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Numerical analysis of the long-term performance of group energy piles with a recovery system

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ABSTRACT: Rapid population growth has driven urbanization to become one of the largest global energy consumers, significantly increasing energy demand and greenhouse gas emissions. These emissions, primarily from the combustion of fossil fuels, trap heat in the Earth's atmosphere, intensifying the global warming crisis and altering the Earth's climate. As a result, addressing the energy consumption of buildings has become a critical global priority, prompting the adoption of innovative strategies to enhance energy efficiency. Net Zero Energy Buildings (NZEBs) have emerged as a key solution, aiming to minimize energy consumption and carbon emissions. Supporting this effort, energy geo-structures, such as energy piles, harness shallow geothermal energy to provide a sustainable and efficient energy supply for buildings. Despite their global recognition, challenges persist, including their long-term performance and efficiency, as well as determining the optimal time for ground recovery. This study aims to assess their long-term performance under buildings' heating and cooling demands by developing a three-dimensional (3D) coupled thermo-hydro-mechanical modelling using COMSOL Multiphysics. Using the developed 3D coupled numerical model, the interactions between individual energy pile and their impact on the system's overall energy efficiency are examined. This study proposes methods on how to optimize/minimizing the ground recovery time in group energy pile systems. The findings will enhance the potential of energy piles as a sustainable and efficient building solution.

KEYWORDS: Energy Pile, Thermo-hydro-mechanical Investigation, Recovery System, Finite Element Method

1 INTRODUCTION

Rising population and energy demand have driven interest in shallow geothermal energy as a sustainable solution for building heating and cooling (Sadeghi et al., 2023). Geothermal energy piles are widely used geostructures that provide structural support while serving as a heat source or sink for ground source heat pump systems used in building heating and cooling (Sadeghi et al., 2024).

Numerous studies have examined the short-term behaviour of single energy piles under thermal loading, including full-scale field tests and laboratory investigations (Bourne-Webb et al., 2009, Faizal et al., 2016). These works revealed that cyclic temperature changes cause thermal stresses and affect shaft capacity and soil–pile interaction. However, most prior studies focus on individual piles and short-term responses, often overlooking the cumulative effects of repeated thermal cycles, energy imbalance, and interactions among multiple piles (Peng et al., 2018, Wang et al., 2015).

The sustainable use of shallow geothermal systems depends on maintaining a balance between heat extraction in winter and heat injection in summer (You et al., 2016). The energy exchanged through piles is largely influenced by the thermal and physical properties of the surrounding soil (Loveridge, 2012). Olgun et al. (2014) emphasized that seasonal demand significantly affects ground temperature, underscoring the importance of local climate conditions in energy pile design. In cold climates, ground source heat pump (GSHP) systems often extract more heat than they reinject, leading to thermal imbalance and progressive ground cooling over time (Saaly et al., 2019).

Abdelaziz et al. (2015) conducted long-term simulations for buildings in three cities, and it was shown that unbalanced thermal loads, whether heating- or cooling-dominated, can lead to continuous shifts in subsurface temperature. In heating-driven systems, the ground cools steadily, while in cooling-dominated regions, excess heat injection can cause subsurface temperatures to rise, reducing thermal efficiency (Beckers et al., 2018). When heating and cooling demands are not balanced, system performance may deteriorate over time, potentially leading to reduced heating capacity and operational challenges (You et al., 2020). To reduce long-term thermal imbalance from unbalanced heating or cooling loads, several strategies have been explored. Solar integration offers seasonal storage and offsets thermal drift (Naranjo-Mendoza et al., 2019), while structural enhancements like wider pipe spacing improve efficiency, albeit with higher costs (Xu et al., 2020). Intermittent operation and duty cycling support soil recovery and long-term performance (Cecinato et al., 2015). Both passive and active recovery methods have shown potential to maintain ground temperature stability and system efficiency (Faizal et al., 2016).

Although thermal recovery strategies for geothermal energy piles are recognized as critical for maintaining subsurface thermal balance and long-term efficiency, they remain insufficiently explored understanding of which operational methodologies are most effective for different pile–soil systems, and how recovery performance varies under continuous versus intermittent loading. This study addresses this gap by evaluating complementary recovery methods for heating-dominant energy pile systems. It involves a dedicated recovery loop that operates independently of the main heating-cooling cycle to regulate subsurface temperatures through controlled heat injection or extraction. A series of three-dimensional (3D) thermo-hydro-mechanical simulations is performed to investigate the impact of the proposed recovery system on system performance, in comparison to conventional continuous operation. The results provide practical insights for improving the long-term resilience and efficiency of energy pile systems.

2 NUMERICAL MODEL DEVELOPMENT AND VALIDATION

A 3D coupled thermo-hydro-mechanical finite element model of a single energy pile was developed in COMSOL Multiphysics to simulate the in-situ performance of a pile installed at Lambeth College, London (Bourne-Webb et al., 2009). The governing equations address the coupled mechanical and thermal behaviour of the energy pile system, including solid deformation (soil and pile), heat conduction and convection, and fluid flow through both the embedded pipe and the saturated soil. With the groundwater table assumed near the surface, the ground is modelled as a fully saturated porous medium. Ambient air temperature effects at the surface are excluded to focus solely on subsurface thermal interactions. The soil layers are treated as linear elastic materials (Kong et al., 2023). The concrete pile is modelled as an isotropic thermo-elastic solid with a U-shaped pipe embedded to transport non-isothermal fluid. The detailed mathematical formulations and numerical modelling approach are comprehensively described in the previous study by Shadabi et al. (2026).

2.1 *Field Data and Model Setup*

The numerical model was validated using data from a 23 m instrumented energy pile tested by Bourne-Webb et al. (2009). The pile was primarily embedded in London Clay, with upper sections passing through man-made fill and river terrace deposits, and the groundwater table located around 3 m deep. It had a tapered diameter, ranging from 610 mm above the clay to 550 mm within, and was designed for a 1200 kN load. Prior to the test, mechanical loading cycles up to 1800 kN were applied. The test included 31 days of cooling and 12 days of heating under combined thermal and mechanical loads, with free head movement.

A perfect bond between soil and pile is assumed, and the simulation includes volumetric strain, heat transfer (conduction and convection), and fluid flow governed by Darcy's law. The pile (0.6 m diameter) contains a 2 cm double U-pipe, and all boundaries are set at 19 °C to prevent thermal interference. Hydraulic conditions include zero pore pressure at the ground surface and no flow at other boundaries. The base is pinned, the sides roller-supported, and an axial load is applied at the pile head. Material properties used are presented in the references (Adinolfi et al., 2018, Gawecka et al., 2017)

2.2 *Validation Results*

The numerical model was validated against field test data by comparing temperature and displacement responses. Figure 1(a) shows the temperature variation at 0.5 m and 2 m radial distances from the pile over 43 days. The model closely matched the field measurements, particularly at 0.5 m, capturing the cooling trend from 20 °C to around 13 °C with an error margin within ±1 °C. At 2 m, temperature changes were more gradual, and the numerical results aligned well with the field data, confirming the model's ability to simulate heat transfer in the surrounding soil.

Figure 1(b) compares pile head displacement from both simulation and field tests. The numerical results accurately reproduced the initial settlement and subsequent movements during cooling and heating cycles, with deviations within ±1 mm. The model also captured the thermal rebound observed during the heating phase. These results confirm that the model reliably reflects the coupled thermo-mechanical behaviour of the energy pile under field conditions.

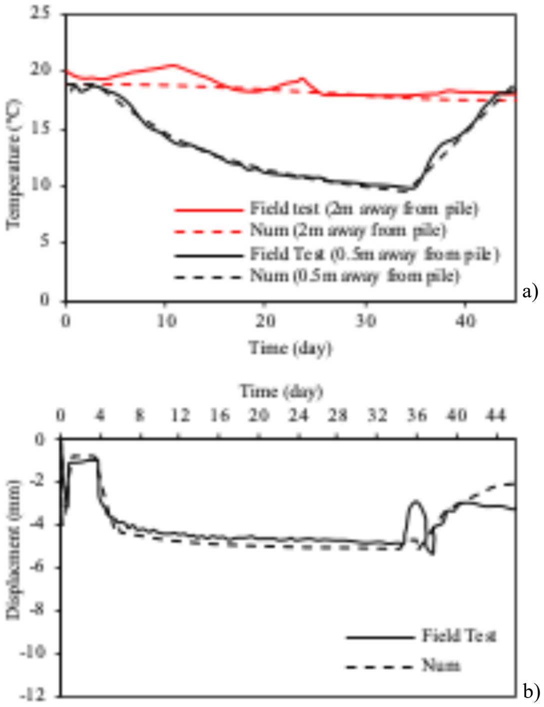

Figure 1. Comparison of the results of numerical simulation with Field test data: a) temperature changes 0.5m and 2 m away from the pile 10m below the surface, b) pile head displacement

3 MODEL DESCRIPTION

The validated Lambeth College model was used as a baseline to assess energy pile performance over one and five years. To address efficiency loss from continuous heating, the study evaluates a thermal recovery strategy, Ground Water Heat Exchangers (GWHE). To mitigate long-term thermal imbalance in energy pile systems, an additional U-shaped pipe is introduced as a dedicated recovery loop (Figure 2). This pipe circulates the same working fluid, typically water, but operates independently from the building's heating and cooling demands. Its purpose is to restore the thermal equilibrium of the piles and surrounding soil, which can be disrupted by a continuous heating operation that gradually lowers soil temperature, specifically in continuous operation mode.

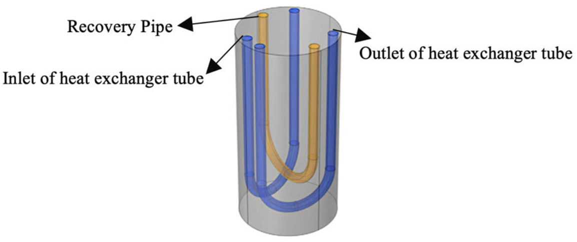

Figure 2. Pipe configuration and implementation of a U-shaped recovery pipe in the pile

The recovery loop functions passively: when the outlet water temperature from the energy pile drops below both the ambient air and the initial soil temperature, ambient-temperature water is circulated through the recovery pipe to transfer heat back into the ground. Based on 2024 London climate data, this condition is met from March to June, during which the Ground Water Heat Exchanger (GWHE) is activated to assist in rebalancing the system and maintaining long-term efficiency. A typical UK residential energy profile was applied, with heating required for eight months and cooling for four (Cui et al., 2018). Loads were scaled for a 1000 m² building. The model was expanded to a five-pile system: one central pile with four surrounding piles spaced over three diameters apart (Figure 3). All original assumptions and properties were retained to simulate realistic structural and thermal behaviour.

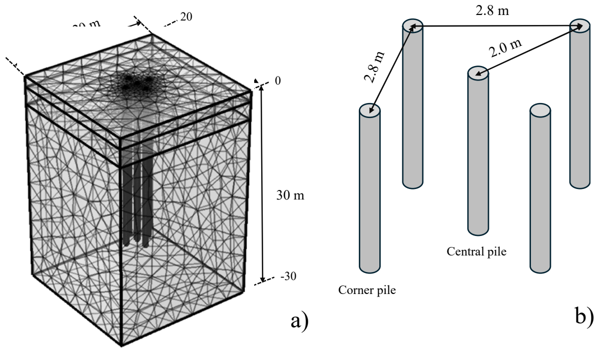

Figure 3. a) 3D geometry and meshing of the model; b) layout of the energy pile group

4 RESULT AND DISCUSSION

Figure 4 presents the inlet and outlet fluid temperature variations over five years (1800 days) for energy pile systems with and without the GWHE thermal recovery. In the case without recovery, the outlet temperature (solid blue line) fluctuates inlet temperature (dashed blue line) ranges from about 4 °C to 11.5 °C. Both curves show a gradual downward trend over time, annually between approximately 4.5 °C and 12.5 °C, while indicating thermal degradation due to continuous heat extraction and insufficient natural recovery. In contrast, the system with recovery (both dashed and solid black lines in Figure 4) maintains more stable temperatures. The outlet temperature (solid black line) remains within 6.5 °C to 13.5 °C, and the inlet temperature (dashed black line) ranges from around 6 °C to 12.5 °C. The inclusion of thermal recovery increases the minimum fluid temperatures by approximately 2 °C and helps sustain higher peak values throughout the simulation. This demonstrates the effectiveness of the recovery strategy in maintaining thermal equilibrium and improving long-term system performance.

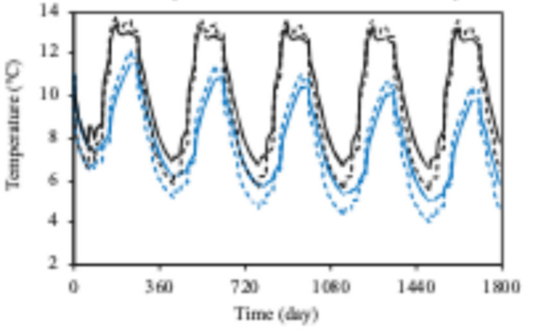

Figure 4. Inlet and outlet heat carrier fluid, both with and without a recovery system

Figure 5 shows the average vertical temperature distribution in the ground (from 0 m to −20 m depth) at the end of each year over a 5-year period, measured 0.5 m from the central pile. The initial soil temperature is shown as a vertical black line, highlighting the nearly uniform starting value of approximately 11 °C. For each year, two operating scenarios are plotted: solid lines represent conditions without thermal recovery, and dashed lines represent conditions with recovery. The yearly profiles are colour-coded from Year 1 to Year 5 (green, yellow, purple, blue, and red, respectively). In the first year, temperature changes are minimal in both scenarios, with values remaining close to the initial profile (around 8.86 °C with recovery and 8.42 °C without recovery), indicating that short-term operation does not yet lead to substantial thermal imbalance. As the operation continues, however, the no-recovery scenario shows a progressive leftward shift in the temperature curves, reflecting continuous cooling of the surrounding soil. By Year 3, these deviations become clearly visible, and by Years 4 and 5, the no-recovery profiles reach temperatures near 6.8 °C, demonstrating a significant loss of ground heat and reduced system efficiency.

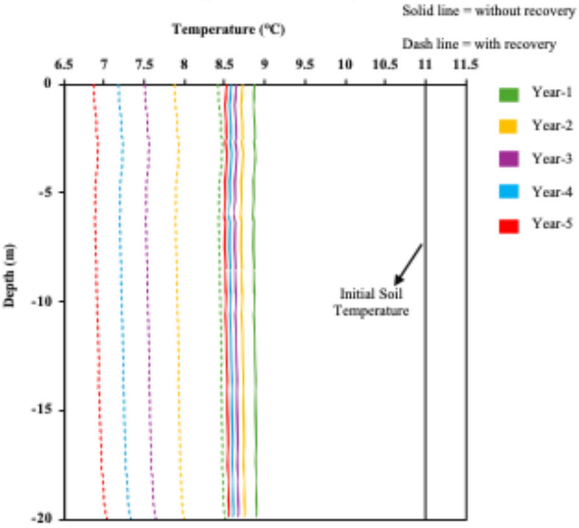

Figure 5. Temperature distribution of the soil profile (0.5 m from the central energy pile) at the end of each year over five years, comparing scenarios with and without the recovery system

In contrast, the recovery scenario maintains a comparatively stable thermal field. Even after five years, the temperature near the pile remains around 8.5 °C, showing only minor deviation from the earlier years. This stability results from the recovery process, which helps replenish subsurface heat during non-operational periods. The widening gap between the solid and dashed curves over time demonstrates that, whereas the no-recovery case experiences a cumulative cooling of more than 4 °C from the initial condition, the recovery scenario limits this drop to less than about 2.5 °C.

Figure 6 shows the radial soil temperature distribution at a depth of 10 m below ground, extending from the central energy pile to a distance of 20 m. At 20 m from the pile, temperatures remain close to the undisturbed ground value of 11 °C, indicating that thermal effects are highly localized. Closer to the pile, significant cooling occurs due to heat extraction. In the no-recovery case, the minimum temperature near the pile drops from about 7.3 °C in Year 1 to 6.4 °C in Year 3, reaching 5.7 °C by Year 5. This progressive decline demonstrates cumulative heat depletion in the surrounding soil. With thermal recovery, the cooling is noticeably reduced. Near-pile temperatures remain around 8 °C in Year 1, decrease to 7.8 °C by Year 3, and stabilize at 7.7 °C in Year 5. The total temperature reduction is less than 0.3 °C, compared to more than 1.5 °C without recovery in 5 years.

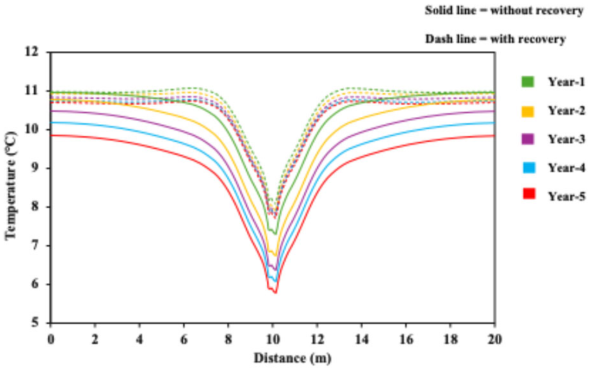

Figure 6. Radial soil temperature distribution at 10 m depth from the central energy pile over five years, comparing end-of-year temperatures for scenarios with and without thermal recovery

5 CONCLUSION

This study developed and validated a 3D coupled thermo-hydro-mechanical (THM) model to evaluate the long-term performance of group energy piles under heating-dominant conditions. A field-calibrated single-pile model was extended to simulate a five-pile group, incorporating a passive thermal recovery strategy using a Ground Water Heat Exchanger (GWHE). The numerical results showed that continuous operation without recovery leads to gradual subsurface temperature degradation, reduced fluid temperatures, and declining system efficiency. In contrast, the inclusion of a recovery loop significantly stabilized ground temperatures and improved energy pile performance over five years.

Temperature profiles and fluid temperature trends confirmed that the recovery system-maintained ground temperatures closer to initial conditions and raised inlet/outlet water temperatures by approximately 2 °C compared to the non-recovery case. These findings validate the effectiveness of passive recovery systems in mitigating long-term thermal imbalance, which is critical for the sustained operation of energy pile systems. Radial temperature analyses at 10 m depth further demonstrated that thermal disturbance remains concentrated near the pile, with more than 1.5 °C cooling over five years without recovery, compared to less than 0.3 °C when recovery is applied.

These findings highlight the effectiveness of passive recovery strategies in mitigating long-term thermal imbalance and improving system resilience. The proposed modelling framework provides practical guidance for sustainable energy pile design, and future work should investigate broader climatic conditions, alternative recovery options, and adaptive control integration.

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