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Modelling Thermal Performance of Helical Steel Piles

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Abstract—Helical steel piles (HSPs) are a specialized type of energy pile designed to efficiently integrate geothermal energy into building foundations. Traditionally used as structural supports, HSPs can also function as heat exchangers, reducing installation costs and complexity compared to conventional geothermal systems that require extensive borehole drilling. This study employs the finite line source (FLS) analytical model to evaluate the thermal performance of HSPs, validating its accuracy against numerical simulation models. Numerical simulations are then used to analyze the short-term behaviour of HSPs, while the FLS model assesses long-term performance. By simulating the thermal behaviour of HSPs on an hourly basis over multiple years and iterating across various pile heights, this study determines the optimal sizing of HSPs to effectively accommodate a synthetic balanced heat load while maintaining temperatures within the operational limits of heat pumps. The results confirm that the FLS model is both accurate and efficient, capable of simulating long-term performance more quickly than detailed simulation. By integrating short-term numerical simulations with the long-term results from the FLS model, the study demonstrates that HSP thermal performance can be accurately modeled across the entire time spectrum with high precision and significantly reduced computational effort. These results can also be used for sizing the HSPs to handle every arbitrary balanced or unbalanced heat load.

Keywords - energy pile; helical steel pile; borehole; finite line source; numerical model; simulation

I. Introduction

Boreholes are one of the most common types of ground source heat exchangers, favored for their efficient performance, minimal land use, and relative independence from external temperature fluctuations. However, the high initial costs and logistical challenges associated with borehole drilling limit their widespread adoption and application [1]. In this regard, helical steel piles (HSPs), a specific type of energy pile, present a promising alternative to boreholes [2]. HSPs are installed at shallow depths, ranging from 10 to 25 m, and are screwed into the ground, unlike boreholes that need to be drilled, thus they have a much lower installation time [3]. By leveraging the structural loading capabilities of steel piles already required for building foundations, HSPs reduce both the financial and environmental costs, as well as the required land space associated with boreholes. Ground Source Heat Pumps (GSHPs) utilizing HSPs also have the potential to achieve higher coefficients of performance (COPs) than conventional systems [4], making them a better alternative, especially in urban settings where space for extensive drilling operations is limited.

Figs. 1.a and 1.b schematically compare the structures of a typical borehole and an HSP, respectively. As shown, a typical borehole is constructed with a U-shaped pipe inserted into thermal grout to ensure efficient heat transfer from the pipe to the ground. In contrast, a typical HSP features a cylindrical steel shell with an offset inlet pipe that allows fluid to flow down to its bottom and then ascend to exit through a short outlet pipe at the top. HSPs also have helical screws on their base near the end tip, which help them to be screwed into sandy or similar softer soils. However, they are unsuitable for rocky or hard soil areas that require drilling. Fig. 1c shows a simplified geometry for the HSP which was adopted in this study and explained in further detail in Methodology.

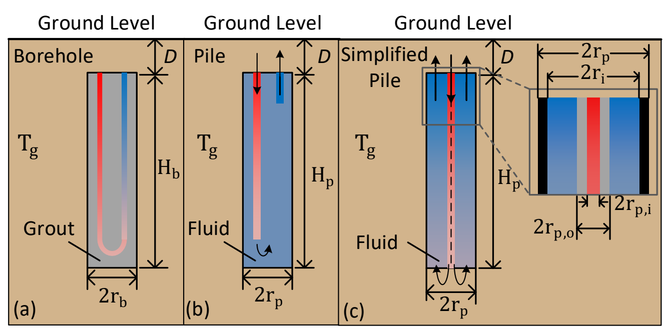

Figure 1. Schematic Diagram of a typical (a) borehole, (b) pile, (c) simplified pile

For accurate design and sizing of HSPs, it is essential to use numerical or analytical models that precisely simulate their thermal behaviour. These models must consider the geometry, size, spacing, and thermal properties of the various components of HSPs, as well as the surrounding ground, to effectively model the performance of HSPs in response to transient ground heat loads. The design of HSPs significantly differs from that of conventional boreholes, making their thermal behaviour simulation considerably more complex. In conventional boreholes, the cross-sectional area of the U-pipe remains uniform along the borehole's length, simplifying heat transfer modelling. Additionally, boreholes have been extensively studied and tested over time, leading to well-established modelling approaches. In contrast, HSPs are a relatively new technology, and their complex geometry, including a varying cross-sectional area where the inlet pipe is significantly smaller than the return channel, presents additional challenges. Furthermore, while boreholes typically involve modelling a single U-pipe, HSPs require simulating a pipe within a pipe, further increasing the complexity of accurately capturing heat transfer and fluid flow interactions within the system.

Methods for determining the thermal performance of an GSHP system can be conducted using numerical models through commercial tools like COMSOL Multiphysics or Fluent [5], [6]. These numerical methods provide detailed insight into heat transfer and fluid flow behaviour within HSPs, making them valuable for design and optimization. However, a significant drawback of numerical simulations is their high computational demand.

There are three main factors contributing to the high computational cost of simulating HSPs using numerical methods. First, their long and slender geometry requires high mesh density to capture detailed thermal and flow characteristics, significantly increasing computational time. Second, modelling long-term performance over the system's decades-long lifespan necessitates extensive simulations, further adding to computational complexity. Third, most HSP systems consist of multiple piles in parallel-series configurations, requiring consideration of thermal interactions, which makes full-scale numerical simulations impractical for real-world applications.

Since HSP systems are a relatively new technology, there is great opportunity for design and improvement. However, to perform these analyses, it is crucial to have a modelling approach that is both quick and accurate, allowing for efficient analysis of different design parameters and operational strategies. In the following section, the literature on HSPs is briefly reviewed to highlight how their performance has been evaluated, and then the discussion will focus on which models could potentially be used to simulate their performance more efficiently.

II. Literature Review

Nicholson et al. [5] investigated the performance of HSPs in multilayered soils by using a validated numerical model to examine the impact of pile geometry and laminar flow rates on thermal performance. Their findings showed that optimizing pile size and flow rates could enhance heat exchange rates by up to 58.6 W/m, reducing the required number of piles and lowering installation and operational costs. Attard et al. [6] conducted field tests on eight HSPs at a demonstration site in Waterloo, Ontario, demonstrating high energy efficiencies, with cooling COP values ranging from 2.13 to 4.5 and a heating COP of around 3.35. Henry-Mathieu et al. [7] further analyzed the effects of soil heterogeneity on HSP performance, confirming that higher soil moisture levels significantly enhanced thermal efficiency, particularly during cooling seasons.

Subsequent studies explored innovative applications of HSPs. Jathunge et al. [8] integrated solar thermal energy with HSPs to mitigate ground thermal imbalance in cold climates. Their numerical simulations indicated a 16.3% performance improvement in the coldest zones compared to non-solar systems, with COPs ranging from 3.72 to 4.24. Later, Jathunge et al. [9] examined the long-term performance of HSPs with unbalanced heat loads, modelling different installation configurations (e.g., under basements or buried underground). Their results showed that an unbalanced load can have significant effects; for example, in the cases examined, the ground temperature declined by −0.18 to −0.41 K/year, depending on the load. The results also indicated that installing piles beneath basements can improve COP and system stability. More recently, Jathunge et al. [10] combined HSPs with photovoltaic/thermal (PVT) collectors, achieving 6.7-19.7% improvements in heat pump performance and generating a net energy surplus with 3.5 m² of solar collectors per pile.

Despite these advancements, several gaps remain in the existing studies, highlighting the need for improved modelling approaches. A key limitation in previous studies is the restricted time range of transient simulations, which typically did not capture long-term system performance due to the substantial computational demands associated with extended simulation periods. The computational demands also make it impractical to model a larger-scale system of interconnected piles. This limitation is particularly significant for optimization, as the high computational cost renders iterative design exploration infeasible. Additionally, most studies assume laminar fluid flow within HSPs, as simulating turbulence requires significantly greater computational intensity, and therefore do not thoroughly analyze its potential impact or compare which flow regime performs better. These factors emphasize the need for more efficient simulation methods capable of capturing both transient effects and large-scale system behaviour while also allowing for the assessment of turbulent flow impacts, all without excessive computational overhead.

For simulating the thermal performance of HSPs, one approach is using analytical methods such as the Infinite Line Source (ILS), Infinite Cylindrical Source (ICS), and Finite Line Source (FLS) models instead of numerical simulations. The ILS model simplifies the heat source around the boreholes as an infinitely long line with heat transfer occurring radially, ignoring longitudinal variations. The ICS model considers the heat transfer around the borehole as an infinite cylinder, offering a closer approximation to real-world scenarios. The FLS model further refines this by taking into account the finite length of boreholes, incorporating axial heat conduction effects to provide a detailed and realistic simulation of borehole performance over time. Philippe et al. [11] studied these models to determine their validity ranges and observed that the ILS model, while useful for long-term estimates, lacks accuracy near the borehole center, particularly over short durations. Conversely, the ICS model is optimal for short-term analysis where radial heat transfer dominates but it is not very precise for long time periods. Among these, the FLS model is the best-suited model, especially for long-term scenarios where axial conduction at the borehole or pile ends is significant. Its only weakness is at short time periods that can be on the order of hours to a few days depending on the length of the pile.

g-Functions provide another way to simulate the performance of HSPs by combining analytical and numerical methods. g-Functions were originally developed by Eskilson [12] for simulating heat transfer around boreholes. Eskilson developed g-functions using an explicit finite difference method and applied a separate radial-axial mesh for each borehole. By temporally and spatially superimposing the temperature distributions around the boreholes, he was able to derive g-functions correctly. These g-functions relate the overall changes in the borehole wall temperature, which is assumed to be uniform along the borehole's length and across the bore field, to the heat exchange rate of the boreholes, which varies spatially and temporally across the system.

g-Functions can also be evaluated analytically using the FLS model. In the literature, numerous studies have explored the evaluation of g-functions using the FLS model for different boundary conditions and have proposed methods to improve their accuracy. One such work is presented by Cimmino and Bernier [13], where a semi-analytical method is applied to generate g-functions. By using a segmentation approach that considers variable heat extraction rates along the boreholes and between different boreholes, the g-functions are generated with high accuracy for different configurations. This work examines three boundary conditions for the boreholes and finds that the boundary condition that assumes uniform borehole wall temperatures produces g-functions closest to those reported by Eskilson, with a deviation of less than 5% for most configurations.

Similar to the FLS model, g-functions are not very accurate at short-time periods, which is due to the simplification of the dynamic behaviour inside the GHEs, which does not consider the fluid, grout, or pipes thermal capacity and the fluids residence time. That's why some researchers, such as Javed and Claesson [14], [15], applied a network of thermal resistances and capacitances to account for the thermal interaction of internal elements, and provided an accurate solution for radial heat transfer of vertical boreholes. Another method, which is more complete and can simulate both short-term and long-term performance of HSPs, is using the thermal resistance capacity (TRCM) model [16]. This model uses a network of thermal resistances and capacitances as well as the FLS model to simulate respectively the thermal behaviour inside and outside the boreholes. This model considers some segments along the borehole length to account for heat exchange rate variations and, in this way, it simulates both radial and axial heat transfer of boreholes accurately in the short- and long-term periods.

In the present study, the FLS model is combined with a numerical simulation to model the thermal behaviour of HSPs across different time scales. The numerical simulation assesses the short-term thermal performance of HSPs (the first hour of operation), while the FLS model simulates long-term behaviour (hours to decades afterwards). By integrating these approaches, the performance of HSPs is analyzed comprehensively over the full-time spectrum. This approach allows for the long-term performance of HSPs to be simulated without relying entirely on costly numerical simulations, thereby limiting their use to short-term periods. This is advantageous because short-term simulations are rapid, and their results can be applied to any series or parallel arrangement of HSPs, since only radial heat transfer occurs in short durations. In contrast, simulating long-term performance is computationally intensive. Over long periods, thermal interactions between piles become significant, and these interactions are effectively accounted for by the FLS model.

In the following sections, the mathematical framework of the proposed methodology is outlined. Subsequently, the model is applied to simulate a test case, and its results are validated against those obtained from a numerical simulation. Finally, the model is utilized for the simulation and sizing of HSPs. The goal is to optimize the design and performance of HSPs, enabling their wider adoption in the industry and contributing to the transition toward a low-carbon built environment.

III. Methodology

In this study, as shown in Fig. 1.c, the structure of HSPs is simplified to two concentric pipes. Numerical simulations indicate that the simplified design maintains comparable thermal performance to the actual HSP, but with significantly less computational intensity. Additionally, the screws near the tip of the HSP are omitted in these models.

In this study, the FLS model used to evaluate the g-functions is developed based on the methodology outlined in [17]. Based on this methodology, the temperature variation at the wall of pile i due to receiving heat transfer from pile j can be evaluated as follows:

$$\Delta T_{ij}(t) = q_j(t) z_{ij}(t) / \left(2\pi k_g H\right) \tag{1}$$

$$z_{ij}(t) = \int_{1/\sqrt{4\alpha_g t}}^{\infty} exp\left(r_{ij}^2 s^2\right) \frac{U(Hs, Ds)}{(H^2 s^2)} ds \tag{2}$$

$$U(d,h) = 2f(2d+h) - f(2d+2h) + 2f(h) - f(2d) \tag{3}$$

$$f(x) = x \cdot erf(x) - \frac{1}{\sqrt{\pi}}\left(1 - e^{-x^2}\right) \tag{4}$$

where H is the pile height, D is the buried depth (see Fig. 1), k_g is the ground thermal conductivity, q_j is the heat exchange rate of pile j, and ΔT_{ij} is the wall temperature change of pile i due to receiving heat from pile j at time t. In Eq. 1, z_{ij} is the thermal response of pile i due to the heat exchange rate from pile j which is evaluated by Eq. 2. In Eq. 2, r_{ij} is the radial distance between piles i and j, α_g is the ground thermal diffusivity, and U and f are two functions that are dependent on the buried depth and height of piles as specified in Eqs. 3 and 4. Note that Eqs. 1 to 4 are simplified versions of those reported in [17]; for their derivation, it is assumed that the buried depth and height of all piles are identical; however, in [17], each pile can have a specific buried depth and height.

To evaluate the g-functions, it is essential to convert Eq. 1 into a non-dimensional form, as shown in Eq. 5. In this equation, $\Delta\theta_{ij}(t)$ represents the non-dimensional wall temperature variation of pile i due to receiving a non-dimensional heat exchange from pile j, denoted as $\tilde{q}_j$, at time t. The term $\tilde{q}_j$ is normalized by dividing the heat exchange rate of pile j by the total heat exchange rate of all piles at time t, represented by $\bar{q}$(t).

As demonstrated in Eq. 6, in a field containing n_p piles, it is necessary to spatially superpose all non-dimensional temperature variations on pile i due to the heat exchange received from other piles, including pile i itself, to evaluate its total non-dimensional wall temperature variation, $\theta_{p,i}$. Assuming uniform wall temperature variations across all piles in a pile field, the parameter $\theta_{p,i}$ serves as the g-function for the pile field. This g-function quantifies the collective thermal response of the entire field to heat exchange processes.

$$\Delta T_{ij}(t) = q_j(t) z_{ij}(t) / \left(2\pi k_g H\right)$$

$$\Delta\theta_{ij}(t) = \frac{\Delta T_{ij}(t)}{\bar{q}(t)/\left(2\pi k_g H\right)} = \frac{q_j(t)}{\bar{q}(t)} z_{ij}(t) = \tilde{q}_j(t) z_{ij}(t) \tag{5}$$

$$g(t) = \theta_{p,i}(t) = \sum_{j=1}^{n_p} \tilde{q}_j(t) z_{ij}(t) \tag{6}$$

Since the heat exchange rate of the piles varies over time, temporal superposition is necessary. The heat exchange rate of the piles varies based on their position in the field, their series-parallel arrangement, and time. In addition, the heat exchange rates vary along the pile's height; therefore, to accurately evaluate the g-functions, it is necessary to divide the pile's height into several segments and analyze the thermal response of each segment separately. In this paper, for brevity, these points are briefly summarized, and for more information, the reader is referred to references [13] and [18]. By considering these factors, a series of equations at each time step can be solved to determine the g-functions of the HSPs accurately. Using the evaluated g-functions, it is now possible to determine the wall temperature of the piles as well as their inlet and outlet temperatures, as illustrated in Eqs. 7 to 9.

$$T_w = \bar{q}(t) g(t) / \left(2\pi k_g H\right) \tag{7}$$

$$T_{out} = \bar{q} R_p^* + T_w - \bar{q} / \left(2\dot{m} C_p\right) \tag{8}$$

$$T_{in} = T_{out} + \bar{q} / \left(\dot{m} C_p\right) \tag{9}$$

where $\dot{m}$ is the fluid mass flow rate, C_p is the fluid specific heat capacity, R_p^* is the effective pile thermal resistance which is used to relate the pile wall temperature, T_w, to the fluid inlet and outlet temperatures. In this paper, R_p^* is evaluated based on the methodology described by Hellström [19] by assuming that the pile wall temperature is uniform along its length. Using these equations, the wall temperature as well as the inlet and outlet temperatures of the piles are evaluated and then compared with the ones evaluated by the numerical simulations. The next section presents the results of this validation.

IV. Results and Discussions

Test 1: Validation of the proposed method

To validate the accuracy of the proposed method the thermal performance of a single HSP was simulated using both the FLS model and the finite element model (FEM) using the COMSOL Multiphysics software. This pile is designed with a height of H_p=20 m, buried at a depth of D=2 m, and embedded in the ground at an initial temperature of T_g=10°C. The ground surface temperature is considered constant, equal to the initial ground temperature, and the pile is assumed to be subjected to a constant cooling load of 1 kW. Additional design parameters include r_p=0.1 m, r_i=0.08 m, $r_{p,o}$=0.03 m, $r_{p,i}$=0.02 m (see Fig. 1), R_p^*=0.15 (m.K)/W, $\dot{m}$=2 kg/min, C_p=3040 J/(kg.K), k_g=1.68 W/(m.K), and α_g=0.0477 m²/day. For simplicity, the thermal properties of the fluid, the pipe, and the casing of the HSP are assumed to be identical to the ground properties previously mentioned.

Fig. 2 illustrates the variations in pile wall temperature as evaluated by both the FLS and COMSOL models. In this figure, two sets of results from the FLS model are reported: one considers only one segment for the pile height, while the other divides the pile height into 24 segments. By adopting these two approaches, different values of g-functions are evaluated, and using Eq. 7, two sets of pile wall temperatures are calculated and then compared with those evaluated by COMSOL. It can be observed that the results from the FLS model with one segment initially correlate well with the COMSOL model but exhibit slight deviations over the long term due to the neglect of variations in the heat exchange rate along the pile wall over time. The results with 24 segments from the FLS model demonstrate much better accuracy and completely align with those obtained by the COMSOL simulation. From this comparison, it can be concluded that the FLS model is capable of accurately simulating the wall temperature changes in HSPs from short-term to long-term periods. However, for accurate long-term predictions, it is essential to consider the variation of the heat exchange rate along the pile height. The short-term period refers to the first hour of simulation, while all subsequent times—covering both independent and interacting borehole thermal behavior—are collectively defined as the long-term period in this paper, as shown in Fig. 3.

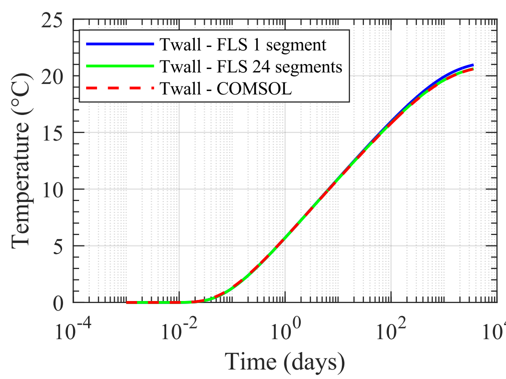

Figure 2: Comparison of wall temperatures evaluated by the FLS model with 1 and 24 segments and by using COMSOL

By using the wall temperatures evaluated by 24 segments and using the effective thermal resistance (see Eq. 8), the inlet and outlet temperatures of the HSP are evaluated, and the results are compared to the ones evaluated by COMSOL. Among inlet and outlet temperatures, the outlet temperature is the primary variable of concern, as it directly serves as the inlet temperature to the heat pump and must remain within its specified operational range. Additionally, since the cooling load is constant, the inlet and outlet temperatures have a constant specific difference with each other (see Eq. 9). Therefore, in Fig. 3, for brevity, only outlet temperatures are compared.

Fig. 3 demonstrates that the FLS model accurately predicts outlet temperatures, closely aligning with the COMSOL results. The difference between these two models decreases to less than 0.5°C after one hour of operation and further reduces to below 0.1°C after a few months. Evaluating these results requires only a few minutes on a standard personal computer for the FLS model, whereas the COMSOL model takes several hours. As shown, the two sets of results exhibit only minor deviations, occurring in the short term (less than one hour). These differences arise because the transient thermal resistance of the pile (R_p^*) in Eq. 8 is assumed to remain constant rather than varying over time. In reality, R_p^* changes over time as heat accumulates or dissipates within the pile, affecting the short-term thermal response of the system. These effects depend on the thermal capacity and geometry of the pile and become significant when there is a noticeable variation in the flow rate, the inlet fluid temperature, or when the pile's heat exchange rate fluctuates significantly.

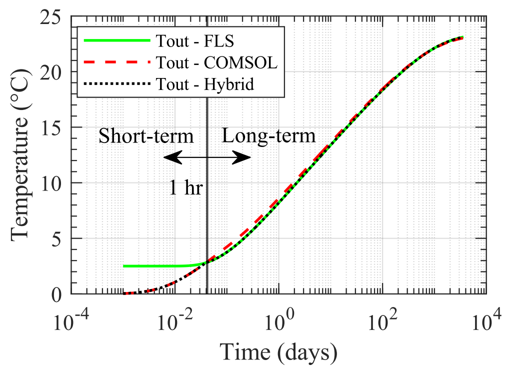

Figure 3. Comparison of outlet temperatures predicted by the FLS model, COMSOL, and the hybrid model

Thus, these effects are independent of the number of piles, their series-parallel arrangement, or their thermal interaction. Instead, if these short-term effects are simulated using a numerical simulation such as FEM in COMSOL, the results can be applied to different scenarios as long as the thermal and geometrical properties of the piles remain unchanged. For these reasons, in this study, the thermal effects of the piles were evaluated over the short term (the first hour) using COMSOL, and then only the FLS model was used to simulate the remaining performance of the HSP, effectively creating a piecewise approach. This hybrid model efficiently simulates the thermal performance of HSPs from minutes to decades, as depicted in Fig. 3. It can be observed that the hybrid model closely matches the COMSOL results, with a 0.1°C difference, except for the first few hours, where its deviation ranges between 0.1°C and 0.5°C.

Test 2: Simulation of the thermal performance a HSP

The test case analyzed here assumes a constant heat exchange rate for the piles; however, in realistic operational scenarios, the heat exchange rate of the HSPs varies over time. To evaluate the applicability of the proposed method under realistic conditions, an analysis was conducted using a hypothetical balanced hourly heating and cooling load profile over one year. This load profile is based on the methodology outlined by Bernier et al. [20] and has an amplitude of 1 kW, which is chosen arbitrarily. For this problem, a single pile with the previously mentioned design parameters is applied, and its thermal performance is simulated using the hybrid model. Since the heat load varies on an hourly basis, temporal superposition is applied, as explained in [21]. By employing temporal superposition, the inlet and outlet temperatures of the HSPs are evaluated to ensure they can handle the given hourly load profile.

Fig. 4 compares the outlet temperatures predicted by the hybrid model with those determined by the COMSOL simulation, as well as their absolute temperature differences. The comparison shows high congruency, with an absolute temperature difference of less than 0.5°C. Since temporal superposition requires results to be sequentially combined, the hybrid model takes slightly longer to solve this problem than in Test 1, where the test case was a constant load—around 10 minutes on a standard desktop computer—but remains significantly faster than COMSOL, which takes 22 hours. The COMSOL simulation and hybrid model with superposition were both performed on a computer equipped with an Intel Core i7 processor (3.5 GHz) and 8 GB of RAM. These results highlight the computational efficiency of the proposed method while maintaining high accuracy. For long-term simulations spanning several years of operation, a more efficient temporal superposition approach, such as the MLAA algorithm introduced in [20], can be used to significantly reduce computation time.

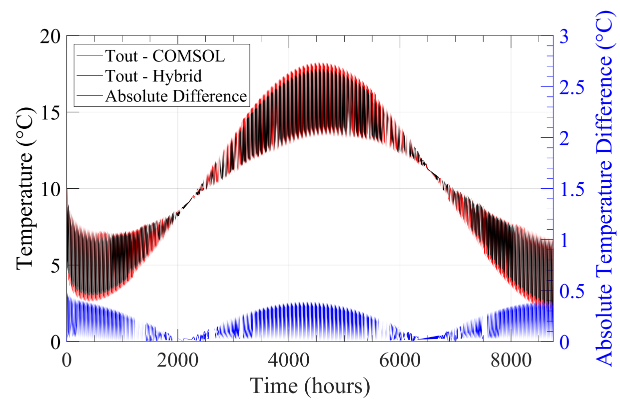

Figure 4. Comparison of pile outlet temperatures predicted by COMSOL and the hybrid model, along with their absolute temperature difference over a year

Test 3: sizing of series-parallel arrangements of HSPs

For the final test, a sizing problem is solved to demonstrate the applicability of the proposed method for design and optimization. In this problem, a 2×3 parallel pile configuration with 5 m spacing is sized to handle the same synthetic load but with an amplitude of 9 kW. The objective is to determine the shortest pile height that ensures the outlet temperature remains within the heat pump's operational limits, which are assumed to be between 0°C and 30°C. Fig. 5 presents the outlet temperatures of three tested pile heights for a duration of three years. It can be observed that the minimum length that satisfies the temperature constraints is 25 m, making it the optimal length for this specific test case. The same methodology can be applied to optimize other design parameters, including pile radius, spacing, flow rate, pile material, number of piles, and overall system capacity.

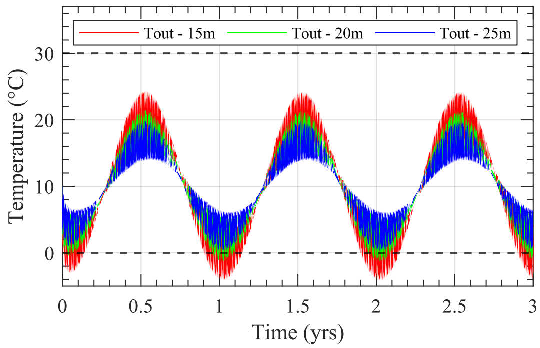

Figure 5. Outlet Temperatures for 15 m, 20 m, 25 m pile height test cases for a 2×3 pile configuration to meet the heat pump's temperature limits

V. Conclusion

This study developed a novel, highly efficient hybrid methodology for simulating the thermal performance of HSPs as geothermal heat exchangers. By integrating the FLS model with numerical simulations from COMSOL Multiphysics, the proposed approach accurately predicts the thermal behaviour of HSPs across various time scales while significantly reducing computational effort. The validation results demonstrated that when the FLS model accounts for heat exchange variations along the pile height through segmentation, it closely matches finite element simulations while maintaining a much lower computation time. Additionally, using an effective pile resistance enabled accurate predictions of inlet and outlet fluid temperatures, with deviations of less than 0.5°C compared to COMSOL results.

To address short-term deviations, a hybrid modelling approach was developed, combining finite element simulations for short-term behaviour with FLS calculations for long-term performance, enhancing accuracy and computational efficiency. The model was successfully applied to a multi-pile sizing problem, demonstrating its potential for optimizing HSP configurations in realistic applications—an outcome that would be computationally intractable using purely simulation methods. While not explored in this paper, the numerical simulations conducted are capable of modelling scenarios where ground properties vary with temperature. Incorporating this variation into analytical models is more complex, as it requires iterative calculations to determine accurate wall temperatures based on temperature changes from both pile operation and seasonal effects. Although feasible, this approach is beyond the scope of the current study and represents a promising area for future research.

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