Modélisation numérique pour l'étude de la rentabilité du stockage de chaleur dans le sol grâce aux géostructures énergétiques

Numerical modeling for studying the feasibility of heat storage in the ground using energy geostructures

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RESUME : Dans les applications classiques des géostructures énergétiques (telles que les pieux, les parois moulées ou les tunnels), la chaleur est transférée dans le sol puis extraite, à l'aide d'un fluide caloporteur, afin d'assurer le chauffage et le refroidissement des bâtiments. L'utilisation d'autres sources de chaleur, comme les technologies solaires, peut entraîner un déséquilibre entre la chaleur disponible et la demande énergétique, à cause des variations saisonnières de température. Dans de nombreux cas, cela se traduit par un surplus de chaleur produit en été et par une dépendance au réseau électrique en hiver. Le stockage de ce surplus de chaleur dans le sol grâce aux geostructures énergétiques constitue un domaine de recherche prometteur. Bien qu'il s'agisse d'une avancée majeure dans l'exploitation des géostructures énergétiques, une question centrale demeure : cette approche est-elle viable tout en prenant en compte : (1) l'influence des conditions du sol, (2) l'impact des variations de température sur les performances mécaniques de la géostructure, et (3) l'optimisation du profil thermique de charge/décharge ? Ces éléments sont essentiels pour évaluer la faisabilité et la rentabilité du procédé. Dans ce travail, ces trois aspects sont étudiés à l'aide d'une modélisation numérique réalisée avec le logiciel COMSOL Multiphysics, appliquée à un pieu énergétique. L'efficacité du stockage et de la restitution de chaleur est évaluée pour deux configurations : (1) un système traditionnel à double boucle en U, et (2) un système innovant à boucle en spirale, simple ou double. Cette étude contribue à améliorer la compréhension et l'efficacité du stockage de chaleur dans le sol, en couplant les geostructures énergétiques avec d'autres sources de chaleur renouvelables. À long terme, de telles innovations favorisent l'intégration accrue des énergies renouvelables dans les infrastructures bâties, participant ainsi activement contre le changement climatique.

ABSTRACT: In conventional applications of energy geostructures (such as piles, diaphragm walls, or tunnels), heat is transferred into the ground and then extracted using a heat transfer fluid to meet heating and cooling needs for buildings. The use of alternative heat sources, such as solar technologies, can lead to an imbalance between available heat and energy demand due to seasonal temperature variations. In many cases, this results in surplus heat production in the summer and reliance on the electrical grid in the winter. Storing this surplus heat in the ground using energy geostructures is a promising area of research. While this represents a major advancement in the use of energy geostructures, a key question remains: is this approach viable while taking into account: (1) the influence of soil conditions, (2) the impact of temperature variations on the geostructure's mechanical performance, and (3) the optimization of the heating/unloading thermal profile? These elements are essential for assessing the feasibility and profitability of the process. In this work, these three aspects are studied using numerical modeling with COMSOL Multiphysics software, applied to an energy pile. The efficiency of heat storage and release is evaluated for two configurations: (1) a traditional double U-loop system, and (2) an innovative single or double spiral loop system. This study contributes to improving the understanding and efficiency of heat storage in the ground by coupling energy geostructures with other renewable heat sources. In the long term, such innovations promote the increased integration of renewable energies into built infrastructure, thus actively contributing to the fight against climate change.

Mots-clés : Stockage de chaleur, géostructure énergétique, modélisation numérique multiphysique, analyse paramétrique.

1 INTRODUCTION

The typical geostructures, such as piles, diaphragm walls, and tunnels, become an energy geostructure when equipped with heat-exchanging tubes attached to the reinforcing steel cage, thereby becoming an integral part of the foundation structure upon concreting. Thereby, in addition to the load bearing and transfer to the sub-surface, they provide a means to exchange the heat from the ground. The usage of energy geostructures (EGs) for heat storage in the ground (as a thermal battery) has the potential to provide a means to balance the demand and supply upon their integration in the fifth-generation district heating and cooling (5G-DHC) system. Some previous work, for instance, by Rotta Loria (2021), presented the potential of heat storage through Energy tunnels. Despite being a promising advancement in the EGs usage, *e.g.*, for the district level heating/cooling, as reported by Aresti et al. (2024), the feasibility aspect of the heat storage to use the integrated ground in the grid as a thermal battery has not been prominently explored.

A comprehensive study considering: (1) the effect of ground conditions (soil type, groundwater flow, water table etc.), (2) the influence of temperature variation on the mechanical performance of the geostructure, and (3) the optimisation of charging/discharging temperature profile, are of interest attempting to answer the posed question on the feasibility of the heat storage.

The heat exchange potential of the ground shall play a key role in controlling the feasibility of heat storage. Here, the previous work by Di Donna et al. (2021) provides a systematic means to explore the influence of ground conditions on storage potential through their numerical investigation on the energy diaphragm wall. The work reported by Behbehani & McCartney (2022), on numerical investigation on the energy pile groups, presents insights into the influence of the soil saturation level on the storage potential. The case study reported by Bosch et al. (2024) on energy pile performance assessment in hot climates through numerical modelling, emphasise its potential for the decarbonised energy supply in buildings.

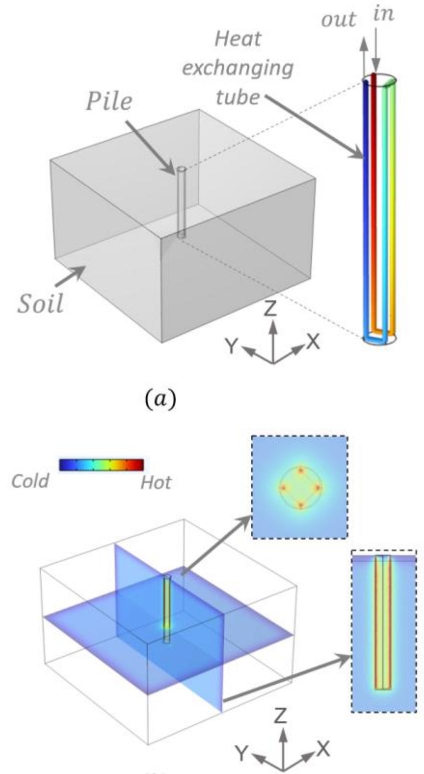
Furthermore, the influence of the changing ground temperature on the geotechnical resistance of the soil is also an important aspect to consider. Here, some previous works, *e.g.*, Nguyen et al. (2017) and Di Donna & Lahoui (2014), provide insights on the exploration of coupled thermo-mechanical behaviour through their reported numerical and experimental work, respectively, on the energy piles. Detailed exploration of the mechanical response influence, such as numerically explored by Dupay et al. (2014) for the seasonal heat storage through energy piles, shall enable assigning an upper limit on the heat storage irrespective of whether the full storage potential is exploited or not!

Moreover, a site-specific closed-loop system to monitor the stored energy levels as per the corresponding thermal potential shall enable the efficient planning of charging/discharging cycles. Subsequently, the integration of multiple such systems in the grid has the potential to further support the efficient use of the thermal battery by exchanging the excess available energy and extra required energy.

In this work, a numerical investigation of different configurations of the heating tube inside an energy pile is presented towards the exploration of the heat storage feasibility. A specific ground condition is examined, and a mid-range temperature profile for the injected fluid is used to limit the influence of the temperature variation on the mechanical performance of the pile. The reduced external variability enables the focused investigation of different heating tube configurations.

2 NUMERICAL MODEL

The numerical modelling of the underlying multiphysics processes in the energy pile is carried out using COMSOL Multiphysics ©. A concept numerical model is developed to study the heat storage potential, presented in Figure 1.



(*a*)

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Figure 1. Illustration of the numerical model of an energy pile system (a) layout and (b) pile-soil heat transfer through heat carrier fluid flow in the heat exchanging tube

Here, the reinforcement steel cage is equipped with a heat-exchanging tube (typically of HDPE – high density polyethylene) before concreting. A double U-loop tube layout is typically used. A heat carrier fluid (HCF), normally water, is circulated through the tube to enable heat transfer between the geostructure and the embedding soil for dissipation/extraction purposes.

2.1 Model definition

The evolution of pile-soil heat transfer is explored to assess the storage feasibility. The constituent geometrical parameters are listed in Table 1.

Table 1. Input physical parameters for the pile embedded in soil and equipped with the heating tube

Pile	**Magnitude**	**Unit**
Outer diameter (D)	0.5	m
Embedded length (L_e)	12	m
Concrete cover (h)	4	cm
Soil	**Magnitude**	**Unit**
Domain width (L_{xy})	30D	m
Domain height (L_z)	1.5L_e	m
Heat Exchange Tube	**Magnitude**	**Unit**
Diameter (d)	18.1	mm
Thickness (w)	1.9	mm
Shortest pitch of loop (α)	12.5	cm

Here, the soil domain is selected wide enough to restrict the potential boundary effects. The bottom surface of the soil domain is thermally insulated, and the open flow is assigned for far vertical boundaries. Pile geometry is considered with reference to the typically deployed in the field. The thermal properties of soil and pile materials are listed in Table 2.

Table 2. Thermal properties of the model constituents

Parameter	**Soil**	**Concrete**	**Unit**
Thermal conductivity (λ)	2.5	1.8	W/(m K)
Density (ρ)	2.0	2.3	t/m^3
Heat capacity (c_p)	900	880	J/(kg K)

Here, pile and soil are considered constituted from concrete and marly sandstone materials, respectively. Thermal conductivity of the HDPE tube is assigned 0.35 W/(m K) following its technical specifications. The heat transfer is modelled purely conductive, per the energy conservation equation:

$$\lambda \nabla^2 T = \rho c_p \, {}^{\partial T}\!/_{\partial t} \qquad (1)$$

where, ∇^2 represents the Laplacian operator, T is the temperature field, and t is time.

The heat carrier fluid (HCF) is circulated through the heating tube to enable heat transfer between the pile and the surrounding soil. The stored and extracted thermal power ($\dot{Q}$) through this process is determined through the following equation:

$$\dot{Q} = \dot{m} c_p \left(T_{in} - T_{out}\right) \qquad (2)$$

where, $\dot{m}$ is the mass flow rate, T_{in} and T_{out} are the mean inlet and outlet fluid temperatures, respectively.

The numerical modelling process for the convective heat transfer is carried out in three phases: initialisation, storage and extraction.

The initialisation phase aims to simulate the history of heat transfer through the top surface of the soil domain through seasonal ambient temperature variation. In the present model, two-years history is assigned with mean temperature variation at monthly resolution, presented in Figure 2.

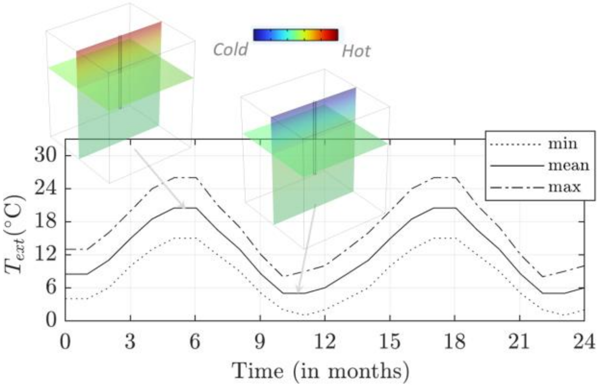

Figure 2. Monthly ambient temperature variation considered starting from March (as month zero)

The minimum and maximum trends of the ambient temperature are presented for completeness, and the mean temperature trend is applied to the model top surface, as also illustrated by a few instances of the temperature field in the soil.

Following this, the heat storage phase is simulated by circulating 45°C HCF through heating tubes for 21 days, as presented in Figure 3. Notably, the temperature colour ranges are inserted differently for storage and extraction phases for a better illustration.

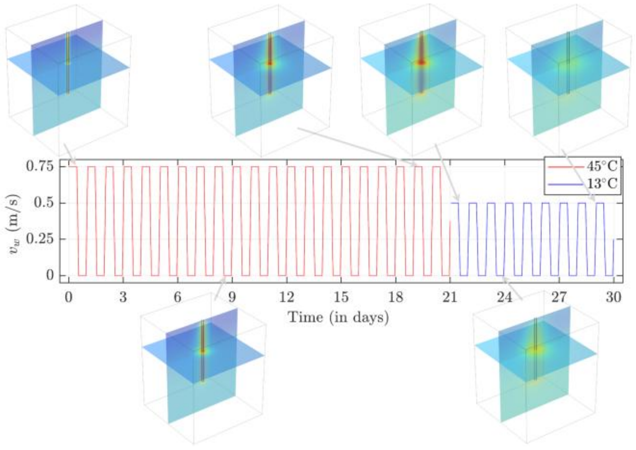

Figure 3. Injected and extracted fluid temperatures during the storage and extraction phases respectively

Here, the circulating fluid is injected for a half-day period at 0.75m/s velocity, followed by a half-day of stop. Presented temperature field instances illustrate the heat transfer between pile and soil.

Further, from 21 to 30 days, the stored heat extraction phase is carried out. For this, a fluid of 13°C is circulated through the tube at 0.5m/s velocity. A few instances of the temperature field demonstrate this exchange. Here, a lower velocity for the cold fluid circulation is chosen to enable relatively more time for stored heat accumulation from the ground during the extraction phase.

2.2 Heat tube configurations

The heat storage feasibility is assessed through the ability of the circulating fluid to efficiently exchange heat with the surrounding soil and retain the stored heat for a longer time period. Three heating tube configurations are simulated: U-loop, one helical loop and two helical loops, presented in Figure 4.

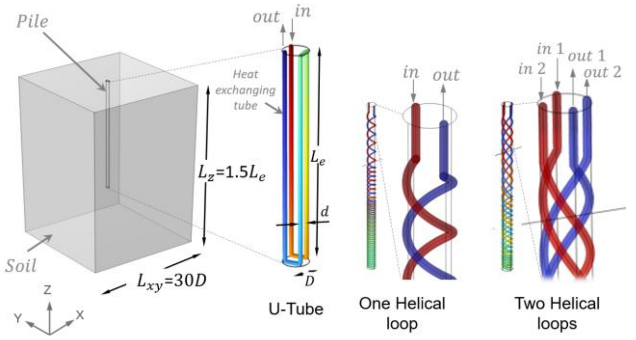

Figure 4. Energy pile with three different heating tube systems (1) U-tube loop, (2) one helical loop and (3) two helical loops

The helical loop enables an increase in the length of the heat tube for the given surface area of the pile curvature and subsequently presents comparatively higher thermal exchange with the surrounding soil compared to a U-loop. The helical loop pitch is varied from 2α for the bottom half of the pile length, 4α for the middle part and 8α for the remaining top part. Here, α is the shortest vertical distance between two segments. This configuration is selected with reference to the relatively stable temperature in the soil from 5m depth onwards. Hence, a denser helical loop allows for a relatively stable heat exchange undeterred by the fluctuating surface temperature.

In addition, the helical loop enables the incorporation of the return loop at an offset with the going loop without direct contact between the two and hence no direct influence on heat exchange. Consequently, the minimum distance between ongoing and return loops is retained at α.

Similarly, the two helical loop system is implemented as an extension to the one-loop system, where another set of going and return loops is implemented at a 90° rotational offset to the first loop. Here, the pitch of both loops is doubled to assimilate both, such that the same α is retained. The two-loop system is chosen to enable the possibility of running storage and extraction phases simultaneously, which is not possible with the other two configurations.

3 RESULTS AND DISCUSSIONS

The thermal phase simulations are carried out for the three configurations for comparative assessment of the heat transfer with the surrounding soil. Notably, the mechanical phase is not implemented in the presented simulations. It is to reduce the variability of the system for the initial assessment of the storage feasibility.

3.1 Storage phase

The comparative assessment of the 21-day storage phase, as per the inlet temperature and circulation velocity profile from Figure 3, is carried out for the soil temperature (T_{soil}) evolution along the pile vertical length and laterally at different depths. For the two-loop system, both inlets are used for the storage. A vertical line segment at a lateral distance of x_1 = 0.1m from the pile curvature is observed for evolving temperature with time, as presented in Figure 5.

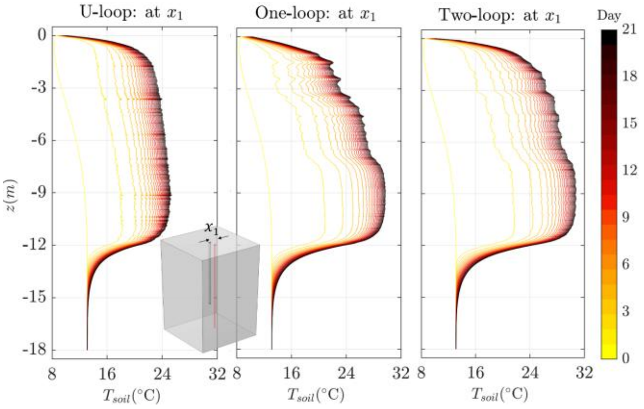

Figure 5. Evolution of the soil temperature during the storage phase of 21 days along a vertical line at x_1 offset from pile length curvature.

Here, a significant difference in the temperature gains up to 6°C in the soil is observed from the U-loop to the helical loop systems for the same inlet temperature of the injected HCF. The influence of the varying surface temperature is observed in all three profiles for up to 1.5m. Notably, the presented storage phase corresponds to the soil surface temperature of 8.5°C (start of the month zero, as per Figure 2), hence, the depth of influence of surface temperature on storage profile shall vary for different seasons.

Further, the influence of varying helical loop pitch over the pile length is also observed through visible steps in the evolving temperature profile. Lastly, the relative rate of daily temperature gain is observed to reduce over each passing day. This enables the definition of criteria to optimise the storage time duration for efficient temperature gain in the soil. In practical applications, the duration will also be influenced by the variability in the hot fluid production source due to the seasonal variation.

Similarly, the lateral evolution of temperature in the soil (and in the pile), is observed through the three-line segments at varying depths, presented in Figure 6.

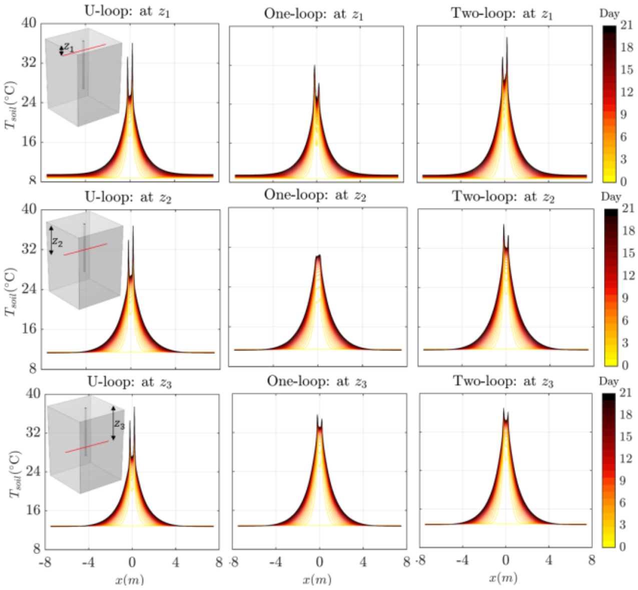

Figure 6. Evolution of the soil temperature along the pile lateral length at three depth levels during 21-day storage.

Here, three depth levels (z_1, z_2, z_3) are selected at the midpoint of the pile segments obtained by dividing the pile length into three segments. The first depth level (z_1) presents the influence of the external temperature on the evolution of heat accumulation in the soil during the storage phase. This influence is observed to reduce with depth as the bottom depth level (z_3) presents nearly no influence. The sharp peaks in the middle of the line (close to $x = 0$) present the temperature very close to the heating tube position. The slightly shorter left peak at all three depth levels for U-loop reflects the temperature close to the returning part of the loop, being lower than the going part due to fluid heat loss during circulation.

The increasing peak temperatures with depth for one and two-loop systems present the corresponding effect of the increasing density of the helical loops with depth. The highest relative gain in the soil temperature is observed for the two-loop system when compared with the one-loop system, which has a higher relative gain than the U-loop system. In addition, similar to vertical line observation, the rate of daily soil temperature gain reduces with time. Lastly, in all cases, the temperature change towards the boundaries is observed to reduce close to zero. It affirms that the soil domain width is appropriate to enable negligible boundary effects on the temperature field. Also, the influence of the surface temperature variation at higher depths is indirectly observed to be negligible towards the bottom depth levels.

3.2 Extraction phase

Following the heat storage for 21 days, the extraction phase is simulated upto 30 days in total. Here, the objective is to assess the heat retention capability of the ground and also the quantity of extractable energy post storage. For this, the HCF is injected at 13°C (equal to soil domain reference temperature) to isolate the amount of heat energy retrived post storage. The extraction phase soil temperature variations between days 22 and 30 are presented in Figure 7 and 8 (along vertical and lateral lines, respectively) for all three heating tube configurations.

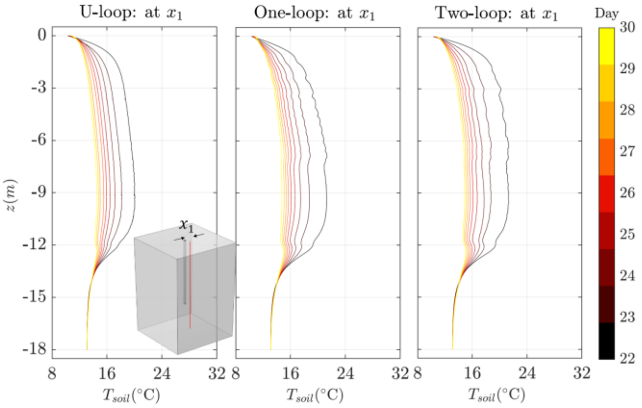

Figure 7. Evolution of the soil temperature along the energy pile vertical depth line during the extraction phase of 9 days.

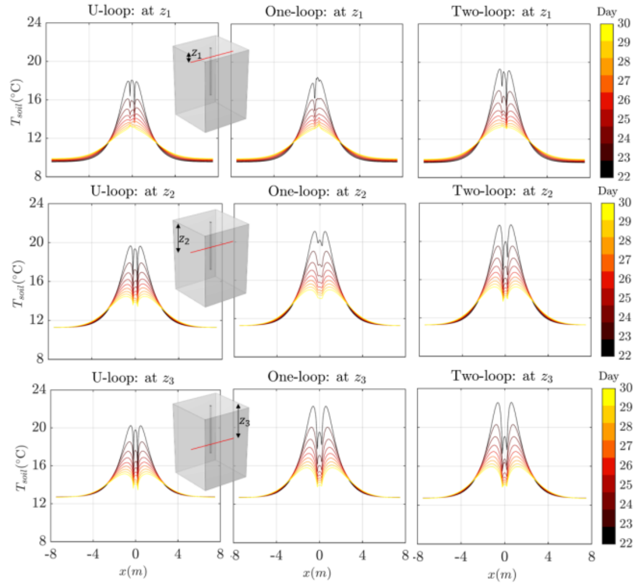

Figure 8. Evolution of the soil temperature along the pile lateral length at three depth levels during 9-day extraction.

Here, both loops in the two-loop system are used for the heat extraction. The overall qualitative trend is observed to be similar for all three configurations. The ambient temperature around the pile reduces close to the reference soil temperature of 13°C at the end of the 30th day. Moreover, the two-loop system presents a relatively higher amount of heat extraction in the first 2-3 days of extraction. Overall, a 2:1 ratio for the time duration of storage and extraction cycle is deemed plausible for the initial cycle. As this monthly cycle repeats with time, the soil temperature will continue to evolve slowly from its initial reference value to a slightly higher one, supporting the intended usage of the ground as a thermal battery.

From Figure 8, the influence of the surface temperature variation remains evidently visible in the initial depth. The effect of a dense heating tube network in a helical loop system near the pile bottom is observed through relatively higher soil temperature during the initial days of heat extraction. The top depth level (z_1) presents a nearly similar quantitative trends for peak temperatures close to the pile. Also, similar to the storage phase assessement, negligible boundary effect is observed.

3.3 Outlet temperature evolution

The time evolution of the HCF temperature recorded at the outlet (T_{out}) for all three heating tube configurations is presented in Figure 9.

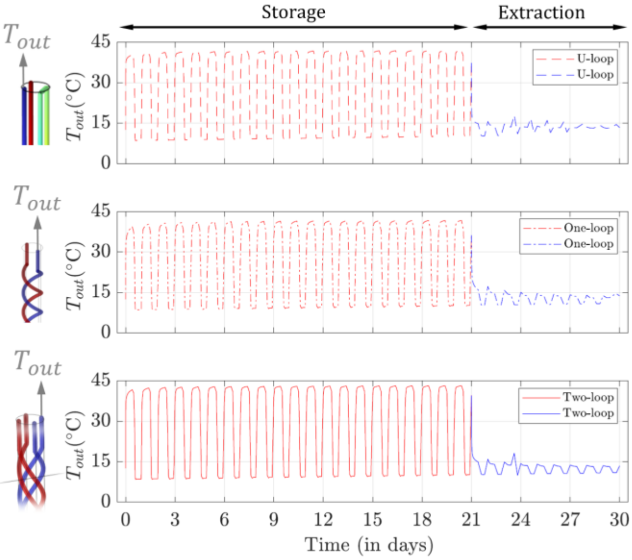

Figure 9. Evolution of HCF temperature at the heating tube outlet during the storage and extraction phases

The outlet temperature evolution is observed to follow the same pattern as the inlet temperature reassuring the continuity in HCF flow in the heating tube. The peak outlet temperature for the daily storage cycle is observed to increase with time, inferring the relative decrease in heat transfer to the ground with each cycle due to an increase in ambient soil temperature. One-loop and U-loop systems present nearly the same quantitative trends for storage, suggesting that the increased length of the tube does not significantly reduce the circulating fluid temperature. A similar observation can be drawn for a two-loop system. Notably, the peak T_{out} for the two-loop system is observed to be higher than for other systems. This is because, here, the trend for only one (out of two) is presented for better readability. It only accounts for half of the total contribution to the heat transfer from two loops.

The extraction phase trend is observed to be nearly the same for all three configurations except for the initial days of extraction. It supports the observation made from the evolving temperature profiles in the soil. The relatively lower T_{out} for one-loop compared to U-loop at the end of 30 days indicates the additional heat loss due to transfer to relatively colder soil in the top depth levels favoured by longer tube length.

3.4 Radial heat flux quantification

The soil temperature evolution for the storage and extraction phases is globally quantified at the mid-pile depth. A radial ring with a diameter of 5D is chosen as representative of the soil domain to present relatively steady average temperature evolution uninfluenced by the fluctuations due to surface temperature variation and due to the proximity with the heating tube. This evolution trend for storage and extraction phases for all three configurations is presented in Figure 10.

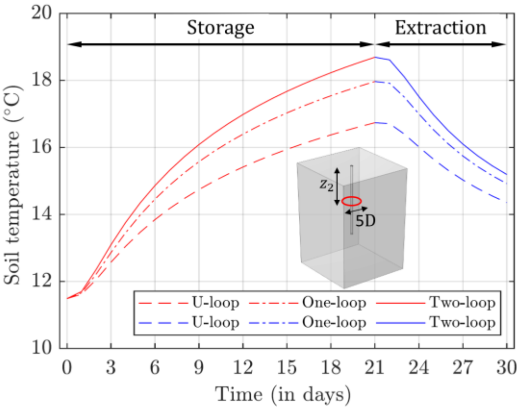

Figure 10. Evolution of soil temperature at a 5D radial distance from the pile center

Here, the global trends of rise and fall in soil temperature for storage and extraction phases, respectively, is analysed. The helical loop systems presents relatively higher temperature gain compared to the traditionally used U-loop system. The two helical loop systems presented a nearly similar trajectory. The soil temperature at the end of the monthly cycle is observed about 1°C higher for the helical loop system compared to the U-loop system. A relatively faster heat depletion is observed for the two-loop system. Overall, a similar level of heat retention capability is observed for all three configurations. The two-loop system enables relatively the highest energy storage and extraction given the similar duration and ground conditions for all three configurations.

3.5 Simultanous storage/extraction

The possibility of independent circulations in two intertwined loops in a two-loop system is explored to assess the heat storage and extraction potential.

Here, the 21-day storage phase is followed exactly as presented in Section 3.1, where both loops are used to circulate 45°C hot HCF through the heating tube and retrieved at both outlets. Following this, one loop is used to extract heat from the ground by circulating 13°C cold HCF while the other continues the storage phase beyond 21 days. The time evolution of soil temperature for the extraction phase period is presented in Figure 11 for vertical and lateral lines.

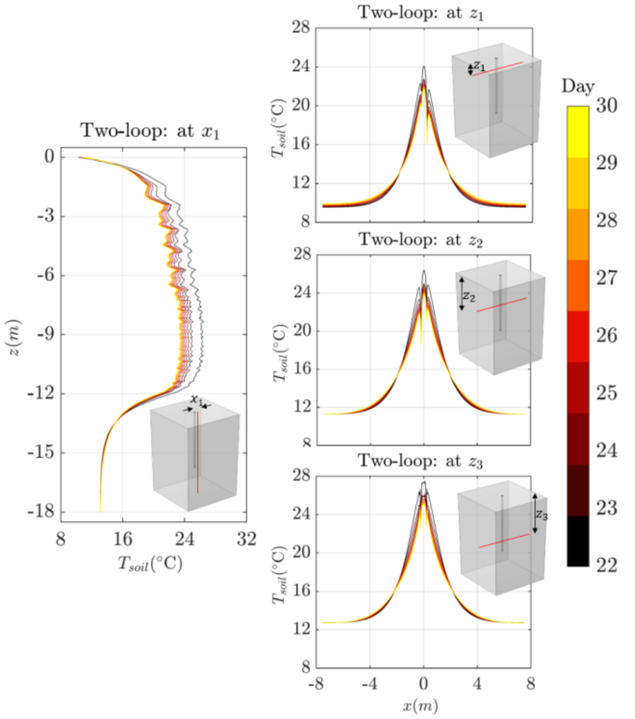

Figure 11. Evolution of the soil temperature along the energy pile vertical depth and at three lateral length levels during the extraction phase of 9 days for two loop system when one is operating in charging phase and other in the extraction phase.

Here, overall higher temperature magnitudes for up to 4°C are observed at the beginning of the extraction phase. A very low temperature depletion for subsequent days of extraction is observed both through vertical and lateral line segments.

Further, the evolutions of the HCF and the soil temperatures in the *5D* lateral ring are estimated, as presented in Figure 12. It is compared with the phase where both loops are engaged for heat extraction. A significantly higher magnitude of extracted T_{out} is observed for the loop circulating cold fluid. Also, a significantly lower rate of heat depletion is observed in the extraction phase through the lateral ring.

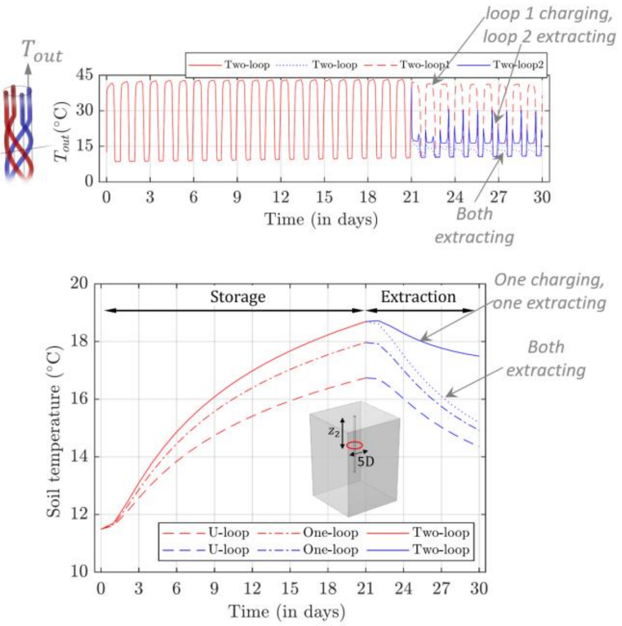

Figure 12. Evolution of outlet water temperature (top) and soil temperature at a 5D radial distance from the pile center for both storage and extraction phases for two-loop system when one is operating in charging phase and other in the extraction phase (bottom).

Thereby, the two-loop system is reported to present a better-stored heat retention capability in the soil when its independent HCF circulation capability is utilised for parallel storage and extraction. This is particularly useful when multiple heat transfers are aspired through multiple sources. For instance, during a typical summer day, the heat retrieval from an indoor unit for cooling application shall be a source of excess heat to store in the ground. In addition, if a solar panel unit is installed in the building, the energy generated shall be an additional source of excess heat to store.

Similarly, for the extraction phase, both loops engaged for extraction can collectively provide sufficient energy to meet the indoor heating requirements during winter. As per the simulation outcomes, the continuous extraction is not deemed long-time sustainable solution. One charging and another discharging, although it is deemed a long-term sustained solution. A sunny day in winter shall enable the continuous storage through one loop while the other engages in the extraction phase to meet the daily heating requirements.

Further exploration of the two-loop system on a different input temperature range constitutes future work. Here, the effect of temperature variation on the mechanical performance of the pile-soil interaction shall also be explored. Also, the effect of groundwater level and its flow shall also be explored for the influence of soil condition on heat exchange performance.

4 CONCLUSIONS

The present work is a numerical modelling exploration of an energy pile to assess the sub-surface heat storage feasibility. Three heating tube configurations, namely U-loop, one-loop and two-loop, are simulated to circulate a heat carrier fluid (HCF) with a monthly cycle comprising 21 days of heat storage followed by 9 days of heat extraction. The HCF circulation is activated for half a day, followed by half a day of relaxation.

The time evolution of heat transfer is monitored in the soil volume and through the HCF temperature at the outlet. The two-loop system is reported as a preferred configuration due to relatively high magnitudes of heat storage and extraction. The independent circulation and higher stored heat retention, enabled by the parallel storage and extraction phases execution also favours this system.

The additional variabilities for different injected temperature profiles, their effect on the mechanical performance of the pile-soil interaction and the consideration for the effect of soil conditions shall be explored in future work on the two-loop configuration.

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