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The Characterization of Helical Steel Pile Performance Under Varying Soil Conditions

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ABSTRACT

Ground-Source Heat Pumps (GSHPs) are a clean alternative to traditional space heating and cooling technologies. GSHPs take advantage of relatively constant ground temperatures as a medium for heat exchange, in contrast to the use of highly variable air temperatures. Conventional systems use a heat pump paired with a borehole heat exchanger to exchange heat with the ground. Widespread use of these systems has been impeded by high initial costs and low short-term return on investment. Helical steel piles (HSP) are structural elements that are drilled into the soil to provide support to buildings. With only minor modifications, these structures have shown promise as a viable alternative to the use of the conventional borehole heat exchanger. At present, there is little understanding of the functionality and the optimal design of HSPs as heat exchangers under different soil properties such as heterogeneity, porosity and saturation content. Therefore, the focus of this paper is to investigate the performance of HSPs under different heterogeneous soil conditions using numerical analysis. This paper presents the results of a numerical study of HSP performance under varying moisture contents.

INTRODUCTION

With calls to reduce greenhouse gas emissions across the globe, there is a significant need for innovative solutions to produce reliable energy with a reduced environmental impact. In Canada, space heating accounts for approximately 80% of energy consumption residentially and 63% of energy consumption globally [1]. Most sustainable energy options are either unreliable in terms of energy production, too expensive or negatively impactful on other components of the environment.

Geothermal energy is considered a viable option for meeting the heating and cooling demands in many climates (including Canada, where this research is being conducted), as opposed to the standard heating and cooling technologies that rely heavily on fossil fuels. This energy source uses a ground source heat pump (GSHP) to supply heating/cooling to buildings. GSHPs work in conjunction with a heat exchanger which carries a working fluid to be the agent for heat exchange in the subsurface. Conventional heat exchangers use a horizontally oriented system or a vertically oriented system. Horizontal ground heat exchangers are buried at shallow depths (~2-3 meters) beneath the surface leaving the system more susceptible to changing soil temperatures. In contrast, vertical heat exchangers use borehole loops with polyethylene (PEX plastic) piping that is drilled to depths of up to 250 m beneath the surface, making use of much more constant soil temperatures [1]. However, as a result of the extensive drilling, geothermal energy has very high installation costs which along with the system's low initial return on investment and long payback periods, has hindered its ability to be implemented widely.

Helical Steel Piles (HSPs), typically between 6 meters and 20 meters in length, are structural elements that are drilled into the ground for the support of buildings. In addition to their structural benefits, HSPs have shown promise as an innovative alternative to the conventional borehole heat exchanger (BHE). However, HSPs require a simpler installation procedure (using threaded or welded connections), and in many cases could further reduce overall costs by serving a dual purpose of structural support and exchanging usable heat to be used for building climate control. HSPs utilize a helix welded to the bottom of the pile which allows the HSP to be screwed into the soil without the need for

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a pre-drilled borehole [2]. The thermal properties of the HSP, soil and working fluid allow for reliable heat transfer throughout the year. During the cooling season (spring/summer months), the warm fluid exchanges heat with the soil to return cooler fluid for the cooling of the building. In the warming season (fall/winter months), the cool fluid extracts heat from the soil to return to the warmer fluid for the heating of buildings. While the shorter nature of HSPs relative to conventional ground heat exchange options is a part of the benefits of the design, this leaves the system more susceptible to the conditions of the soil surface and thus soil properties may play an important role in their performance. The use of steel piles as a heat exchanger has been featured in numerous studies such as those conducted by Jalaluddin et al. [3] and Lyu et al. [8] which focus on evaluating the performance of pile heat exchangers with a variation of pile designs. As a result of impactful research, many pile systems have also been installed across the globe in the past decade. While pile heat exchange as a whole is not a new concept, the structural configuration suggested by Nicholson et al. [1] is unique. The proposed pile design uses tubular steel piles fit with PEX plastic piping for fluid flow into the pile. The fluid can then circulate through the volume of the steel pile casing to exchange heat with the surrounding soil. This design also implores a laminar flow regime rather than turbulent flow, the commonly used flow regime in ground heat exchange systems.

Past computational work has focused on optimizing the performance of the piles for the application in a real-world system. A model of a single HSP was created by Nicholson et al. [1] and validated using experimental data of a heat exchange system from Jalaluddin, et al. [3] and Jalaluddin, et al. [4], that closely represented the proposed HSPs. This model was also used to optimize the performance of the HSP based on its geometry (length and overall geometry). While the implications of various thermal properties on heat transfer are generally well defined, understanding the extent to which these properties impact heat exchange using a helical steel pile is critical in understanding the system's overall performance. To better understand the functionality of HSPs as heat exchangers, a numerical analysis was conducted to further evaluate the HSP's energy performance under varying soil conditions. The main objective of this paper is to validate the thermodynamics and heat exchange behaviour of an HSP by comparing the numerical predictions of the previously built CFD model with experimental data, as well as to further evaluate the HSP's energy performance under varying soil conditions using the validated model.

METHODOLOGY

Model development

To investigate the performance of the helical piles as heat exchangers in different soil conditions, a combination of numerical modelling and experimental testing was needed. In this study, a numerical modelling approach was followed. The original numerical model was developed using the COMSOL Multiphysics ® software [7] and solved the governing equations using coupled (laminar flow) fluid dynamics and heat transfer.

Model Validation

The present research seeks to build on the results of an ongoing experimental/modelling research campaign being conducted by the co-authors. Previous modelling and optimization work focused on the initial design and characterization of the heat transfer performance of a novel helical steel pile as an in-ground heat exchanger [1].

An experimental site with eight piles has been installed at the Eby Rush Transformer Station in Waterloo, Canada. The pilot project focused on the design, installation, and commissioning of an eight-geo-pile GSHP test site. The Eby Rush experiments have yielded operational data from the summer cooling season (August 2021) to the fall/winter heating season (November 2021), which were analyzed and used for model validation in the present work. More details of the experimental setup can be found in [2].

The numerical models were developed using the COMSOL Multiphysics ® software [7] and solved for the governing equations using coupled (laminar flow) fluid dynamics and heat transfer. The HSP modelled in this work has a length of 20 m with an outer diameter of 13.97 cm (5.5 inches). The numerical outlet temperature results were compared with the experimentally measured results given the same inlet water temperature and flow rate values obtained from the tests conducted at the Eby Rush site. A diagram of the HSP can be seen in Figure 1.

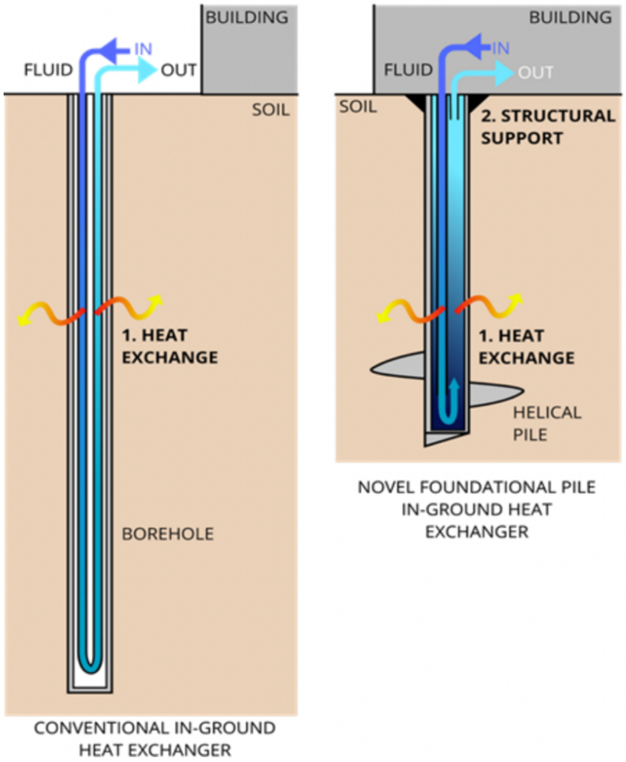

Figure 1: Comparison between a conventional u-tube in-ground heat exchanger (left) and the novel pile design (right) proposed by Nicholson et al. [1]

The far-field ground temperature in the model was kept constant at 12°C throughout the depth of the soil column during both the heating and cooling seasons to reduce simulation costs (time constraints). This was due to a lack of soil temperature data for the location, varying with time and depth. The physical and thermal material properties of the HSP and interior piping can be further found in [2]. The fluid (water) and solid material properties of the pipe are calculated as functions of temperature.

The boundary and initial conditions applied for heat transfer and laminar flow used in this work are:

- Both the pile and soil domain are initially at rest, maintaining an initial temperature of 12°C
- The inlet flow is defined by a time-dependent boundary temperature with a 1-minute time step, which varies across the test period.
- A constant flow rate of 2.6 L/min was applied as a normal inflow at the inlet pipe boundary. The value was kept constant for all the tests based on the experimental data.
- The outlet pipe boundary is defined as an outflow/outlet.
- No heat flux was applied at the topsoil surface boundary (adiabatic).
- The far-field soil was kept at a constant temperature of 12°C.

Model Modification

The original single pile model was modified to consider different soil properties within the physics of heat transfer. The focus of this study is to assess the performance of an HSP as a heat exchanger under different moisture contents. To complete this analysis, data retrieved from the literature [5] was used to alter the thermophysical properties of the soil (soil thermal conductivity, porosity, particle density and texture). One location (Ontario, Canada) was chosen from the dataset for two unique soil types (sandy soil and loamy soil).
The particle densities from the respective Ontario soils were used to calculate the dry bulk densities of the soil using formula 1.

$$\rho_b = (1-\eta) * \rho_s \tag{1}$$

Where ρ_s is the particle density of the soil, ρ_b is the bulk density of the soil and η is the soil porosity of the soil.

Soil heat capacity (C_p) was also taken from the literature [6]. Due to a lack of relevant soil data, the heat capacities of both sandy and loamy soils were considered to be between 830-1483 J/kg*K and 1140-2090 J/kg*K respectively, ranging from low to high moisture content in the soil. This was done as generally; soil heat capacity and soil moisture content are positively correlated. In a second simulation, soil heterogeneity was also created manually by adhering to general soil principles with depth, specifically ensuring that high porosity soils remained closer to the surface. This was done to simulate what is often seen in soils with multiple layers as soils deeper beneath the surface often have lower porosities due to soil compaction. Soil compaction is also related to higher bulk density and this concept was adhered to while creating heterogeneity in the soil. The soil data used in each of the simulations (thermal conductivity and heat capacity) can be found in Table 1.

TABLE 1

Soil Type/ Soil ID	λ_{dry}	$\lambda_{0.25}$	$\lambda_{0.50}$	$\lambda_{0.75}$	λ_{sat}	Cp_{dry}	$Cp_{0.25}$	$Cp_{0.50}$	$Cp_{0.75}$	Cp_{sat}
ON-04, Sandy Soil	0.261	1.12	1.438	1.49	1.67	830	997	1165	1324	1483
ON-03, Loamy Soil	0.21	0.983	1.15	1.35	1.52	1140	1377	1615	1852	2090

λ = Soil Thermal Conductivity in W/m*K

Cp = Soil Heat Capacity in J/kg*K

Model Mesh and Solver

A finite element mesh was used to simulate heat transfer using the single HSP. The mesh included the fluid within the pile, the pile walls as well as the surrounding soil. A free tetrahedral shape mesh was used across the larger surfaces in the model with the entire model domain containing 280,029 total mesh elements (Figure 2).

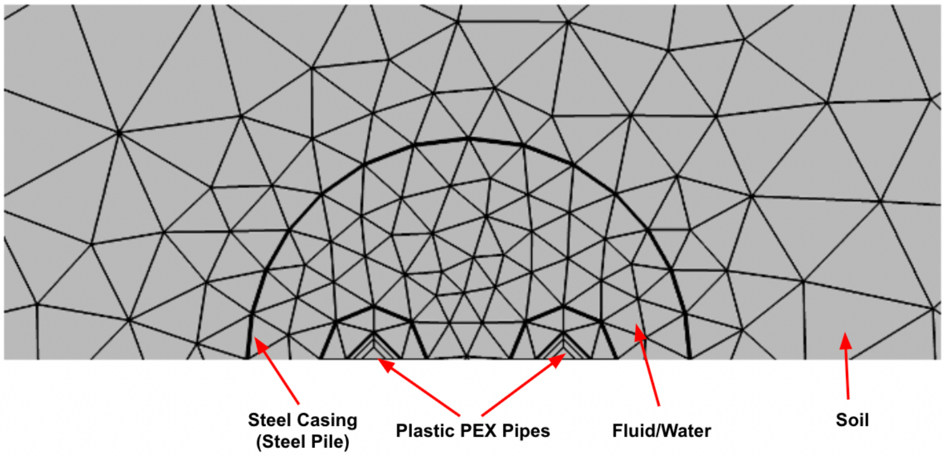

Figure 2: Single helical steel pile COMSOL model mesh components

Calculating Heat Exchange

Based on the results of the simulations for both soil types, the magnitude of heat exchange at each time interval was calculated using formula 2.

$$HE = Q * \rho * Cp * (Tin\text{-}Tout) \tag{2}$$

Where HE is the heat exchange across a single HSP, Tin is the inlet water temperature to the HSP, Tout is the outlet temperature coming out of the HSP, Q is the flow rate of the water into the pile, ρ is the density of water and Cp is the specific heat capacity of water. The heat exchange values for each testing date, soil type, and saturation level were averaged and used for an analysis of the system's performance under varying soil moisture contents.

RESULTS AND DISCUSSION

It is well understood that heat transfer as a whole is susceptible to the changing thermal properties within soil throughout seasons and across climate regions. An experimental study done by Hu et al. [9] investigated the importance of soil moisture content and soil thermal conductivity as they relate to heat exchange. The results of this study showed the critical nature of these soil properties for both a geothermal system's performance as well as the recovery of the soil following intermittent use. It is unclear however the extent to which soil thermal properties such as thermal conductivity and heat capacity would impact a helical steel pile's ability for heat exchange. The main objective of this study is to characterize the soil's impact and generate information that is needed in the consideration of the industrial implementation of HSPs.

The modified CFD model was used in this study to evaluate the impact of soil thermal properties on its performance based on simulated heat exchange values. The CFD model was validated and compared to experimental data. To validate the model, it was assumed that the soil temperature remained at an undisturbed 12 °C during each test and that the soil volume is considered a non-porous, homogeneous solid medium. Following model validation, data from each of the Ontario soil simulations were post-processed and used to calculate the average heat exchange between the soil and the piles for each soil type in both heating and cooling seasons. The following sections outline the result of each simulation.

A. Model Validation Results

Model validation results were analyzed using absolute error which is defined as the difference between the observed value and the true value. The model validation used inlet temperature data collected from tests done at the pilot project site. Figure 3 shows the results of two different days in summer, requiring the pile to return cooler water temperatures to the outlet of the pipe that would be used for the cooling of the building. The results of the August 22nd and August 24th cooling validation simulations yielded an absolute error of 1.22 K and 1.26 K respectively. This level of error could be reduced by using data closer to the soil properties of the test site. The results of both the simulations and the experimental tests resulted in a difference in temperature (ΔT) of 10°C between the inlet and the outlet of the pile. The large difference in temperature can be attributed to both the structural design of the steel piles as well as the flow regime used for fluid flow (Figure 1). The laminar flow regime allows the water to have a longer residence time as it circulates throughout the interior volume of the steel pile. In effect, greater heat exchange can take place.

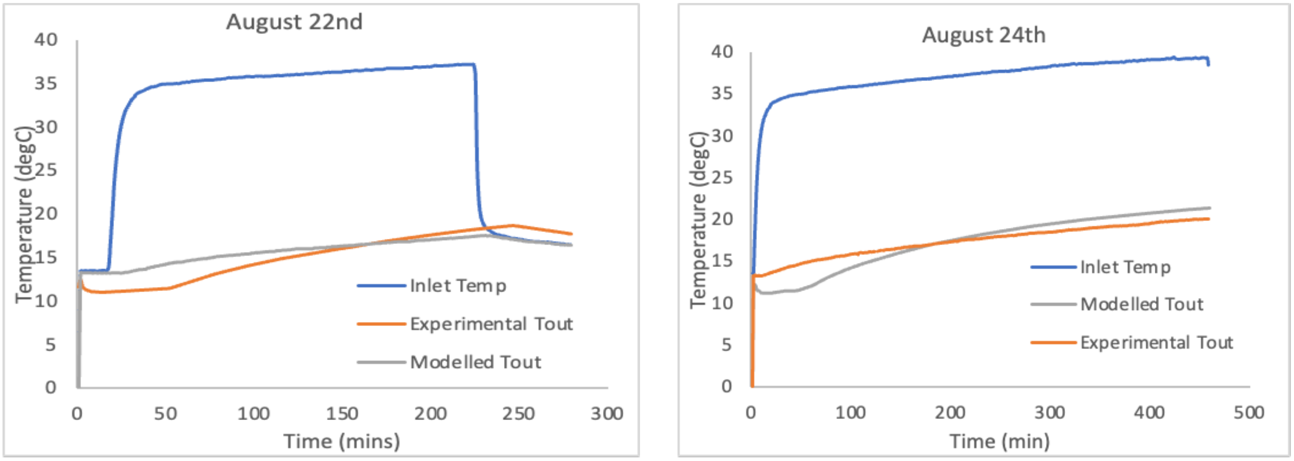

Figure 3: Model validation results for August 22nd and August 24th (cooling season)

Figure 4 shows the results of a cooling test taking place late in the cooling season (early autumn). The experimental outlet temperatures and the modelled outlet temperatures both remained relatively constant throughout the entirety of the test, likely due to the low-temperature difference between soil and air at this point in the season. The October 4th and October 6th simulations yielded an absolute error of 0.49 K and 0.85 K respectively.

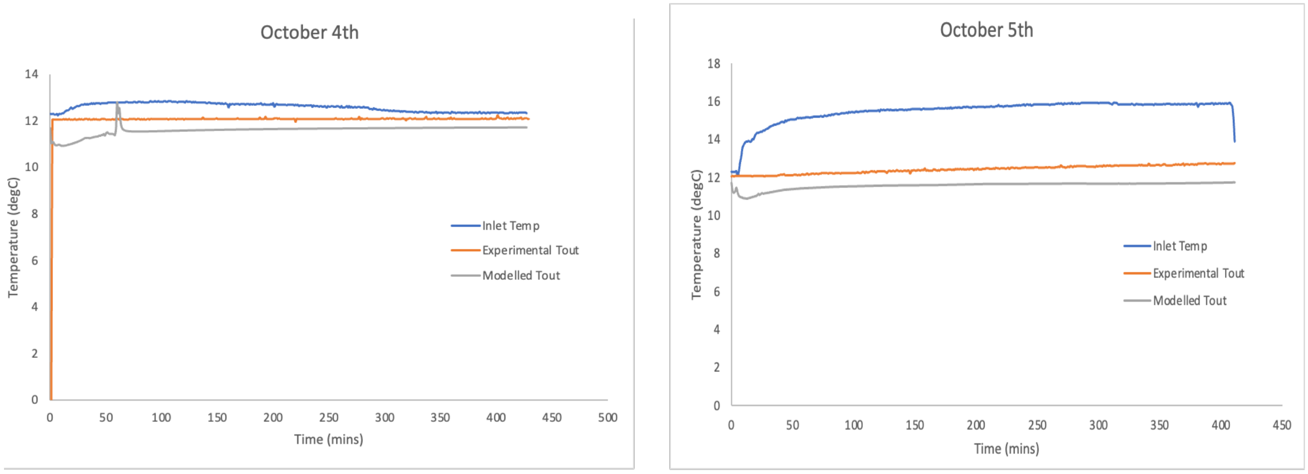

Figure 4: Model validation results for October 4th and October 5th (heating season)

Finally, Figure 5 shows the results of two heating simulations using inlet temperatures from November. The simulations for November 23rd and 24th yielded much higher absolute and relative error, 1.96 K and 2.39 K respectively. This result was expected due to the assumption that the soil temperature would remain at a constant 12 °C. This assumption is not realistic to the seasonal behaviour of the soil.
Reducing the soil temperature to between 6°C and 8 °C would potentially have yielded closer results to the experimental data.

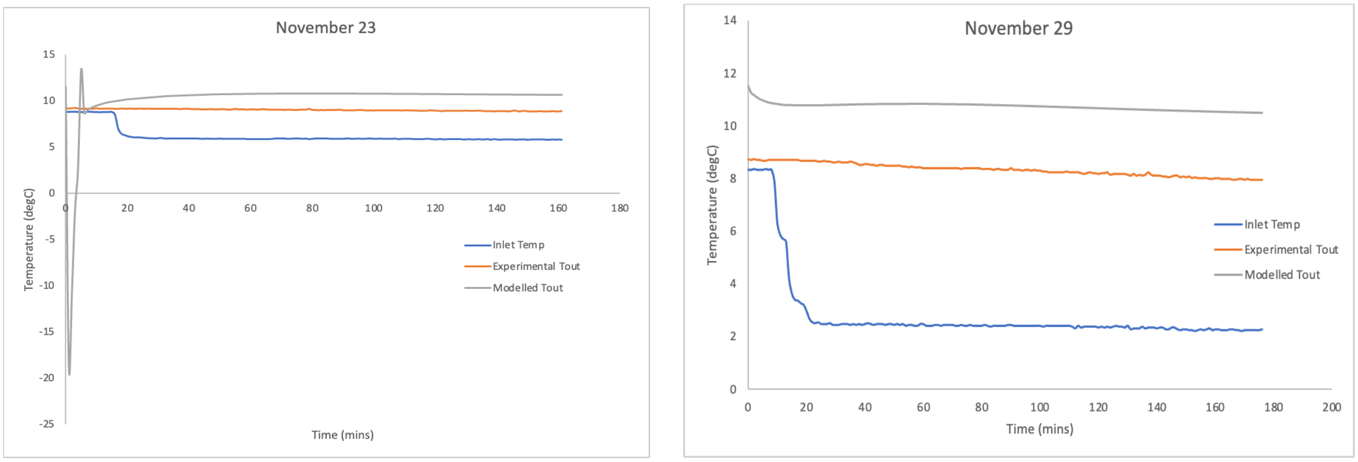

Figure 5: Model validation results for November 23rd and November 29th (cooling season)

B. Sandy Soil Simulations

Ontario soil data (ON-04) from literature [5] was used to simulate a homogeneous sandy soil under different soil saturation contents. Due to both software limitations and time constraints, it was assumed that the soil was solid, however, varying thermal properties were used to simulate the behaviour of soil and heat transfer under the chosen saturation conditions. Table 2 below shows the results of each simulation.

TABLE 2

Thermal Load	**HE$_{Dry}$**	**HE $_{0.25}$**	**HE$_{0.50}$**	**HE$_{0.75}$**	**HE$_{Sat}$**
Cooling	3094.15 W	3456.6 W	3581 W	3581 W	3641.2 W
Heating	791 W	793 W	793 W	793 W	795 W

The results of the cooling simulation for sandy soil showed that while there is a significant amount of heat exchange when the soil is dry, heat exchange increases with saturation content. The simulation for fully saturated soil amounted to 3641.2 W of average heat exchange by the single pile in, a nearly 600 W difference in heat exchange from the dry soil. This is likely due to the thermal properties of water which significantly improve the thermal capabilities of soil, showing the importance of soil moisture content to heat exchange, particularly under a cooling thermal load (Figure 6). These values can also be attributed to high inlet temperatures during the experimental tests (as high as 35°C). The presence of a heat exchanger between the HSPs and the heat pump at the pilot site in conjunction with the design of the HSPs allow for the observed inlet temperatures. Similar inlet temperatures were used to test energy piles using a different structural configuration by You et al. [10] which yielded comparable heat exchange results (inlet temperature of 35°C yielding a total heat exchange rate of 2100W), further confirming the heat exchange capacity of energy piles as a whole. However, inlet temperatures at such high values would not typically be seen in a fully operational system due to the system specifications of the heat pump and thus is a limitation of this study. Further simulations are needed to simulate the HSPs performance without the use of the heat exchanger however, this is beyond the scope of this study.

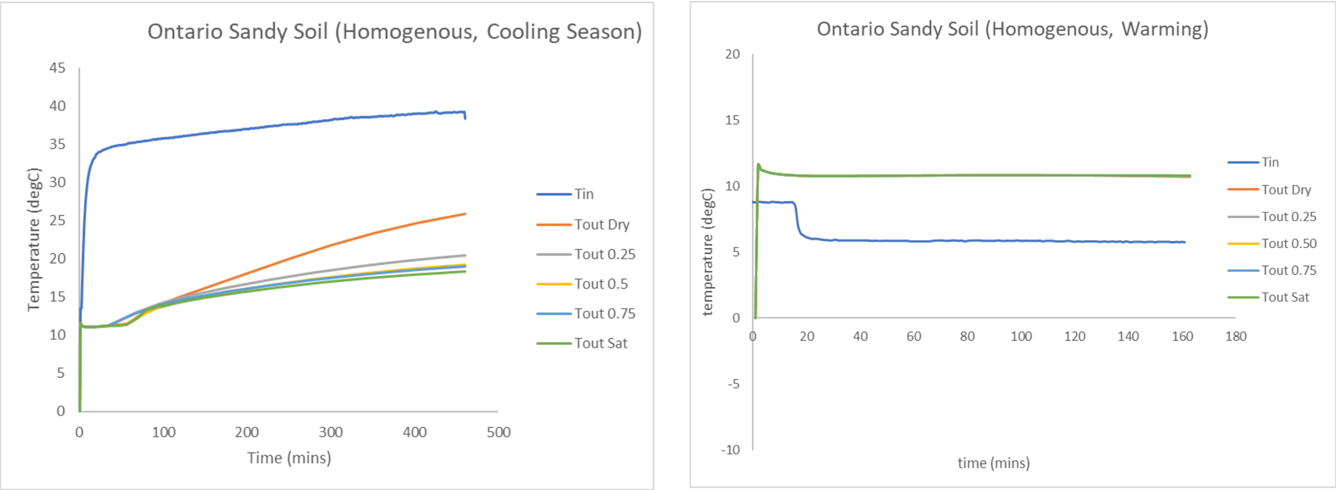

Figure 6: Homogeneous sandy soil model results using saturation levels from dry to fully saturated in increments of 0.25

The heating test for sandy soil presented significantly different results. Overall, the difference in heat exchange with varying water content can be considered negligible during the heating tests (November data). Simulations at each of the saturation levels during the heating season resulted in an average heat exchange of 794 W, a drastic difference from the cooling season results. It is possible that having inlet temperatures that are so close to the soil temperatures resulted in little variation in heat exchange. As seen in the validation data for November 23rd in figure 5, the ΔT of the experimental inlet and outlet temperatures is only 2.82°C. Greater average heat exchange may have been seen with the use of inlet temperature data from a colder time of the year (January or February). Another possibility for the general reduction in heat exchange is that the density of water is slightly greater at lower temperatures which impacts thermal conductivity. This may cause an innate reduction in heat exchange during the colder seasons for saturated soils.

C. Loamy Soil Simulations

Ontario soil data (ON-03) from literature [5] was used to simulate a homogeneous loamy soil under different soil saturation contents. The same assumptions made for the simulation of an HSP in sandy soil were made for the loamy soil simulation and thus it yielded similar results. Heat transfer between the soil and fluid domains was the greatest under fully saturated conditions during the cooling season, with an average heat exchange of 3668.5 W. For the heating season, the loamy soil also had relatively low heat exchange rates with an average of 793 W of heat exchanged at each saturation level. Table 3 shows the complete heat exchange results for each test.

TABLE 3

Thermal Load	**HE_{Dry}**	**$HE_{0.25}$**	**$HE_{0.50}$**	**$HE_{0.75}$**	**HE_{Sat}**
Cooling	3150W	3523.2W	3569.4W	3625.8W	3668.5W
Heating	793W	793W	793W	793W	793W

Overall, the results of the loamy soil simulations were very similar to that of the sandy soil. The cooling season yielded high heat exchange values whereas the heating simulations for each saturation content had negligible differences in the magnitude of heat exchange (Figure 7).

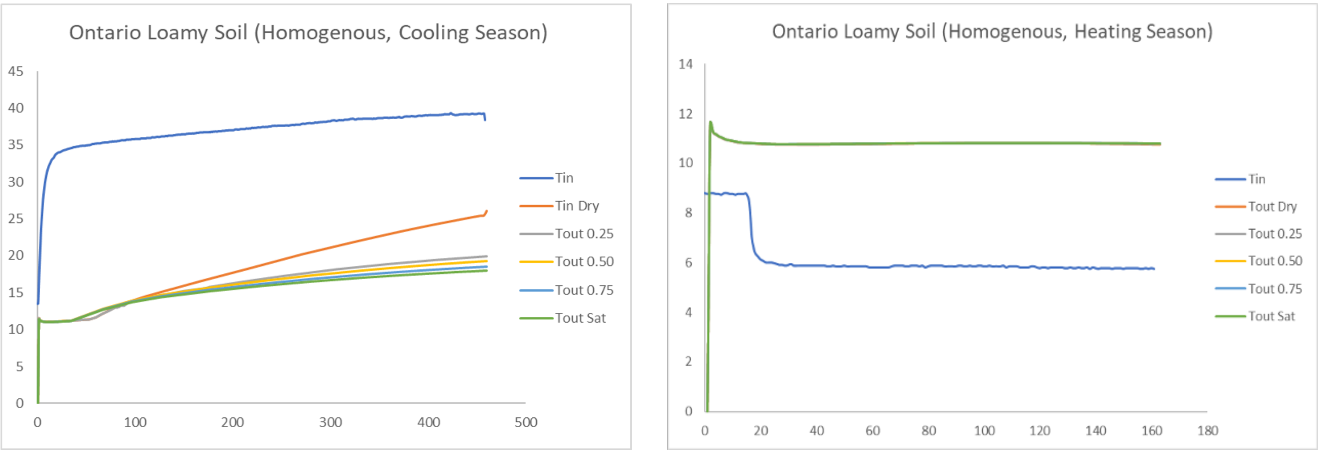

Figure 7: Homogeneous loamy soil model results using saturation levels from dry to fully saturated in increments of 0.25

D. Heterogeneous Soil Simulation

Soil data in Canada is sparse and incomplete which poses a barrier for soil-related research. As a result, a heterogeneous soil was created manually using three Ontario soil datasets (ON-04, ON-05 and ON-06) from the literature [5] and creating soil layers beneath the soil surface. As the soil layers were created manually, certain soil principles were followed to mimic what would more likely be seen in nature. The results of this simulation would not reproduce the exact heat exchange magnitude of an HSP in these conditions but rather speak to the general behaviour of the pile. Inlet temperatures from the cooling season were used in this test due to the negligible fluctuations in heat transfer seen in the homogenous tests during the heating season. As seen in Table 4 the difference in heat exchange between dry soil and the fully saturated soil was approximately 366 W, which is 121 W less than the heat exchange seen under homogeneous sandy soil conditions. This small difference is due to the weighted average of thermal conductivities used to create the heterogeneous soil. While the weighted average of the heterogeneous saturated thermal conductivity is the same as that of the homogenous sand, the dry thermal conductivity of the heterogeneous soil is slightly lower than the sandy soil under the same thermal load (figure 8). This would have caused a slight reduction in heat exchange under fully saturated soil conditions.

TABLE 4

Thermal Load	**HE_{Dry}**	**$HE_{0.25}$**	**$HE_{0.50}$**	**$HE_{0.75}$**	**HE_{Sat}**
Cooling	3254.8W	3502.7W	3547.2W	3588.2W	3620.7W

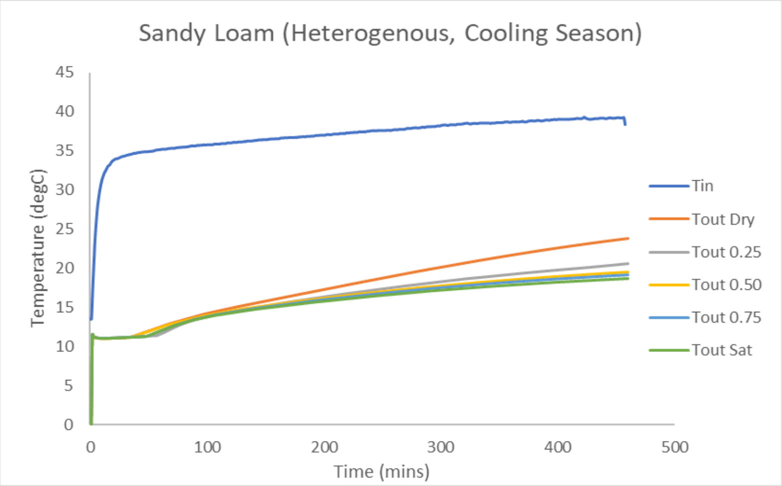

Figure 8: Simulation results for the heterogeneous soil (Sandy Loam) created under a cooling load

E. Limitations

As aforementioned, to reduce simulation times, the soil domain was considered a solid with varying soil physical and thermal properties based on the outlined simulation purposes. This assumption does not fully take into account the convective heating that takes place within the pores of the soils when filled with water. As such, this particular model could only allude to the HSP's general heat exchange behaviour and may not produce exact values. In addition, due to a lack of usable Canadian soil data, many assumptions were made regarding soil thermal properties, namely the specific ranges of heat capacity used for each soil type. Using these ranges assumes that heat capacity and water content have a directly linear relationship; this may not be necessarily the case depending on the other soil properties involved and the changes in soil thermal properties with temperature. In addition, the tests used in this study were short in duration and thus do not represent the steady state operation of the system. As such, longer tests are both necessary and planned as part of our future work.

SUMMARY AND CONCLUSIONS

Due to high costs, low initial return on investment and long payback periods, conventional geothermal systems have not seen widespread implantation across the globe. Helical steel piles have the potential to operate as a dual-purpose system, providing structural support to buildings while also acting as a heat exchanger for ground source heat pumps. This aspect of helical steel piles would reduce the associated costs of geothermal installations, addressing a key barrier. By modifying an existing COMSOL model of a single HSP that was validated with experimental data from a pilot project installed at our partner facility, the system's performance was simulated under varying soil conditions. The soil conditions were varied based on saturation content and heterogeneity using sand and loam soil data from two Ontario, Canada soils.

The results of the sandy soil model indicated that during the cooling season the greatest heat exchange can be seen under full soil saturation, yielding a change in temperature of 3641.2 W. During the heating tests for the same soil, however, heat exchange values were very small with an average of 793 W across all saturation types, likely due to the inlet temperatures being very close to the ground temperatures at the time that the inlet temperature data was taken (November). These trends were also seen in the simulation for the loamy soil. Under a cooling thermal load, the highest heat exchange was 3668.5 W under fully saturated conditions in the loamy soil. Under a heating load, the loam soil simulation also only predicted a temperature difference of 793 W. Heterogeneous soil was created using three Ontario, Canada soils and simulated under a cooling load for varying saturation contents. Overall, the results of the simulation were similar to both the sand and loam in terms of the HSP's heat exchange behaviour, however, the difference in heat exchange between dry heterogeneous soil and saturated heterogeneous soil was less than that of the homogenous soils. This was due to a lower weighted average of soil thermal conductivities under saturated conditions in the heterogeneous soil. Overall, soil moisture does play an important role as it pertains to ground heat exchange in the warmer months. However, the results of the heating season simulations did not indicate as strong of a dependence. To confirm this connection, it would be beneficial to improve the heating season simulations using data from colder months in the winter season. Future work will aim to focus on applying different physics to the COMSOL model to take into account the convective heat transfer within the pores of the soil as well as the impact of groundwater flow on heat transfer.

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REFERENCES

[1] Nicholson, S. R. (2021). Characterization of a novel in-ground heat exchanger for applications in sustainable building energy and maintaining permafrost. https://doi.org/10.32920/19852672.v1

[2] Nicholson, S.R., Mwesigye, A., Dworkin, S.B., 2019. Modelling and optimization of helical steel piles as in-ground heat exchangers for Ground-Source Heat Pumps. IOP Conf. Ser.: Mater. Sci. Eng. 609, 052026. https://doi.org/10.1088/1757-899X/609/5/052026

[3] Jalaluddin, A. Miyara, K. Tsubaki, S. Inoue, and K. Yoshida, "Experimental study of several types of ground heat exchanger using a steel pile foundation," Renewable Energy, vol. 36, no. 2, pp. 764–771, 2011.

[4] Jalaluddin, Jalaluddin & Miyara, Akio. (2012). Thermal performance investigation of several types of vertical ground heat exchangers with different operation mode. Applied Thermal Engineering. s 33–34. 167–174. 10.1016/j.applthermaleng.2011.09.030.

[5] Tarnawski, V. R., Momose, T., McCombie, M. L., & Leong, W. H. (2014). Canadian field soils III. thermal-conductivity data and modeling. *International Journal of Thermophysics*, *36*(1), 119– 156. https://doi.org/10.1007/s10765-014-1793-z

[6] Alnefaie, K. A., & Abu-Hamdeh, N. H. (2020). Specific heat and volumetric heat capacity of some Saudian soils as affected by moisture and density. *International Journal of Materials*, *7*. https://doi.org/10.46300/91018.2020.7.8

[7] COMSOL Multiphysics (R) v. 5.3 (Stockholm: COMSOL AB)

[8] Lyu, W., Pu, H., & Chen, J. (N. (2020). Thermal performance of an energy pile group with a deeply penetrating U-shaped heat exchanger. *Energies*, *13*(21), 5822. https://doi.org/10.3390/en13215822

[9] Hu, Z., Zhu, M., He, W., Meng, X., Yang, C., & Xu, Z. (2022). Experimental study and performance evaluation of a ground heat exchanger with different intermittent ratios and soil thermal properties. *Geothermics*, *102*, 102402. https://doi.org/10.1016/j.geothermics.2022.102402

[10] You, S., Cheng, X., Guo, H., & Yao, Z. (2014). In-situ experimental study of heat exchange capacity of CFG pile geothermal exchangers. *Energy and Buildings*, *79*, 23–31. https://doi.org/10.1016/j.enbuild.2014.04.021