

Experimental and Digital Twin approach for enhancing thermal efficiency of energy piles

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ABSTRACT: The growing global demand for sustainable energy and efforts to reduce reliance on fossil fuels and mitigate climate change, highlights the need for reliable renewable energy sources. Geothermal energy, available continuously throughout the year and almost available everywhere, offers a potential solution. Energy piles offer both structural and geothermal functions that have gained popularity due to their dual role in supporting buildings and harnessing geothermal energy. This study presents a small-scale laboratory experimental investigation of the thermal performance of a model energy pile embedded in dry sand, subjected to both heating and cooling conditions. This experiment aims to evaluate heat transfer trends within the pile–soil system. Key factors such as ambient temperature effects, thermal zoning within the soil, and heat dissipation patterns were assessed. A digital twin framework was implemented to dynamically control inlet fluid temperature based on real-time ambient data, significantly enhancing thermal efficiency and system stability. The results highlight the importance of mid-depth heat exchange zones, the influence of ambient interference, and the potential of real-time adaptive control for optimising energy pile performance. The results demonstrate that thermal dissipation patterns in energy piles can be differentiated into soil zones with middle third of the pile emerging as most efficient region for radial heat exchange. Distinct dissipation patterns and the successful integration of a real-time digital twin highlight the potential for smarter thermal control, improved soil recovery, and more efficient design of energy piles in practical geo-energy applications. These findings contribute to improved design strategies and long-term resilience of geothermal energy systems.

KEYWORDS: Geothermal energy, energy piles, thermal performance, small scale laboratory testing, digital twin, soil-structure interactions, thermal zoning

1 INTRODUCTION

The rising global demand for energy, global movement to reduce reliance on fossil fuels and increasing adverse impacts of climate change posing a significant challenge to the sustainability of renewable energy sources. Among various sources of renewable energies, geothermal energy, can provide a promising solution to address above challenges. Geothermal energy is available 24/7, 365 days a year and almost all around the world. Energy geostructures, such as energy piles, have proven a popular and successful solution, combining structural load-bearing capabilities with ability to harness geothermal energy (P. Bourne-Webb et al., 2016).

A significant number of studies have been carried out to understand the thermo-hydro-mechanical behaviour of energy piles under cooling and heating thermal loadings (Sutman et al. 2016, C.L. Wang et al, 2017, Rotta Loria et al 2016, Laloui et al 2019, Di Donna et al, 2016, Ng et al, 2021, Wu et al, 2018, Bao et al, 2021, Faizal et al., 2016, McCartney and Murphy, 2014, Murphy et al, 2015) Furthermore, several studies have focused on experimental testing to assess the short-term and long-term thermo-hydro-mechanical performance of energy piles (Ghasemi-Fare et al 2018, Loveridge et al 2020, Lao et al 2016, Sani et al 2019, van Tri Nguyen et al 2020).

Experimental studies are crucial in understanding and developing knowledge of thermos-hydro-mechanical behaviour of energy piles. Behaviour of energy piles can be simulated in various experimental approaches such as full-scale testing, centrifuge testing and laboratory testing. These testing provide crucial information in understanding short-term and long-term behaviour of energy piles in close to real-life conditions, support in enhancement of our knowledge, can be used to validate numerical models and collated data, if implemented appropriately, can be used to improve design of energy piles. (Laloui et al 2006, Zhong et al 2022).

Despite several research conducted in the field, there is limited research on thermal performance and optimisation of

energy piles. Laboratory small scale testing is a cost and time effective substitute for field testing. Additionally, they allow for testing of thermal performance of energy piles under controlled environment and conditions. Furthermore, this facilitates instrumentation and monitoring which often will provide significantly wider range and data compared to field testing. Sani et al (2019) conducted a small scale laboratory experiment and investigated thermo-hydraulic behaviour of a single energy pile in unsaturated soil. Their study involved model-scale laboratory testing as well as parametric analysis using the COMPASS code. Zhong et al, (2022) assessed the effects of thermally activating different piles in energy piled. The results demonstrated that increasing spacing between thermally active piles can thermally improve efficiency of the system to over 70% compared to close spacings. Zhao et al (2018) proposed an experimental set up to study the thermal performance of energy piles with spiral pipe configurations against borehole heat exchangers with double U-shape pipe configurations. Their results demonstrated that the heat transfer rate per unit length of pile and pipe is greater in energy piles compared to borehole heat exchangers. Ghasemi-Fare et al (2018) investigated the heat transfer in saturated and unsaturated soil through laboratory and numerical testing. they performed a parametric study to investigate the impact of various ground and operation conditions to determine optimal design factors. The authors concluded that heat transfer is directly proportional to contact area and temperature differences between adjacent soil/pile contact surface. Increase in flow rate of carrier fluid resulted in increase in thermal performance however, this was not directly proportional as at significantly high flow rates, there is not sufficient contact time for heat transfer.

The limited research into the thermal performance of energy piles may be due to energy production being a secondary function of these systems. Most studies focus on the mechanical impact of geothermal processes on the structural capacity of energy piles, with comparatively less attention given to

investigating and optimizing their thermal efficiency and long-term performance for life cycle design.

This research presents an experimental setup designed to investigate the thermal performance of energy piles embedded in dry sand under both cooling and heating. The study aims to improve thermal efficiency by examining the effects of thermal interference and heat dissipation within the surrounding soil. It further incorporates real-time data within a digital twin framework to optimize system performance. Finally, this research addresses soil thermal recovery as a key critical factor in ensuring the long-term longevity and resilience of energy pile systems.

2 MATERIALS AND METHODS

2.1 Experimental Set-up

The experimental investigation was conducted using a custom-built 1g physical model comprising a square soil box with internal dimensions of 1m × 1m (Figure 2a). The size and boundary conditions of the box were determined through a preliminary numerical analysis using the finite element modelling software COMSOL Multiphysics, ensuring minimal boundary effects on thermal behavior. The sand used in the experiments was sourced from Tarmac Hints Quarry in Tamworth (UK). The original poorly graded sand and gravel mixture was sieved to obtain a fine to coarse sand, which was classified by several testing such as compaction tests, porosity, particle size distribution testing, and thermal property testing (thermal conductivity and specific heat capacity) using a portable thermal conductivity meter. Sand was dried for testing to eliminate the influence of moisture on heat transfer, thereby isolating thermal interactions for more accurate interpretation. To control ambient conditions, the entire test setup was placed inside a temperature-controlled room. This enabled consistent monitoring and adjustment of ambient air temperature, allowing a more precise study of external thermal influences on the pile–soil system. During the initial calibration stage, the room temperature was controlled at 20 °C, however, following the observations regarding the influence of ambient temperature discussed in Section 3.1, the temperature control unit was turned off, allowing the room temperature to equilibrate with the external conditions, which varies considerably during the UK summer between sunny and non-sunny days and between morning and afternoon, as shown in the Figure 1 below.

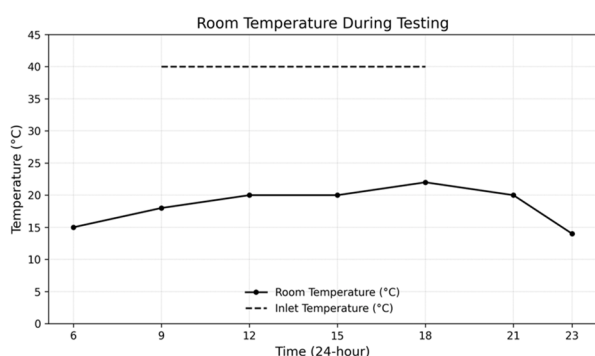


Figure 1. Room temperature during testing and fluid inlet temperature during testing.

2.2 Instrumentation and Monitoring

A comprehensive instrumentation strategy was implemented to capture the thermal behavior and interference of the energy pile and surrounding soil. The monitoring system included a total of

17 embedded temperature sensors, validated and calibrated by multiple external measurement devices.

The model pile was instrumented with seven K-type thermocouples, selected for their small size and fast response time, allowing accurate measurement of pile temperatures and varying depths (Figure 2b). In the surrounding soil, ten Campbell Scientific 107 temperature probes were installed at various depths, selected based on normalized pile depth and anticipated thermal response of the soil informed by preliminary numerical modelling. This layout provided detailed spatial resolution of the thermal gradient during heating and cooling phases. To monitor ambient and surface conditions, additional sensors were deployed. An eighth K-type thermocouple was positioned within the experimental room to record ambient air temperature. A manual thermometer and an infrared (IR) thermometer were also used for cross-validation and spot measurements of the room temperature, soil surface temperature, and bath water temperature. Furthermore, the PT100 sensor integrated with the Dyneo DD Julabo circulator provided real-time monitoring of the inlet bath water temperature. This combination of embedded and external sensors ensured accurate tracking of temperature within the pile and soil, and throughout monitoring of ambient temperature and fluid control systems allowing data collection for analysis of thermal performance.

2.3 Model Pile

The model pile was cylindrical, measuring 50 mm in diameter and 200 mm in length, and constructed from a rapid set cement concrete mix with a water-to-cement ratio of 0.4 (Figure 2b). A U-shaped copper pipe with internal diameter of 2mm was embedded within the pile to allow controlled circulation of fluid for thermal loading. This configuration and pipe sizing was chosen for its practical simplicity and consistency with common energy pile designs. The thermal properties of both the concrete and copper pipe were determined using Tempos thermal probes, providing measurements of thermal conductivity and specific heat capacity.

The copper U-shaped pipe configuration with internal diameter of 2mm was connected to a 4mm internal diameter silicone tubing rubber hose which was connected to the circulator unit. The silicone tubing was selected based on its flexibility and for insulating properties in order to reduce energy loss between the circulator unit and the pile compared to more thermally conductive steel tubing. Given the outer diameter difference between the copper pipe and silicone tubing, a pneumatic reducing 6mm to 3mm pipe fitting was utilised to connect the copper pipe and the silicone tubing. (Figure 3).

2.4 Heating and Cooling Circulator Unit

A Dyneo DD Julabo circulator (Figure 3e) was used to regulate fluid temperature and insert flow through the copper pipe embedded in the model pile. The system was operated in a closed-loop mode with continuous flow to maintain consistent thermal conditions. Two operational modes were tested: a cooling mode with fluid temperature set to 40°C, and a heating mode with fluid temperature set to 10°C. These settings were selected to provide measurable thermal gradients without exceeding material or equipment limits.

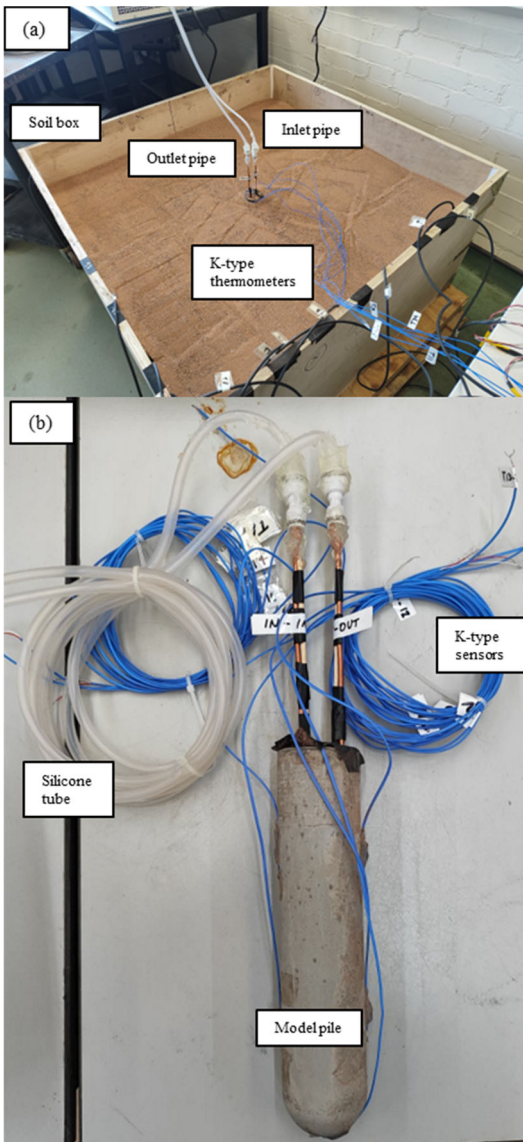


Figure 2. (a) Testing apparatus for a single energy pile configuration consisting of dry sand (b) Model energy pile with a U-shaped pipe configuration.



Figure 3. Experimental apparatus (a) Silicone tubing (b) pneumatic pipe fitting to connect copper pipe and silicone tubing (c) K-type thermocouple (d) 107 temperature probe (e) Dyneo DD Julabo circulator unit

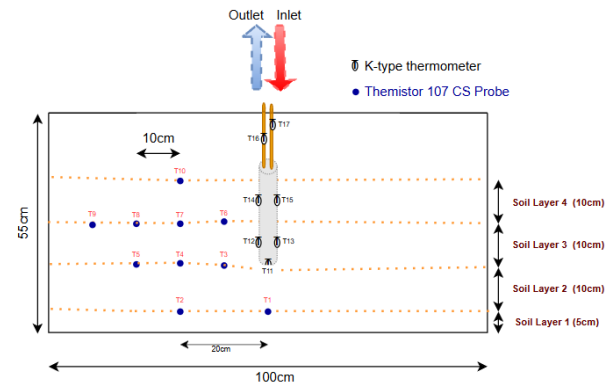


Figure 4. Monitoring diagram comprising of 107 thermistors in the soil and K-type thermometers on the model energy pile

2.5 Digital Twin

A digital twin framework was implemented to optimise thermal performance of the energy pile by integrating real-time ambient temperature data, captured by K-type thermocouples and validated with infrared and manual thermometers. This framework was integrated into a MATLAB-COMSOL interface via the Application Builder. An algorithm was developed to dynamically adjust the inlet fluid temperature to maintain a consistent temperature differential (ΔT) between the ambient room and the inlet temperature of the circulating fluid.

A flowchart of the digital twin framework is provided (Figure 5). The sensor data was programmed to record readings every one second. These readings were presented real-time using PC400 datalogger support software. A MATLAB toolbox was utilised to read specific sensor real-time data. A trigger value range associated with ambient temperature were defined and once these values were triggered an adjustment of the inlet fluid temperature was required. To simulate this and integrate a physics-based simulation, COMSOL's MATLAB LiveLink and Application Builder were utilised to use live sensor data as input for boundary condition checks and predict system behaviour based on real data.

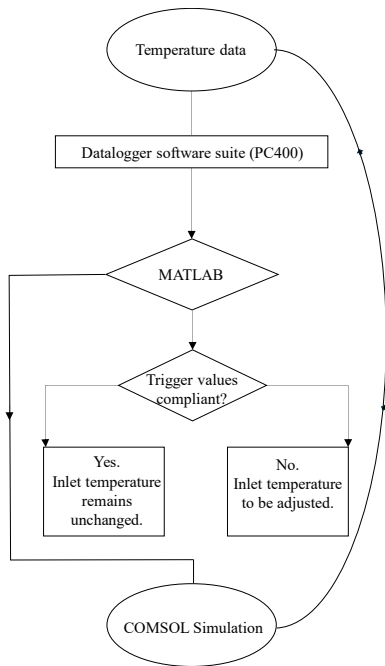


Figure 5. Digital Twin workflow adopted to integrate real-time ambient temperature data to enhance efficiency of the system.

3 RESULTS

3.1 Influence of Ambient Temperature on Heat Transfer

During the initial calibration phase of the experimental program, tests were conducted under both heating and cooling conditions while maintaining the air-conditioning (A/C) system of the temperature-controlled room in operation. The intention was to evaluate the thermal behavior and calibrate sensor accuracy under controlled but realistic environmental conditions. However, it was observed that the ambient room temperature was a dominant influence on the overall heat transfer process. Regardless of the magnitude of the inlet fluid temperature, the temperature dissipation within the soil only minor temperature changes were observed. This unexpected result can be attributed to the relatively small scale and low thermal mass of the model energy pile, which, when operating in a confined, climate controlled environment, was unable to compete with the larger and more thermally dominant heat exchange mechanisms of the A/C unit. The heating or cooling loads introduced by the energy pile were several orders of magnitude lower than those by the A/C unit resulting in a ‘thermal overshadowing’. This forced heat transfer effect from the room’s HVAC system dominated the model pile thermal diffusion capabilities and strongly influenced the boundary conditions of the soil mass in the soil box. To mitigate this issue, subsequent tests were conducted with the air-conditioning (A/C) system turned off, allowing a more isolated analysis of heat transfer between the energy pile and the soil. This enabled the ambient room temperature to stabilise and vary more gradually, reducing external thermal gradients and facilitating more natural and representative heat transfer behavior from the energy pile into the surrounding soil.

Temperature dissipation around the energy pile and inside the soil is demonstrated using 2D contour maps and 3D temperature isopachytes generated from the monitoring points distributed as shown in Figure 8. The results consistently show that the highest temperatures occur closest to the energy pile, with a clear radial dissipation trend moving outward from the

pile in both the 10 cm (upper) and 20 cm (lower) monitoring layers. The dissipation patterns indicate that the lower monitoring layer demonstrates slightly higher temperatures and dissipation gradient compared with the upper layer. This behaviour is attributed to reduced interaction with ambient conditions, allowing heat dissipate more.

3.2 Heat dissipation pattern in cooling operation mode

In the cooling operation testing, a fluid inlet temperature of 40°C was circulated through the model pile. The system reached a steady state within approximately 250 minutes from the start of the operation. Soil temperature sensors were installed every 10cm from based on numerical modelling: the top third, middle third, and bottom third of the pile’s length. These zones were selected based on the anticipated temperature dissipation within the soil and influence of the ambient temperature on the soil and the energy pile. The top 10cm of the soil where the first monitoring sensors were installed, located near the soil surface, was anticipated to be heavily affected by ambient temperature, while the middle third was expected to be the main heat exchange zone. The bottom third was expected to show minimal ambient influence but retain some capacity for thermal transfer. Experimental results (Figure 7 (a)) confirmed the above expectations and revealed the mechanism/pattern of heat dissipation in the soil. The middle section of the pile demonstrated the most significant radial heat dissipation, confirming it as the critical zone for the heat exchange. However, the bottom third demonstrated negligible thermal response, indicating limited thermal penetration and dissipation at depth. This finding suggests that design strategies for energy piles should priorities enhanced thermal exchange mechanisms in the middle zone. For instance, incorporating a spiral pipe configuration in this region may improve heat extraction and system efficiency in large scale applications.

3.3 Heat dissipation pattern in heating operation mode

In the heating operation testing, with an inlet temperature of 10°C, a different and opposite heat dissipation pattern was observed (Figure 7 (b)). Temperature distribution in the soil formed an inverted conical shape extending downward from the center of the pile. The thermal response was strongest from the middle of the pile downward, with minimal influence near the surface. These results can be significant for implications of thermal recovery and system resilience, particularly in regions with cooling dominant climates. Optimising the design for vertical heat transfer in such scenarios could improve long-term efficiency and sustainability.

3.4 Impact of the developed Real-Time Digital Twin on Thermal Performance

The digital twin framework was employed to improve the efficiency of the system and the results of the digital twin approach (DT) in cooling application is shown in Figure 5. This figure shows outlet temperature over time, with and without the application of the digital twin. During a two day trial testing, first day, the Digital Twin framework was not active and therefore, the system was not informed by real-time changes in ambient temperature. During trial day 2, the digital twin framework was activated and real-time changes in ambient temperature was recorded and inlet temperature was adjusted accordingly. Results showed a notable improvement in thermal efficiency and stability. It can be seen that compared to the fixed temperature runs, the dynamically controlled system via digital twin demonstrated more consistent heat transfer rates. The temperature gradients in the soil were more stable, and a higher thermal exchange rate in the mid-pile zone was observed. These findings validate the feasibility of real-time digital feedback

systems in geothermal applications and highlight the potential for data-driven thermal management strategies to significantly enhance the performance, responsiveness, and longevity of energy pile systems. The system was turned off after 400 and 350 minutes on Day 1 and Day 2 testing respectively, and a quick recovery within the pile can be observed. This demonstrates high thermal conductivity and heat dissipation within the model pile.

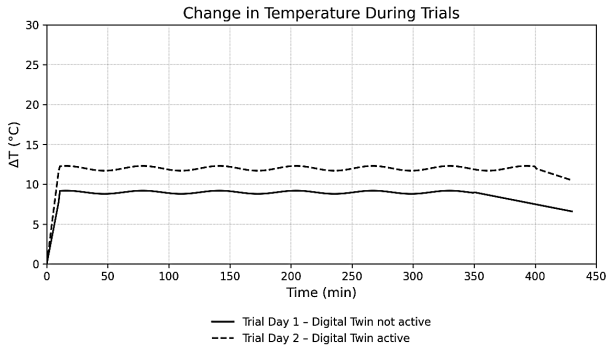


Figure 6. Cooling operation with and without digital twin (DT) framework. Trial Day 1 testing comprised recording of ambient temperature and ΔT (ambient temperature against outlet temperature) on side of the model pile without the use of Digital twin and real-time data integration. Trial Day 2 testing included recording of ambient temperature and ΔT and integration of a Digital twin to integrate real-time data in the testing.

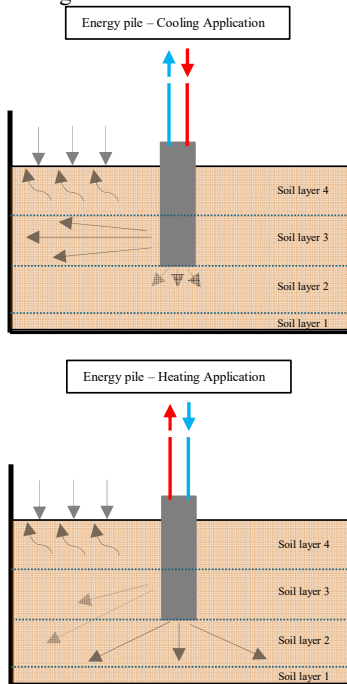


Figure 7. (a-b). Heat dissipation in (a) cooling and (b) heating

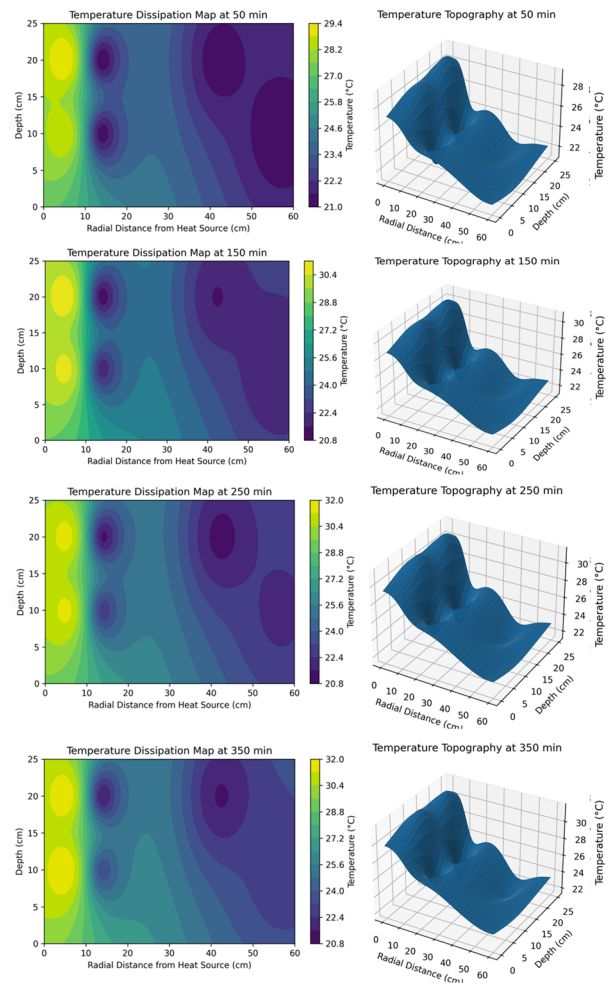


Figure 8. 2D and 3D temperature isopachytes maps demonstrating the spatial dissipation of heat from the model energy pile at monitoring points at different times since the start of the experiment (at 50mins, 150mins, 250mins and 350mins)

4 CONCLUSIONS

This study presented a experimental investigation into the thermal performance of energy piles in dry sand under climate controlled heating and cooling applications. A 1g laboratory scale model was designed with a robust instrumentation and monitoring informed by numerical modelling using COMSOL, to assess thermal behavior in various ‘zones’ of the pile–soil contact area. The key findings and their contributions are summarised as follows:

- Effect of ambient temperature: Initial calibration tests revealed that ambient room temperature in mechanically controlled environments can have an adverse impact on heat transfer in small-scale energy pile models. This effect can overshadow the thermal processes from the pile to soil due to the magnitude of the energy produced by each. Future experimental setups for energy pile testing should mitigate ambient influence or simulate real-world conditions more accurately to allow reliable interpretation of thermal data.
- “Thermal zoning” within the soil and design implications: the cooling tests confirmed the different thermal zones along the depth of the pile. These zones can be differentiated into three main zones. The upper third of the pile was heavily influenced by ambient temperature and showed limited thermal response to the inlet temperature.

The middle third of the model demonstrated as the primary zone for radial heat dissipation and transfer, showing consistent and stable temperature gradients. The lower third demonstrated limited heat exchange, indicating weak thermal interaction at depth. These observations suggest that in practice, thermal design of energy piles should focus on enhancing heat exchange in the middle depth range, potentially by introducing more efficient pipe configurations (e.g., spiral loops) in this zone. These findings can have significant implications and cost savings due to reduction in material, labour and construction programme if implemented in design of energy piles.

- A substantially distinctive temperature dissipation pattern was observed in the heating applications which would have diverse implications on system recovery in heating applications. A similar thermal zoning along the depth of the pile was observed. The upper third of the pile was again heavily affected by the ambient temperature. However, in contrast to cooling applications, where a radial heat dissipation pattern was observed, an inverted conical heat dissipation pattern was recorded, extending vertically downward from the middle depth of the pile. This finding highlights the potential for thermal recovery in deeper soil sections. For energy piles used primarily in cooling-dominant climates, this insight could inform strategies for thermal recharge and soil recovery during off-peak periods, consequently improving the long-term resilience and efficiency of the system by efficient recovery of the soil.
- Application of a real-time Digital Twin (DT) for adaptive thermal control: a digital twin approach, developed using MATLAB and COMSOL, was implemented to adjust the inlet fluid temperature based on real-time ambient readings. This model maintained a consistent temperature difference (ΔT) between inlet temperature and room conditions, significantly improving the stability and efficiency of the system. This demonstrates the viability of smart control systems for real-world geothermal installations, where environmental conditions vary seasonally and even daily. Incorporating such real-time feedback mechanisms could lead to more responsive and energy-efficient shallow energy geo-structures.

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