Thermal efficiency of energy piles in stratified soil under unbalanced operation

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ABSTRACT

Shallow geothermal energy piles are novel and cost-effective heat exchangers used in ground source heat pump systems for heating and cooling buildings. Pile foundations are used to exchange heat with ground besides structural support. Ground thermal conductivity is a decisive design parameter in shallow geothermal applications. Ground homogeneity relying on depth-weighted averaging has been the common assumption in wide research around energy piles in recent years, with soil layering influence remaining mostly unexplored. This becomes particularly important under unbalanced thermal operation, due to thermal accumulation in the ground. To explore this influence, a 3D finite element numerical model is built to solve for the heat conduction-convection multi-physics of energy piles embedded in layered soil. Unbalanced thermal load regimes with different building cooling-to-heating ratios are adopted for long-term assessment, showcasing the effect of this controllable parameter, for soil profiles with different thermal conductivity distributions. Results underscore the necessity to account for the thermal properties' spatial variability in layered soil and recommend depth-specific thermal conductivity testing under unbalanced thermal load conditions. The thermal performance of the energy pile system in the considered stratified soils is shown to differ from that of their equivalent depth-weighted homogeneous ground owing to the growing difference in the accumulated temperature over the operation life, leading to underpredict the actual thermal conductivity by up to 31.5% as the contrast between layers grows and the unbalanced cooling-to-heating ratios increase. Furthermore, the depth sequence of ground layers of different conductivities is found to be important in predicting the thermal performance of energy piles.

Keywords: Shallow geothermal energy, soil layering, energy piles, unbalanced thermal load, thermal conductivity

1 INTRODUCTION

Shallow geothermal energy technology is a cost-effective and environmentally friendly alternative to traditional electric and fuel-based heating and cooling systems, reducing carbon emissions and saving up to 75% of the consumed energy (Banks 2012). The technology benefits from the steady ground temperature after few meters from the surface, which makes the ground an efficient and indeed sustainable medium to exchange heat over the year, regardless of the air temperature. The heat exchange process is performed with the help of a Ground Source Heat Pump (GSHP) that links a hydronic system composed of a primary circuit of buried Ground Heat Exchangers (GHEs) in the ground and a secondary distribution circuit inside the building. The GHEs used in shallow geothermal systems are usually made of High-density Polyethylene (HDPE) pipes filled with circulating fluid (usually water or a mixture of water and antifreeze), and they are buried inside a purpose drilled-borehole at depths typically less than 200m (Cunha et al. 2022). However, the associated drilling cost is significant (Lu et al. 2019). Instead, incorporating the GHEs within the pile foundations to serve as heat exchanger elements, known as energy piles (Brandl 2006), besides their primary structural role has emerged as a cost-effective option compared to the drilled-borehole in the last two decades.

The design of shallow geothermal systems involves various essential aspects related to the ground, such as geotechnical, thermal, and hydrological conditions (Sani et al. 2019). Regarding the ground thermal properties, the thermal conductivity, λ_s [W/(m·K)], is found to be among the most decisive design parameters of shallow geothermal energy systems (Mikhaylova et al. 2016). A study shows that a 10% uncertainty in λ_s value affected the design length of the considered GHEs to up to 5.8% (Kavanaugh, 2000).

The effective thermal conductivity, $\lambda_{eff.}$ [W/(m·K)], of the ground can be measured through an in-situ test called Thermal Response Test (TRT). While this conventional TRT technique assumes the ground as a single homogeneous medium, other advanced TRT techniques have been developed afterwards to consider ground layering, such as the Distributed Thermal Response Test (DTRT). However, in-situ testing of the ground thermal conductivity is not usually performed in practice during the design stage of shallow geothermal systems due to time and cost aspects (Tang et al. 2019; Franco and Conti 2020), and it is recommended only when thermal loads are at least 50kW (Europe I.E. Training Manual 2011). Instead, empirical data from the literature, technical standards, or "rules of thumb" are usually used to estimate the ground thermal conductivity (Kavanaugh and Rafferty 1997; Europe I.E. Training Manual 2011).

However, ground layering naturally exists and usually has greater variation in thermal properties at shallower depths, making a higher impact on the thermal design of energy piles than on deeper boreholes. This variation in terms of thermal conductivity could be from 0.15W/(m·K) for medium-dry sand to 3.0W/(m·K) for wet gravel with sand, and could reach up to 6.5W/(m·K) for sandstone (Dalla Santa et al. 2020). A study performed a full-scale experiment on a high-strength concrete energy pile in layered ground showed that the in-situ measured effective thermal conductivity was double that obtained from the laboratory (Guo et al. 2018). Therefore, designing the energy piles based on a single homogeneous value of the ground thermal conductivity may imply inaccurate long-term thermal performance of the energy piles. This becomes particularly important under unbalanced thermal load operation, when the annual heating demand is not equal to the annual cooling demand, leading to a progressive heat accumulation in the ground (Alqawasmeh et al. 2024).

Exploring the thermal performance of energy piles considering layered ground and investigating the thermal processes between the overlaying layers is still needed to enhance the collective knowledge around energy piles. To this end, this paper aims to investigate the long-term thermal performance of energy piles embedded in contrasting multi-layered soils in terms of thermal conductivity under different unbalanced thermal load operations and compare them to their equivalent depth-weighted homogeneous assumption. This enables quantifying the uncertainty associated with the commonly used homogeneous assumption in predicting the thermal performance of energy piles under unbalanced thermal conditions and exploring the important contribution of the ground beneath the pile.

2 METHODOLOGY

2.1 Overview

A 3D finite element model is established in COMSOL® Multiphysics to study the heat transfer phenomena in energy piles. The modelled ground surrounding the energy piles considers four different layers evenly distributed along the depth to represent various geological settings. Each geological setting selected represents a case of thermal conductivity distribution for the layers. For comparison reasons, all cases adopted have the same depth-weighted average thermal properties along the depth of the energy piles. Since the interpretation of the effective thermal conductivity using the conventional TRT considers the ground body that only surrounds the GHEs with radial heat flux, the depth-weighted averaging is calculated considering the ground only in contact with the pile body, allowing the investigation of the long-term influence of this approximation.

A 25-year design period for the energy piles is adopted considering three building cooling-dominant unbalanced annual thermal load ratios (1.5, 2.0, and 2.5). The thermal loads considered assume a sinusoidal distribution, allowing to cover small, moderate, and peak operation schemes over the heating and cooling cycles. For instance, the unbalanced thermal ratio of 2 represents injecting 1kW to the ground from each energy pile during peak cooling operation over six months to 0.5kW extracted power during peak heating operation over the rest of the six months of the year.

Results from different ground configurations and thermal load scenarios are then compared based on a main thermal performance indicator (average fluid temperature between inlet and outlet, $T_{avg.}$ [°C]) against the equivalent homogeneous case.

2.2 Numerical model specifications

The numerical model established in COMSOL® Multiphysics is capable of coupling the heat convicted through the circulating fluid within the GHEs with the surrounding medium through their wall, where the heat is then transferred by conduction from the GHEs wall to the concrete body of the pile and finally to the ground. The GHEs are modelled as HDPE of 0.48W/(m·K) thermal conductivity and with 25.4mm and 33.4mm inner and outer diameters, respectively. Accordingly, the circulating fluid flow rate is set to 9.3l/min, ensuring a proper Reynolds number (Re) for efficient heat transfer. To take advantage of the whole space inside the piles, the designed GHEs form a 4U-loop shape, and they are distributed around the pile's perimeter with a typical 35cm spacing between their legs. The concrete piles have 80cm diameter and 20m length with selected thermal conductivity, density, and heat capacity of concrete as 2.1W/(m·K), 2,300kg/m^3, and 880J/(kg·K), respectively.

The unit cell approach method is used to isolate a typical single energy pile out of arrays of energy piles in both horizontal directions with symmetrical distant boundary conditions. This boundary condition allows to account for any potential thermal effect from adjacent piles (10m apart) with a significant reduction in computing cost. Thermal insulation on the top surface is used, as piles are assumed to be covered by their superstructure. The bottom surface is located 10m below the piles' toe and a constant far-field temperature of 18.2°C is adopted, ensuring no boundary effect at that depth. The initial undisturbed temperature for the model is set to 18.2°C. Two sizes of free tetrahedral elements are considered to discretise the numerical model domains such that a finer mesh is assigned to the energy pile compared to that of the ground, resulting in a total number of 125,350 tetrahedral elements (37,497 elements for the energy pile and 87,853 elements for the ground). Figure 1-a shows the numerical model established with its specifications, mesh, and boundary conditions.

2.3 Validation

The numerical model is validated against a well-known analytical method called the Finite Line Source Model (FLSM) (Lamarche and Beauchamp, 2007). The method normally assumes a homogeneous ground surrounding a borehole. Therefore, the average fluid temperature arising from solving the numerical model of the energy pile in a homogeneous ground, considering 1kW thermal injection for 300hours, is compared to that from FLSM as shown in Figure 1-b. The excellent agreement between the resulting average fluid temperature from the numerical and the analytical solutions suggests that the numerical model built can be confidently involved in performing this study.

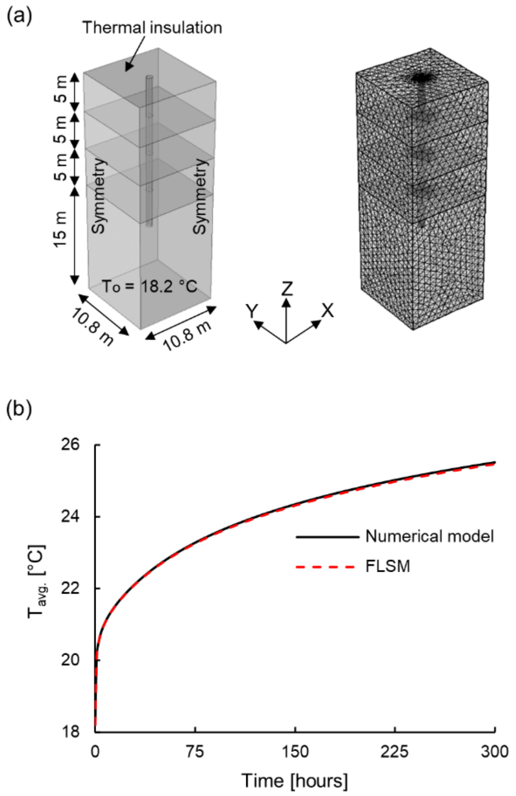

Figure 1. Numerical model details and mesh (a) and validation against FLSM (b).

2.4 Numerical simulations

The study involves two main sets of numerical simulations. The first set contains three ground configuration cases. The ground around the energy pile in each case is divided evenly into four layers. A selected thermal conductivity value between 0.5 and 3.5W/(m·K) is assigned to each layer, considering the thermal conductivity is increasing with depth. The resulting thermal conductivity distributions represent three cases, as shown in Figure 2-a, with low (Case 1), moderate (Case 2), and high (Case 3) contrasting levels (or standard deviation σ), yet their depth-weighted average along the pile's depth is fixed at 2.0W/(m·K). Given that the ground tends to be denser with depth, the densities of 1,200, 1,480, 2,120, and 2,400kg/m^3 are assumed for the first, second, third, and fourth layers, respectively, such that their depth-weighted average along the pile's depth is 1,800kg/m^3. A specific heat capacity value of 1,500J/(kg·K) is assumed for all layers. The selected properties of the ground layers in terms of density and specific heat capacity are kept similar for the three cases, allowing to exclude their effect. In addition, their variation and impact on shallow geothermal design are usually less significant than those of thermal conductivity. Long-term analyses are performed on the three cases at different unbalanced thermal ratios (1.5, 2.0, and 2.5) and compared to the homogeneous case with thermal conductivity, density, and heat capacity of 2.0W/(m·K), 1,800kg/m^3, and 1,500J/(kg·K), respectively.

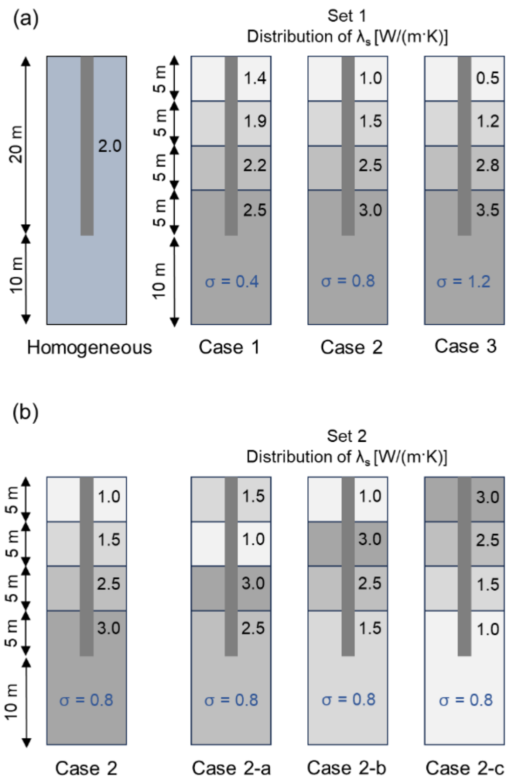

Figure 2. Thermal conductivity distribution of the layered ground for numerical simulation: set 1 (a) and set 2 (b).

The second set of numerical simulations is designed to investigate the influence of the order of the layers. For this reason, the moderate case (Case 2) from the previous analysis is selected as a base case and its layers order has been changed, resulting in three subcases (Case 2-a, Case 2-b, and Case 2-c) as shown in Figure 2-b. Afterwards, a long-term thermal performance comparison is performed considering an unbalanced ratio of 2.5.

3 RESULTS AND DISCUSSION

3.1 Numerical simulations – Set 1

The first set of simulations is performed for Cases 1, 2, and 3 in Figure 2-a considering unbalance ratios set at 1.5, 2.0, and 2.5, and compared to the homogeneous case. Cases 1, 2, and 3 represent low, moderate, and high contrasting ground configurations in terms of thermal conductivity distribution, respectively. However, their depth-weighted average along the pile depth is set at 2.0W/(m·K).

The unbalanced heat extracted from and injected to the ground over the operating period leads to a progressive temperature accumulation in both the ground and the circulating fluid, decreasing the thermal performance of energy pile system. Figure 3 shows the maximum average fluid temperature reached at the end of each annual building cooling cycle over the 25-year operation for Cases 1-3 compared to their equivalent depth-weighted homogeneous case under different unbalanced thermal operations.

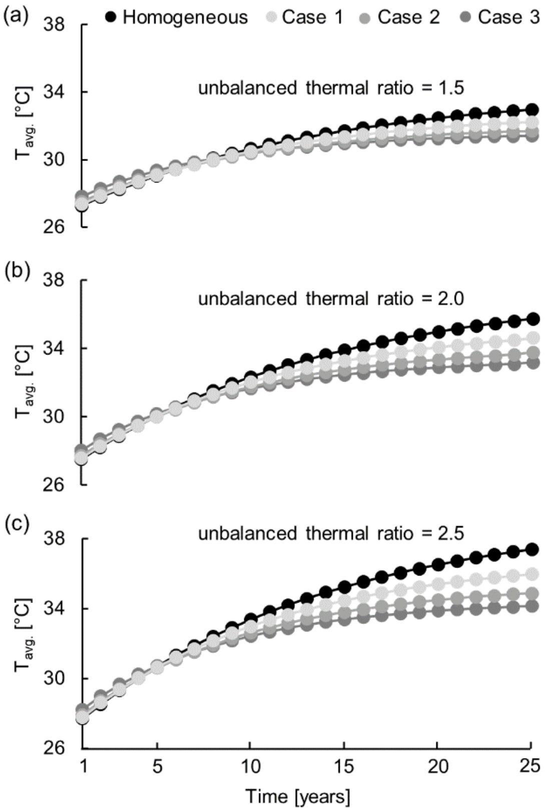

Figure 3. Annual average fluid temperature at the end of building cooling cycles over 25 years for cases in set 1 with unbalanced thermal ratio: 1.5 (a), 2.0 (b), and 2.5 (c).

It is evident that the progressive temperature accumulated for the homogeneous case is higher than that of the layered cases for all unbalanced operations. The higher the thermal conductivity variation in layered cases, the greater the difference compared to the homogeneous case, and this increases for higher unbalanced operation. The difference between homogeneous and layered cases in terms of heat accumulated after 25 years compared to the first year reaches up to 2.1°C (36.7%), 3.1°C (37.5%), and 3.8°C (38.8%) for unbalanced thermal ratios of 1.5, 2.0, and 2.5, respectively. Practically, for an efficient operation of a ground source heat pump, 3 to 5°C is the design goal for the temperature difference between GHE's inlet and outlet. Therefore, these differences in average fluid temperature, which indeed affect the GHE's inlet and outlet temperatures to fulfil the thermal load required, might significantly impact the performance of the ground source heat pump.

Moreover, it can be observed that the rate at which the average fluid temperature increases varies for different cases. The homogeneous profile exhibits a rapid increase with the steepest slope compared to the other layered cases. Since GSHPs are typically designed to operate efficiently within a specific range of fluid temperature, which depends on the manufacturer's specifications, this rapid increase might reach the maximum operating temperature of the selected GSHP. Consequently, this could lead the designer to select a higher performance GSHP, increasing the initial and circulating costs.

A further interesting observation is that during the first 3 to 5 years of operation, depending on the unbalanced thermal ratio, the homogeneous profile shows better performance with less heat accumulation before becoming the worst performer over the rest of the operating period. In contrast, the layered cases exhibit the opposite behaviour, with Case 3 performing the worst at the beginning before achieving the best performance over time. Given that all cases have the same depth-weighted average thermal conductivity, this observation suggests a need to investigate the impact of layer position and ordering with depth, which is discussed in the following section.

To estimate the *actual* (or correct) homogeneous ground thermal conductivity, λ^* [W/(m·K)], that provides the same thermal performance as the layered cases after 25-year operation, a parametric analysis is performed on the depth-weighted homogeneous profile by changing its thermal conductivity, and the results are summarised in Table 1. The higher the contrast between the layers' thermal conductivities, the greater the increase in the difference between their *actual* homogeneous value (λ^*) away from the depth-weighted homogeneous assumption (i.e., 2.0W/(m·K)). This is enhanced with the increase of the unbalanced thermal ratio. The depth-weighted homogeneous assumption underestimates the *actual* average thermal conductivity that leads to the same temperature accumulation response as the layered cases after the 25-year operation. The underestimation reaches up to 17.5%, 26.5%, and 31.5% for unbalanced thermal ratios of 1.5, 2.0, and 2.5, respectively.

Table 1. Actual homogeneous ground thermal conductivity (equivalent to layered cases).

Unbalanced ratio	Case	λ^* [W/(m·K)]
1.5	1	2.17
	2	2.30
	3	2.35
2.0	1	2.22
	2	2.40
	3	2.53
2.5	1	2.26
	2	2.48
	3	2.63

3.2 Numerical simulations – Set 2

To further explore the uncertainty associated with the homogeneous assumption and the impact of layer location with depth, Case 2, as an example, is selected as a base case to derive three subcases (Case 2-a, Case 2-b, and Case 2-c). The layers of Case 2 are swapped, forming three profiles (Figure 2-b) with the same thermal conductivity variation between layers. The subcases are run under an unbalanced thermal ratio of 2.5, as an example, and compared to the homogeneous case, allowing to investigate the importance of layer order.

Figure 4 shows the average fluid temperature resulting during 25-year operation for different layers positioning of the base case (i.e., Case 2), compared to the homogeneous profile. The differences in the thermal performance of the subcases compared to their base layered Case 2 and the homogeneous assumption are apparent. Case 2 and Case 2-a are underpredicted by the homogeneous assumption, while Case 2-b and Case 2-c are overpredicted.

The contrast drastically increases as the thermal conductivity of the bottom layers exhibits lower values than that of the top layers.

While a situation such as Case 2-c is unlikely to be encountered in nature due to natural composition processes that make ground tends to become rockier with depth, these results show the important contribution of the ground not only along the energy pile depth but also below the pile's toe which is not considered when interpreting the effective thermal conductivity by TRT. Furthermore, it shows the impact of layer location on thermal performance even though the subcases considered have the same overall variation (or standard deviation σ) of thermal conductivity distribution.

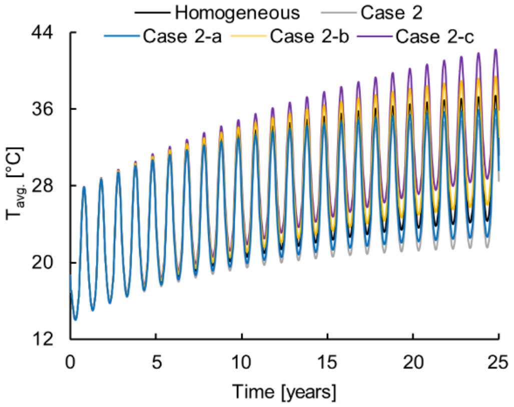

Figure 4. Average fluid temperature for the homogeneous and set 2 layered cases over 25 years under an unbalanced thermal ratio of 2.5.

Figure 5 shows vertical cross-sections of the temperature distribution across the centreline of the energy pile and the surrounding ground after 5 years, compared to 25 years of operation. While the contrast in temperature distribution among all profiles appears to be minimal after 5 years of operation, a profound difference is noticed after 25 years as the thermal conductivity of the bottom layers becomes lower from subcase 2-a to 2-c. This is because the heat

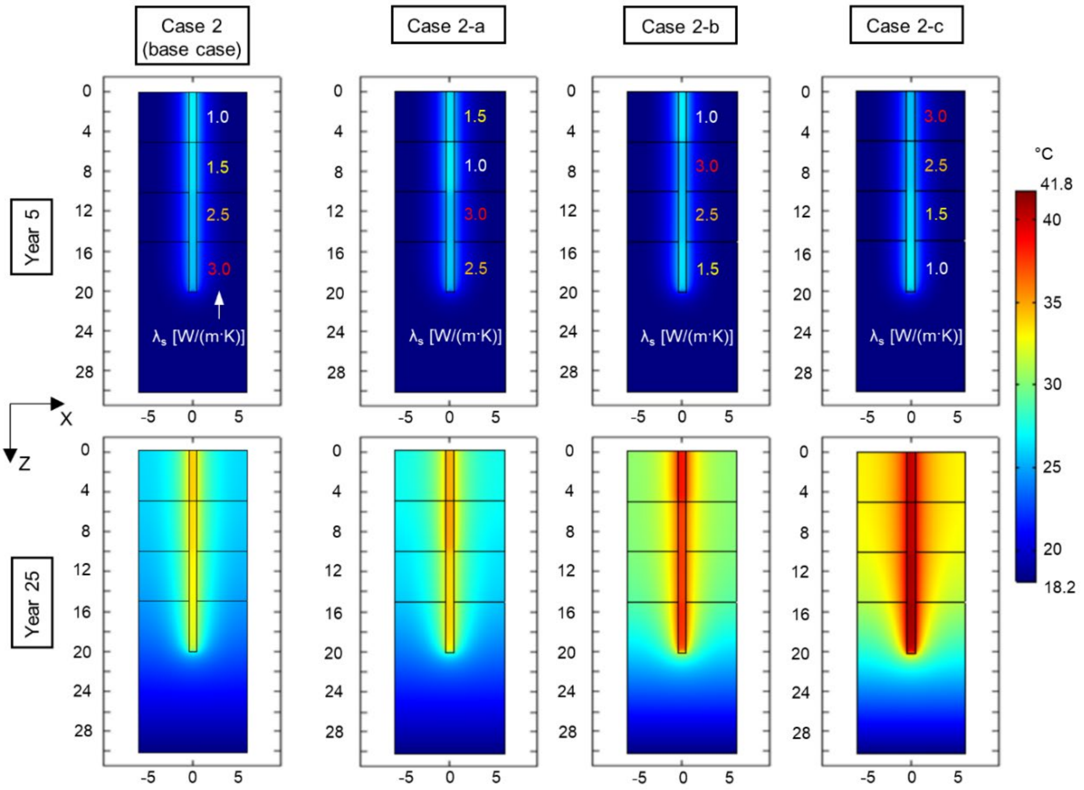

Figure 5. Symmetrical vertical cross-sections across the centreline of the energy pile and ground show the temperature distribution for cases in set 2 at the end of the building cooling cycle for year 5 and year 25.

accumulated tends to transfer toward the lower portion of the ground, as it has a larger volume to store energy, which helps in recovering the ground temperature. However, when the thermal conductivity of the bottom layer is lower than that of the top layer, the efficiency of temperature recovery decreases. In Case 2-a, which represents swapping only the first layer with the second, and the third layer with the fourth of the base Case 2, the temperature distribution in the bottom layer becomes wider which means a larger volume of the ground is involved in the recovery process. This increases for Case 2-b, as the bottom layer becomes lower in thermal conductivity, with the worst-case scenario when all layers of the base Case 2 are swapped, as represented in Case 2-c.

Another reason might be related to the different vertical interactions between layers for the subcases considered, in terms of inter-layer vertical heat flux. A higher thermal conductivity in the bottom layer leads to a positive upward heat flux, reducing thermal accumulation in the top layer, which has lower thermal conductivity. However, in Case 2-c, the lower thermal conductivity of the bottom layer fails to produce a positive upward heat flux, resulting in the highest progressive temperature accumulation over time. This leaves Case 2-c with the worst performance.

These results show the importance of considering not only the overall variability in thermal conductivity of layered ground but also the layers' location and their thermal conductivity distribution with depth.

4 CONCLUSION

The study shows the important contribution of the ground layers not only along the energy pile depth but also underneath its toe. The homogeneous ground relying on depth-weighted averaging along the pile depth underpredicts the actual thermal conductivity equivalent to the layered ground by up to 31.5% as both the contrast between layers and the unbalanced cooling-to-heating ratios increase.

Furthermore, the study highlights the importance of considering the layers' distribution and location along the depth, as it can lead to significant inaccuracy in predicting long-term thermal performance. Therefore, performing advanced depth-specific testing techniques to measure the thermal conductivity of layers is recommended, particularly for high ground variability and unbalanced thermal operation, reducing the uncertainty in predicting the *actual* ground thermal conductivity that contributes to the energy system's thermal performance.

More investigation considering different energy pile lengths, number of layers and uneven layer thicknesses is worth considering in future work.

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