Modelling and optimization of helical steel piles as in-ground heat exchangers for Ground-Source Heat Pumps

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Abstract. Ground source heat pumps are a sustainable way to provide building heating and cooling due to their efficient use of near-constant ground temperatures as mediums for heat exchange. Conventional in-ground heat exchangers are limited by the large size of required borehole field installations and the high economic costs, therefore the pairing of in-ground structural helical piles with these heat exchangers offers a system of geothermal heating and cooling which can be more accessible and lower cost than traditional equipment. In this research, a novel helical steel pile was modelled using a 3-D numerical model and finite element analysis. This model was first validated with experimental data from a double-tube pile, with 24-hr transient operation outlet temperatures accurate within 3%. Finally, the steady state heat exchange rate per unit area was calculated, with the new helical steel pile geometry yielding an increase of 8.6 W/m, 13.2 W/m, and 16.2 W/m (for 2 L/min, 4 L/min, and 8 L/min flowrates respectively) over the validation model.

1. Introduction
Heat pumps allow for a sustainable future by meeting heating and cooling loads efficiently due to their ability to provide up to three times more output energy than input energy required [1]. Furthermore, in climates with large variations in seasonal temperatures, Ground-Source Heat Pumps (GSHPs) offer more economical options than traditional equipment [1]. Geothermal heating and cooling systems take advantage of the nearly constant temperatures of deep soil to provide heating or cooling through a heat pump to various building types. This is considered a renewable energy system because – if designed well to avoid thermal imbalance – the in-ground heat exchangers are reversible, and the only energy demand is by the heat pump equipment [1]. Implementation benefits include the minimally intrusive nature of the borehole fields, and the fact that they are less visible than other renewable energy sources (such as solar or wind) [2]. However, installation of these efficient systems has been limited by the high capital costs of constructing the required borefields through which GSHPs transfer heat, and so they have been predominantly installed in large building applications [3]. Shorter boreholes can be a more sustainable, economically worthwhile, and accessible to a wider range of applications – however, their thermal performances are reduced [3].

Structural piles are existing components which anchor a building within its soil base. They have the potential to offer the benefits of a shallow borehole, while also providing two functions for one installation cost [3]. Studies have mainly focused on cement piles [3], however this report will investigate the potential implementation of helical steel piles as in-ground heat exchangers. These steel components employ a welded helix and a capped tip to drive their motion into the soil, and are fitted with plastic inner piping for fluid. A comparison of the proposed helical pile and conventional borehole heat exchangers is depicted in Figure 1.
With a helical steel pile in-ground heat exchanger, the hollow inside is flushed with circulating fluid to provide the same mechanisms of heat exchange with the soil that is offered in conventional vertical boreholes. However, these systems may improve upon conventional equipment by improving ease-of-installation, and reducing costs. Some existing literature on the use of geothermal energy pile foundations (GEPs) suggests that these systems can meet heating and cooling needs in an ideally renewable way [4].

2. Model Development

To investigate the performance of the helical piles as heat exchangers, a combination of numerical modelling and experimental testing and validation is needed. In this study, a numerical modelling approach was followed. The numerical models were developed using the COMSOL Multiphysics® software [5], and solved for the governing equations using coupled (laminar flow) fluid dynamics and heat transfer. This research aims to quantify the performance of a novel helical pile that has not yet been analyzed (Pile 2). Figure 2 is a comparison of a helical pile with a double-tube configuration (studied in [6]) with the novel helical pile. Since there does not yet exist experimental data on the helical pile in this study, a numerical model was created that duplicated an existing experiment to validate this study (Pile 1).

The piles are modelled with a single, simplified, solid soil domain with constant thermal properties. The pile connections and length above the ground level are not considered, and a constant soil temperature of 17.5°C is applied. The materials and geometry of Pile 2 are described in Table 1, and the parameters of Pile 1 (which uses a steel pile and polyvinyl chloride outlet pipe with larger diameters than Pile 2) are detailed in [6].

| Table 1. Helical pile (Pile 2) material and dimensions. |
|--------------------------------------------------------|
| Pile casing | Inlet and outlet pipes |
| Material | AISI 4340 Steel | PEX Plastic |
| Outer diameter, \(d_o\) (m) | 0.114 | 0.032 |
| Inner diameter, \(d_i\) (m) | 0.100 | 0.024 |
The helical steel pile has a length of 20 m, while the plastic inlet pipe fits to within 1.52 m (5 ft) of the bottom of the pile. The helix has an outer radius of 0.179 m (7 in), and begins 0.051 m (2 in) from the bottom of the pile. The helixes are welded to the outer pipe at regular 6.10 m (20 ft) installations along the length. Though initially investigated, the helix and the cap tips were removed (in Pile 1 and 2) to simplify the geometry and make the large models less computational expensive — their impacts will be explored in further research. The thermal material properties for this pile are presented in Table 2. The fluid (water) material properties are calculated as functions of temperature along the pile.

The boundary conditions applied for heat transfer and laminar flow (used in both models) are:
- The entire domain is initially at rest, with the same temperature as the ground.
- The inlet flow is defined by a time-dependent boundary temperature, which varies across the 24-hour study period as per experimental data [6], and is applied as a normal inflow velocity at this same boundary.
- The corresponding fluid boundary is defined as an outflow/outlet.
- The external environment is modelled by a heat flux with a low heat transfer coefficient of 2.5 W/m²•K, at the soil temperature for the submerged edges, and the given experimental ambient temperature at the surface. This aims to mimic the heat transfer between the exterior of the domain and the far field conditions.

The model is meshed with 144,574 mesh vertices, which are arranged to best capture the boundary behaviours at the pipe walls (that have a no slip condition) and the critical flow points.

3. Model Validation
The numerical model was validated using experimental data for a double-tube helical pile in Jalaluddin et al. [6], which was tested in Japan. Using the given outlet and inlet water temperature results, material properties, average ambient temperature and geometry, the experimental pile was recreated using the finite element method in COMSOL Multiphysics® [5]. From here, the heat transfer and fluid dynamics conditions were validated using the method described in Figure 3.
Figure 3. Methodology for validating the model. 1. Initial conditions, boundary conditions, and material properties are specified in the software, 2. A 3-D numerical model is constructed, 3. Transient temperature data is computed from the model, 4. The data is compared to experimental values, 5. Validation is achieved when the model matches the experimental data within appropriate error, otherwise the steps are repeated at 1, 6. The new pile geometry, and materials are specified, 7. A new model is constructed using the validated conditions of 1, 8. Results of the new pile are computed.

The model’s outlet temperature results were compared with the experimentally measured results given the same inlet water temperature and flow criteria. This process was repeated for entry flow rates of 2 L/min, 4 L/min and 8 L/min. The results in Figure 4 are presented for the 2 L/min flow.

Figure 4. Validation of the developed numerical model, and performance of the new helical pile model at 2L/min flowrate.

The validation model generated transient results that are within 3% experimental error bars across 24-hours of operation, this validation is achieved even though the numerical model does not account for the above ground pile section present in the experimental data’s setup. Using the same soil, inlet temperatures, and boundary conditions, Pile 2 was generated and tested for the purpose of a performance comparison. As the figure indicates, Pile 2 performs better than the experimental pile, as it achieves a lower outlet water temperature across time – meaning a greater change in working fluid temperature is achievable through this heat exchanger.

4. Heat Exchange Performance Comparisons
Pile 2 displayed similar temperature distribution profiles to the validation model, and other in-ground heat exchangers – wherein the pile transferred heat via conduction and convection from the incoming water in a gradient through the soil. Figure 5 graphically represents this phenomena for the steady state results within Pile 2 at a 4 L/min flowrate.
Figure 5. Temperature distribution for 4 L/min flow (a) within the entire domain and (b) along the x-axis at 10m depth below the surface.

A comparison of the heat exchange rate for these in-ground heat exchangers can give important insights into the viability of this technology and the potential improvements this novel system can offer. Therefore, the heat exchange \( Q \) through the pile was calculated with Equation 1.

\[
Q = \dot{m} C_p \Delta T
\]  

(1)

Where \( \dot{m} \) is the mass flow rate, the specific heat capacity of water is \( C_p \), and \( \Delta T \) is the change in fluid temperature from the inlet to the outlet. This exchange rate is further modified to calculate the heat exchange per unit length \( \bar{Q} \) shown in Equation 2.

\[
\bar{Q} = Q / L
\]  

(2)

In which \( L \) is the total length of the pile in the ground. From the steady state analysis on the three flow rates, the heat exchange per unit length of Pile 1 and Pile 2 are compared in Figure 6.

Figure 6. Heat exchange rate per unit length steady state comparison at three flow rates.

Here, the new helical pile had a higher heat exchange rate per unit length than the validation model did by 8.6 W/m, 13.2 W/m, and 16.2 W/m (for 2 L/min, 4 L/min, and 8 L/min flowrates respectively). With the smaller diameter inlet pipe, the surface area of the flow is reduced, and the velocity of the fluid is increased. As this velocity increases, the heat exchange by convection will also increase, thereby increasing the rate. This condition is reflected in the numerical model results via the outlet velocity differences between the two piles supplied with the same flow rates – wherein the outlet
diameter of the new pile was 40% smaller than Pile 1, and the outlet velocity magnitude was 123% larger for the 2 L/min flow. This result indicates that there is potential to improve the performance of GEPs by implementing pile designs which funnel flow to a higher velocity through small inlet and outlet diameters. In this study, the change yielded a lower outlet flow temperature for Pile 2 under the same soil and boundary conditions as the validation model (also shown in the transient results presented in Figure 4).

5. Conclusion
This study analysed the performance of a new helical steel pile design as an in-ground heat exchanger. The model was validated using experimental data of a double-tube pile, and then a comparison was made between the heat exchange capabilities of these two models under the same operating (and environmental) conditions. The proposed helical steel pile had greater heat exchange per unit length than the comparison model, and this improvement increased as the flow rate increased. The difference is attributed to higher velocities achieved throughout the pile via the geometry of the inlet and outlet pipes. Therefore, this novel component has the potential to increase the operating efficiency of helical steel piles in GSHP systems, while maintaining the sustainability, and economic benefits of these dual purpose, shallower pile heat exchangers. Further investigations will aim to quantify these potential economic, and efficiency improvements modelled in various settings and environmental conditions for heating and cooling, and parametric studies of the diameters of the pipes in the model will investigate an optimal ratio between heat exchange surface area, and higher fluid velocity for various pile applications.

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