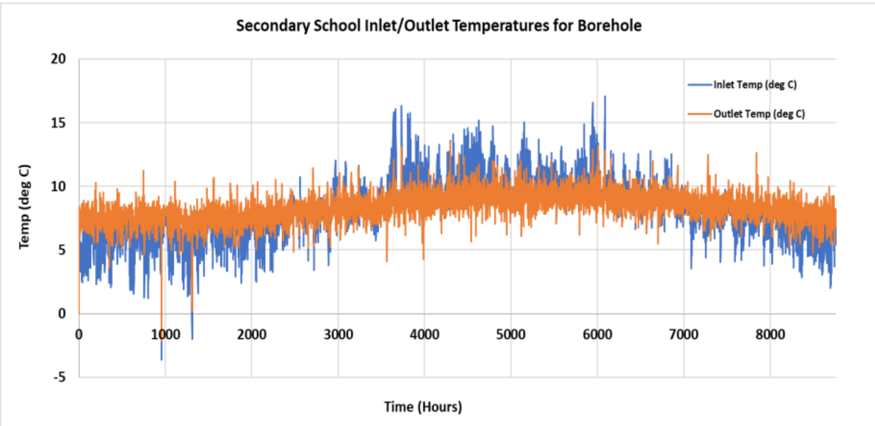


Figure 8. Borehole Inlet and Outlet Temperatures for the Secondary School

This behavior arises from the much greater installation depth of the vertical borehole. Referring to the ground temperature distribution in Figure 4, the subsurface temperature becomes effectively constant at approximately 10 °C beyond a depth of 7 m, regardless of surface weather patterns or seasonal variations. Vertical ground heat exchangers (GHEs) benefit substantially from these thermally stable deep-soil conditions, which insulate the system from atmospheric temperature swings, solar radiation effects, and shallow-depth temperature gradients. Consequently, borehole systems generally display smoother temperature profiles, more predictable thermal performance, and reduced sensitivity to short-term environmental fluctuations—attributes that contribute to their reliability and high efficiency in conventional GSHP installations.

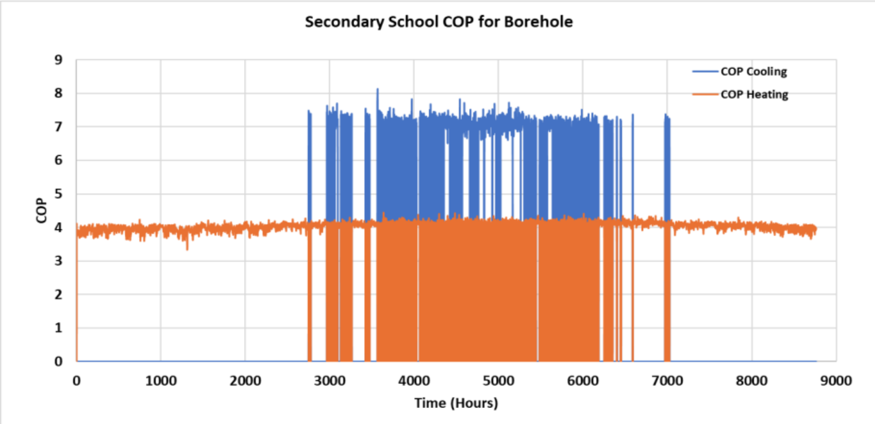


Figure 9. Borehole COP for the Secondary School

Table 2 summarizes the key performance parameters used to evaluate the feasibility of GSHP deployment for the secondary school. Both systems have comparable total pipe lengths within the soil—approximately 69 m for the horizontal PGEP and 80 m for the vertical borehole. The results indicate that the horizontal PGEP achieved a higher maximum capacity of 1.5 tons, whereas the borehole system reached only 1.0 ton. Although the borehole could reliably meet a 1-ton load, it was unable to support 1.5 tons without exceeding the allowable entering water temperature (EWT) limits of the heat pump. The reported average COP values were calculated as energy-weighted seasonal performance factors (SPF), defined as the ratio of cumulative useful thermal energy delivered to total electrical energy consumed over the simulation period.

This performance difference is primarily attributed to the substantially larger heat-transfer surface area of the PGEP. The horizontal PGEP uses a 14.7 cm diameter HDPE casing, which provides significantly greater soil contact compared to the 2.1 cm U-tube used in the borehole. Additionally, the larger hydraulic diameter of the PGEP results in laminar flow at 11 l/min, increasing the residence time of the working fluid and enhancing conductive heat exchange with the surrounding soil. In contrast, the borehole experiences turbulent flow under the same conditions due to its smaller pipe diameter. As a result, the horizontal PGEP demonstrates superior thermal performance despite being installed at shallower depths.

Table 2. Key Parameters for Horizontal PGEP and Borehole

Parameters	Horizontal PGEP	Borehole
Max System Capacity (tons)	1.5	1
Min Outlet Temp (°C)	-2.5	-2
Max Outlet Temp (°C)	13.5	19.3
Avg Annual COP	3.70	4.29
Avg COP Heating	3.58	4.18
Avg COP Cooling	7.13	7.10
Total Heating Electricity (kWh)	412	352
Total Cooling Electricity (kWh)	15	15

Additionally, it was observed that the 6.1 m installation depth of the horizontal PGEP occupies a thermally favorable zone. At this depth, the soil is shallow enough to still benefit from seasonal solar radiation, allowing heat to be stored in the ground during warmer months, yet deep enough to provide sufficient thermal insulation, preventing rapid dissipation of this stored heat. This seasonal recharge effect proved advantageous during the winter, as the PGEP was able to extract heat from a warmer soil domain. Consequently, the ground temperature surrounding the 6.1 m PGEP remained higher than the stable 10 °C typically observed around an 80 m deep borehole, enhancing the heating performance of the system.

This difference in capacity has direct implications for system sizing. For example, if a building requires 3 tons of heating or cooling, a horizontal PGEP system would need approximately 140 m of heat-exchanger piping installed via HDD (i.e., two 69-m segments). While this configuration requires more available land area, it eliminates the need for multiple deep wells, which in a borehole system would substantially increase drilling cost and permitting complexity despite requiring less surface footprint. Because drilling typically represents nearly half of GSHP installation costs, the HDD-based installation of PGEPs remains a significantly more cost-effective option, particularly since HDD is already widely used for installing utilities such as fiber-optic, water, and natural gas lines. Overall, the horizontal PGEP system offers higher capacity per meter of exchanger, lower installation cost, and strong thermal performance, making it a compelling alternative to traditional vertical configurations when sufficient land area is available.

6. Conclusion

This study demonstrates that Horizontal Plastic Geo-Exchange Pipes (PGEPs) installed using HDD offer a compelling alternative to traditional deep vertical boreholes for small- to medium-scale GSHP applications. Through validated numerical modeling and full-year energy simulations, the horizontal PGEP exhibited a higher maximum capacity (1.5 tons) and comparable annual COP to the vertical system while requiring only shallow drilling. The larger thermal contact area, laminar-flow-driven heat transfer, and beneficial seasonal heat recharge at a 6.1 m burial depth significantly enhance the PGEP's heating performance relative to an 80 m borehole. System-level analyses illustrate clear economic and practical advantages: HDD installation is less expensive, and widely accessible through existing utility-installation practices, while vertical drilling constitutes nearly half of GSHP capital costs. Although the horizontal PGEP requires more land area, it avoids the need for multiple costly deep wells and supports modular expansion. For buildings with adequate site availability, PGEPs deliver higher capacity per meter of exchanger and reduced installation cost, positioning the technology as a strong, scalable solution for broad GSHP deployment.

Future work should further investigate the long-term thermal behavior of PGEP systems, particularly by monitoring multi-season operation to better understand the influence of seasonal ground-heat recharge on system performance. Additional studies should also explore the impact of flow-rate optimization, building on the promising results observed at 11 l/min, and evaluate whether variable-speed pumping can provide further efficiency gains. Finally, larger-scale simulations and field installations are needed to assess modular PGEP arrays, where multiple units operate in parallel to meet higher building loads. Such work will help establish practical design guidelines for array spacing, hydraulic balancing, and thermal interactions, supporting broader adoption of PGEPs as a cost-effective alternative to vertical boreholes.

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Nomenclature

T	=	Temperature
QGHE	=	Building Load
ρ	=	Density of Working Fluid
Cp	=	Specific Heat Capacity of Working Fluid
(T)	=	Function of Temperature
Qin	=	Flowrate at Inlet
COP	=	Coefficient of Performance
A	=	Heating Mode (ON/OFF)
B	=	Cooling Mode (ON/OFF)
(t)	=	Function of Time
z	=	Depth (m)
Ts	=	Soil Temperature
Tmean	=	Annual Average Temperature
Tamp	=	Amplitude Temperature of the Annual Temperature
w	=	Angular Frequency of Annual Temperature Variations
tc	=	Coldest Day of the Year
a	=	Thermal Diffusivity of Soil

Nu	=	Nusselt Number
Re	=	Reynolds Number
Pr	=	Prandtl Number
n	=	Constant for Heating or Cooling
α	=	Soil Thermal Diffusivity
HA, HB, HC	=	Heating COP Coefficients
CA, CB, CC	=	Cooling COP Coefficients

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