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Performance of energy piles foundation in hot-dominated climate: A case study in Dubai

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A B S T R A C T

Energy piles represent an innovative technology that can help provide sustainable geothermal heating or cooling energy for thermal conditioning purposes. In hot-dominated climates, the interest is to inject heat in the ground and extract energy for space-cooling purposes. This study evaluates the feasibility of energy piles in these regions through three-dimensional numerical modelling. The modelling framework is validated against a published experiment and is able to sufficiently capture the development of outlet temperature over time. The numerical analysis is then used to evaluate a case study in Dubai where it is targeted to provide 40 % of the cooling demand of a typical building. The unbalanced energy demand causes an increase in the outlet temperature of the heat carrier fluid and the radial temperature over time. However, observation of long-term behaviour indicates that the temperature increase is most significant in the initial years and gradually stabilizes over time. This stabilization enables to respect the outlet temperature limitation of the heat pump over 50 years. A sensitivity analysis confirms these observations with respect to system dimensioning variables. The obtained results highlight the effectiveness of energy piles to decarbonize energy supply in buildings in hot-dominated climates via the use of renewable energy sources.

1. Introduction

One of the challenges of the 21st century is providing energy for a growing world population. At the same time, emissions of greenhouse gasses and the dependency on fossil fuels have to be reduced and therefore, it is important to focus on the role that sustainable energy sources can play. Especially the building sector is one of the large emitters of greenhouse gases [1], with thermal conditioning of space being an important contributor, and should therefore increase its effort to reduce its impact on the climate. For hot-dominated climates, space cooling is often a large contributor to the total residential energy use due to the high air temperatures. The use of energy for space cooling is also the fastest-growing electricity demand in buildings worldwide today and it is predicted that this energy demand for space cooling will more than triple by 2050 [2]. An example of a region where this is a large contributor is Dubai, UAE, where space cooling represents approximately 50–60 % of residential energy use [3]. On top of this, the more than doubling of CO_2 emissions from the United Arab Emirates in the latest 30 years further highlights the need for sustainable energy sources in these regions [4].

Shallow geothermal energy systems are an innovative technology that targets the use of a sustainable energy source. Through these systems, heating or cooling energy is extracted from the shallow part of the Earth’s crust. Ground-embedded structures that enable the extraction of this energy source through thermally activating them, are called energy geostructures. An energy pile is a type of energy geostructures, where a conventional foundation pile is geothermally activated by integrating a ground heat exchange element. Energy piles have been the main focus of the energy geostructures evaluated in literature in the last three decades and have shown highly adequate performance in their applications (e.g. Ref. [5–7]).

Most of the energy piles research has focused on using this innovative technology for extracting energy for heating. Numerous case studies in the literature have been presented, analysing the extent to which energy piles can fulfil the energy demands (e.g., Ref. [5,8]). This extent should in general be evaluated on a case-by-case base, depending on the energy needs of the building and its available number of piles.

Less focus has been on the implementation of energy geostructures in hot-dominated areas, where these geostructures can be used to inject heat and extract cooling energy, thus contributing to sustainable cooling

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of space in these regions. One of the related topics that has been explored for energy piles in hot-dominated regions is the impact of the unbalanced thermal load on the system. This leads to an increase in soil and pile temperatures over time, which impacts the efficiency of the system [8–12]. Alshehri et al. [13] labelled this as one of the key challenges for working with ground source heat pump (GSHP) systems in hot climates. The impact of the increasing temperature on thermo-mechanical aspects has mostly been explored for clay soils [11,14,15]. A last explored topic in this framework is the influence of unsaturated ground conditions. These conditions can cause a reduction in efficiency of energy piles with reported values up to 40 % [16–18]. However, there is insufficient information available regarding the use of energy piles in arid regions over the long-term, and their viability has not been extensively studied.

The unbalanced thermal loading of energy piles in hot-dominated climates is an important aspect to consider for these applications. Having an unbalanced thermal load can lead to an increase in soil and pile temperatures over time which then leads to a decrease in the efficiency of the system in the long term [9]. Olgun et al. [11] found that the extent of the increase in ground temperature is closely linked to the seasonal energy demand of the area where energy piles are located. This highlights the significance of this factor when considering the use of energy piles in regions with varying climatic conditions. Akrouch et al. [10] evaluated the use of energy piles in hot-dominated climates through a full-scale case study in Texas, USA, where both heating and cooling where applied, with the cooling load predominating. The results from this case study were then exploited in an economic study on the implementation of energy piles in hot-dominated climates and the study showed that a payback period of approximately 13 years could be obtained in hot-dominated climates where energy piles are used mainly for cooling energy extraction. This is therefore higher than the 2–10 years usually expected in temperate areas [5,19]. However, these assessments were based on the duct storage model and thus based on a simplified approach, stated by the author himself, who notes the need for further advanced finite element analysis to confirm these observations.

Neither of these studies investigated the utilization of energy piles for cooling purposes only, and they were specifically focused on the implementation of energy piles in Texas, USA. Therefore, there is no available research on the potential impact of energy piles for cooling-only use in different locations. At the same time, it is expected that the profile of energy needs for only cooling extraction is not necessarily similar to the one of heating extraction. There is a difference in the time profile of heat injection or heat extraction, which needs to be studied case by case. For hot-dominated climates as targeted in this study, there is a necessity for cooling all the year while in contrast heating is not often needed all the year, usually there is some recovery period included. This leads to the necessity to further examine cooling operation in more detail.

To further improve the knowledge about this innovative technology, the goal of this study is to explore the feasibility and long-term energy performance of extracting cooling energy with energy piles in hot-dominated climates. This is done through 3D time-dependent numerical modelling simulating the use of a reverse heat pump while considering a representative energy demand and soil temperatures for Dubai, thus looking at system operating conditions for an arid region. The work uses the operational limit of the heat pump as a representative functioning limitation [5,6,10,13] for the case study evaluations in hot-dominated climates. The applied modelling framework and verification of this approach with the experimental study of Akrouch et al. [10] are first presented after which the study will focus on the evaluation of a case study in Dubai, UAE which target to meet 40 % of the thermal loads of a building, to implement energy piles for space cooling purposes.

2. Methodology and mathematical formulation

The functioning of energy piles in cooling-dominated regions can be evaluated by looking at their energy performance and their impact on the surrounding environment. A modelling framework that includes heat transfer in solids and in the geothermal pipes is used in this study to simulate these components through numerical modelling. Heat transfer in solids is used to evaluate the heat transfer in the soil, by means of an equivalent thermal conductivity to represent the soil as a solid medium, in the concrete of the energy pile and in the high-density polyethylene (HDPE) pipe walls. Similar frameworks have previously been used in the evaluation of energy geostructures and have proven to be effective to evaluate the behaviour of these structures (e.g. Ref. [6,20]).

For a situation without groundwater flow, heat transfer in the soil, concrete and pipe walls is assumed to be characterised only by conduction. The energy conservation equation for this is

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \bullet (\lambda \nabla T) = 0 \tag{1}$$

where ρ is the material density [kg/m^3], c_p is the specific heat capacity of the material [J/kg°C], T is the temperature [°C] and t is the time [s] and λ the thermal conductivity of the medium [W/m°C],

Both convection and conduction are considered for the heat carrier fluid (HCF) in the geothermal pipes. This is described by the energy conservation equation for an incompressible fluid, Eq. (2), which accounts for the variation of internal energy, convection and conduction, friction heat dissipation due to viscous shear and external heat exchange through the pipe wall,

$$\rho_f A_p c_f \frac{\partial T_f}{\partial t} + \rho_f A_p c_f \overline{v}_f \nabla T_f = \nabla \bullet A_p \left(\lambda_f \nabla T_f\right) + f_D \frac{\rho_f A_p}{2 d_h} \left|\overline{v}_f\right| \overline{v}_f^2 + q_{wall} \tag{2}$$

with ρ_f being the density of the fluid [kg/m^3], A_p the area of the pipe cross-section [m^2], c_f the specific heat capacity of the fluid at constant pressure [J/kg°C], T_f the fluid temperature [°C], $\overline{v}_f$ the fluid velocity [m/s], λ_f the thermal conductivity of the fluid [W/m°C], f_D the Darcy friction factor [−], which can be evaluated through the Churchill equation, and d_h the mean hydraulic diameter [m]. In this energy conservation equation, the term q_{wall} is a function of the temperature of the pipe wall T_s [°C] and the average temperature of the fluid $\overline{T}_f$ [°C], as expressed here,

$$q_{wall} = f\left(T_s, \overline{T}_f\right) \tag{3}$$

The temperature that is extracted by circulating the fluid in the energy piles is not equal to the temperature that is required to cover the cooling needs. For this purpose, the level of temperature needs to be reduced and a heat pump is used. The heat pump is simulated by relating the temperature of the inlet flow of the HCF, T_{in} [°C], to the power of the heat pump, P [W], according to Newton's Law of cooling,

$$T_{in} = T_{out} - \frac{P}{\rho_f c_f \dot{V}} \tag{4}$$

in which T_{out} is the temperature of the fluid at the outlet of the pipes [°C] and $\dot{V}$ is the volumetric flow rate of the fluid [m^3/s].

It is possible to simulate daily operation of the heat pump according to a specified energy demand. Heat extraction or injection is simulated until the energy extracted, which is calculated at every timestep in the model, is equal to the daily demand. At this point the reverse heat pump switches off and the extraction or injection is stopped. To simulate real operation conditions of the technology, fluid flow in the pipes is still continuing at 1/10th of the normal operating rate. This pattern is repeated for each individual day in the model simulations. In the current modelling framework this pattern is repeated every 24 h without specifying the exact time of day. When time-dependent air temperature boundary conditions are used in a modelling framework, the time of day becomes an important consideration to make sure the heat pump is on during the day time. This methodology has been previously applied successfully by Sutman et al. [8] and Ravera [21]. In practice, a reversed heat pump is used for cooling energy extraction that is characterised by the same principles as a regular heat pump [22].

A negative power or negative energy demand in this study is used to indicate extraction of cooling energy (heat injection). Positive values of these parameters indicate heat extraction in this study. The power of the heat pump and the daily energy demand are defined as

$$P(t) = P_{heat}(t) - P_{cool}(t) \tag{5}$$

$$E(t) = E_{heat}(t) - E_{cool}(t) \tag{6}$$

where P_{heat} is the heating power [W], P_{cool} is the cooling power [W], E_{heat} is the daily heating demand [kWh] and E_{cool} is the daily cooling demand [kWh]. All components can vary over time, specifying them per day or any larger time period.

3. Model verification

3.1. Experimental setup

A published experiment reported in Akrouch et al. [10] is used to validate the aforementioned modelling framework through which both heat extraction and injection can be simulated. The aspects of main interest of the experiment are briefly summarized here. Three piles with a length of 18 m and a diameter of 0.45 m were fitted with HDPE pipes in a single U-shaped loop. The pipes had 0.2 m between the centres of the loop legs. These energy piles are part of the foundation of the Liberal Arts Building at the Texas A&M University Campus, USA. The soil profile consisted of three clay layers and Akrouch et al. [10] evaluated soil samples from varying locations and depth to come to an estimation of average thermal properties of the site.

The pile group was tested according to a full-scale testing protocol over 400 h with intermittent modes of heating and cooling. Temperatures of the HCF at the inlet and outlet were measured during this operation using thermistors and the flow rate was measured with an installed flowmeter. All details of the experimental setup can be found in Akrouch et al. [10].

3.2. Numerical analysis

A 3D finite element model is created in COMSOL Multiphysics 5.6 [23] to simulate this experiment, which allows to describe the heat transfer processes occurring in the soil, concrete and pipes as described in section 2. The soil domain, three foundation piles and geothermal pipes embedded within them from the experiment of Akrouch et al. [10] are represented in this analysis. The three energy piles are located in the centre of the soil domain. Fig. 1 illustrates the initial and boundary conditions and the meshing that are used. The mesh adopted for the simulation is composed of 106988 tetrahedral elements, 1704 pyramids,

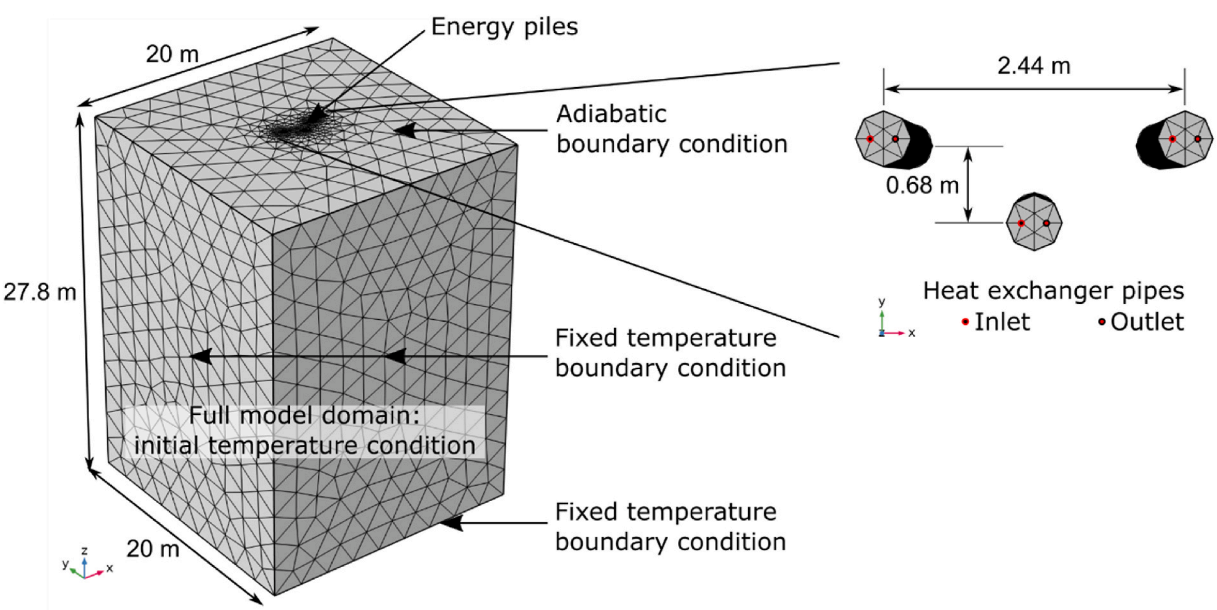

Fig. 1. 3D numerical model setup including applied boundary conditions and meshing to represent the published experiment of Akrouch et al. [10].

Table 1
Energy piles and soil characteristics in the numerical model.

Material	Thermal conductivity [W/(m·°C)]	Density [kg/m³]	Specific heat [J/(kg·°C)]
Ground	0.61	1368[a]	1970[a]
Reinforced concrete	2.30	2300	880
Pipe wall	0.42		
HCF (Water)	[b] $\lambda_{wat}(T)$	[c] $\rho_{wat}(T)$	[d] $c_{p_{wat}}(T)$

[a] *Average value from reported values* [24].

[b] $\lambda_{wat}(T) = -0.869083936 + 0.00894880345 \bullet T - 1.58366345E^{-5} \bullet T^2 + 7.97543259E^{-9} \bullet T^3$.

[c] $\rho_{wat}(T) = \begin{cases} -950.704055329848 + 18.9229382407066 \bullet T - 0.060367639882855 \bullet T^2 + 0.000063092789034 \bullet T^3, 0 < T < 20^\circ C \\ 432.257114008512 + 4.9692888332655160 \bullet T - 0.013395065634452 \bullet T^2 + 0.000010335053319 \bullet T^3, 20 < T < 100^\circ C \end{cases}$.

[d] $c_{p_{wat}}(T) = 12010.1471 - 80.4072879 \cdot T + 0.309866854 \cdot T^2 - 5.38186884E^{-4} \cdot T^3 + 3.62536437E^{-7} \cdot T^4$.

Table 2
Heat pump power over time for one energy pile in the experiment of Akrouch et al. [10].

		P_{inj} [kW]	P_{prod} [kW]
Time *[hrs]*	0–80	8/3	0
	80–145	0	0
	145–184	8/3	0
	184–220	0	0
	220–315	0	0
	315–318	0	8/3
	318–400	2/3	0

2982 prisms, 2218 triangles, 1704 quads and 1563 vertex and edge elements to model the pipes in the energy piles. The mesh density is higher in the area of the energy piles and coarser towards the model boundaries.

The soil domain is assumed to be homogeneous with a temperature of 19.6 °C, representative of the average air temperature at the location, initially imposed on the whole model domain. A fixed temperature boundary condition of the temperature being equal to this ground temperature is applied on the far field side and bottom boundary to represent the unimpacted far field situation. An adiabatic boundary condition is used at the surface, representing the scenario with an insulated surface representing the pile cap in the experiment. A value of 0.61 W/(m°C) was reported by Akrouch et al. [10] as the measured average thermal conductivity on the test site and for the thermal conductivity of the reinforced concrete, they indicated a value of 2.30 W/(m°C). Therefore, these values were used to represent respectively these materials and a constant thermal conductivity over the depth of this soil profile was used. The remaining test conditions are set up to represent the experimental setup and all are presented in Table 1.

The time pattern of heating and cooling and the respective heat pump power in the experiment from Akrouch et al. [10] are used as model input. This eliminates the need for the daily heat pump simulation, with a daily energy demand, but instead a prescribed functionality of the heat pump is used for this specific case. While the authors mention active cooling of the soil during three time periods, in this study natural cooling is simulated in the first and second cooling phases. Values used as input for the power over time for one energy pile are shown in Table 2.

Water was used as the heat carrier fluid in this published experiment. Since the three energy piles were in a parallel circuit, a flowrate of 648 cm^3/s is used for the circulating flow in each energy pile. This is one third of the total flowrate indicated in Akrouch et al. [10].

3.3. Comparison of experimental and numerical results

A comparison of the numerical results of average outlet temperature of the three piles with the experimental results from Akrouch et al. [10] is presented in Fig. 2. The HCF outlet temperatures measured and computed for this model validation case study are very high. The reported values in this experiment do not represent normal operation outlet temperatures for energy piles, but are part of an experiment designed to gather data for model calibration purposes [10].

Some differences between the modelling results and the experimental results are observed. At the end of the cooling extraction phases the outlet temperature of the HCF is overestimated compared to the experimental values, while at the end of the heat extraction period it is underestimated. The differences between the model results and the experimental results presents an average error of 13 %. Despite the significant magnitude differences, especially in the cooling extraction phases, the model is able to capture the observed pattern.

Several factors of the experiment that was performed are simplified in the numerical model, which can play a role in the differences

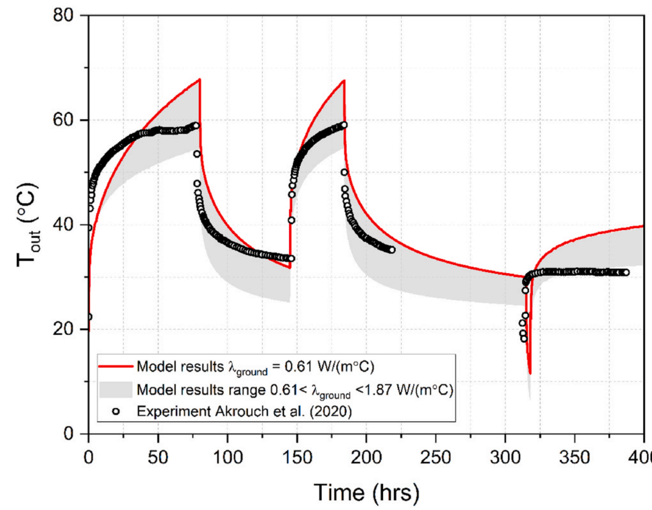

Fig. 2. Comparison of the outlet temperature of the HCF over time from the numerical simulations with the measured results from Akrouch et al. [10].

observed between the model and experimental results. In the numerical model, a uniform soil profile is used, with a constant density, thermal conductivity and initial temperature over the depth. In reality, there were different soil layers at the location of the energy piles, which causes a difference between the model simulations and reality. The study of Akrouch et al. [10] also suggests some uncertainty for the average thermal conductivity of the ground. To account for this potential source of error, the range of the model results using the suggested uncertainty in thermal conductivity for the ground is indicated in Fig. 2. Moreover, in the simulations, constant values of the heat pump power over the different time periods are used whereas the experimental data from Ref. [10] suggests some variability of these values over time.

It is concluded that both qualitatively and quantitatively the results of this simulation match with the pattern found by Akrouch et al. [10]. Overall, based on the performed simulations it is concluded that the developed numerical model is reasonably able to capture the behaviour of both heat injection and heat extraction. Thereby proving the suitability of the employed modelling approach to capture the behaviour of energy piles in real-world situations.

4. Model application

The modelling approach is then applied to a case study in an arid region, to evaluate the feasibility of energy piles in these regions. The target of this evaluation is to provide 40 % of the total cooling demand of a typical building in Dubai through its energy foundation. The main limitation of the energy piles performance considered in this case study is that the outlet temperature (T_{out}) of the heat carrier fluid has to remain within the capacity limits of the heat pump over its full lifetime. Alshehri et al. [13] also specified this parameter as the parameter that determines the applicability of GSHP systems in hot-dominated climates.

4.1. Case study Dubai details

A foundation for a private villa building with a built-up area of 975 m^2 in the coastal belt region of Dubai is envisaged with 33 concrete piles that are 20 m in length and have a diameter of 0.8 m. The geothermal use of this foundation is evaluated, where 18 m of the total pile length of each foundation pile is activated by installing geothermal pipes with a single U-shape pipe configuration. The pipe spacing is set as 0.53 m centre-to-centre.

The soil stratigraphy at the location of this building is characterized by a sandy soil with a variation in thermal conductivity over depth. This

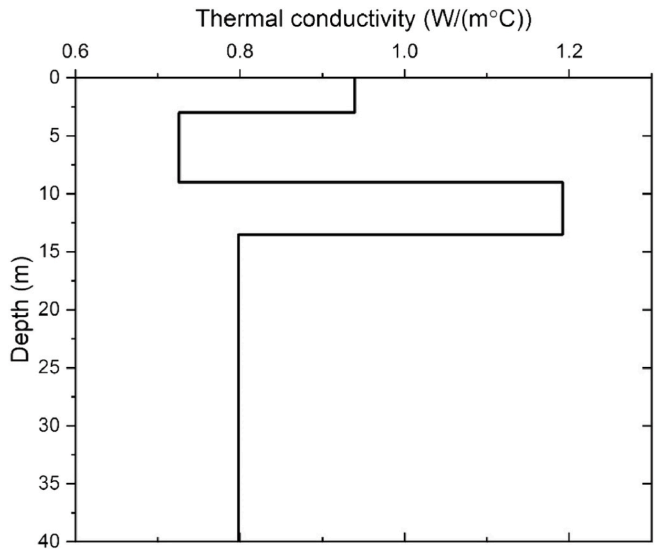

Fig. 3. Variation of the ground thermal conductivity over depth.

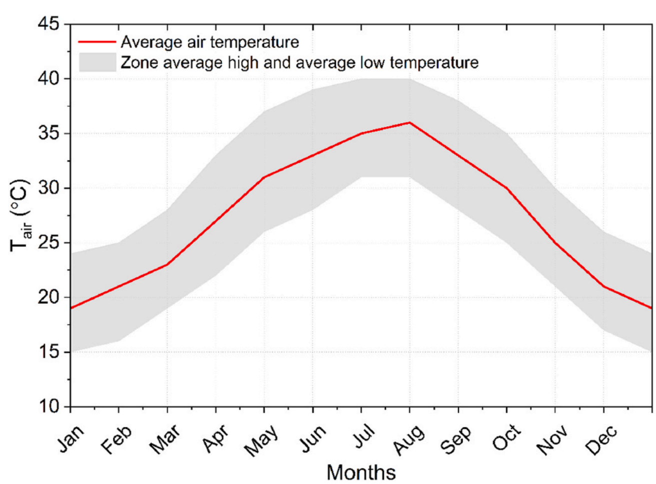

Fig. 4. Air temperature variation over a year, based on weather data from Dubai International Airport weather station.

variation is shown in Fig. 3. By including this representative profile over depth indirectly some effect of unsaturated behaviour is accounted for.

Due to the high air temperatures in Dubai (Fig. 4) there is a dominant cooling need for the case study. A representative cooling energy demand for the building is known. Using the assumption that 13 % of this demand can be compensated with hot water use as often used in typical countries of the Organization for Economic and Co-operation and Development (OECD) [25], the targeted 40 % of the cooling demand through its energy foundation is calculated, represented in Fig. 5A. This leads to the daily energy demand for one energy pile as in Fig. 5B, with a monthly variation of this value.

The highest daily cooling demand is found in the summer period (July–August) and in the winter period (December–January) the cooling demand is lowest. This profile highlights the unbalanced thermal load applied to the system, where cooling energy needs to be extracted all year and there is no time period with heat extraction or natural recovery which would allow thermal recovery of the soil in the long term.

The use of a Daikin RWEYQ-T reversed heat pump is envisaged for this case study. This heat pump has a cooling capacity of 0.68 kW per energy pile. The energy efficiency ratio (EER) of the heat pump is 5.07 and is taken as a constant in this study. The operation range of heat pump for inlet water temperatures is up to 45 °C. The maximum allowable outlet temperature of the heat carrier fluid is thus determined as 45 °C and is used as limitation in this analysis.

4.2. Numerical model

The long-term effect of having an unbalanced heating demand is evaluated using a 3D finite element model with one energy pile in COMSOL Multiphysics 5.6 [23] where the heat transfer processes occurring in the soil, concrete and the pipes are modelled as described in section 2. The backward differentiation formula (BDF) solver of COMSOL is used for this model with an adaptive time stepping scheme. Fig. 6 shows the initial and boundary conditions applied for this study. Fixed temperature boundary conditions are applied to the side and bottom boundaries of the model, where the temperature remains equal to the initial ground temperature. The initial ground temperature is taken as 30 °C based on the measured undisturbed ground temperature at the case study location, which also approximates the yearly average air temperature in Dubai and was used by Ghaith et al. [26] as a representative ground temperature for Dubai. A thermal insulation boundary condition is applied at the surface of the model, meaning there is no heat

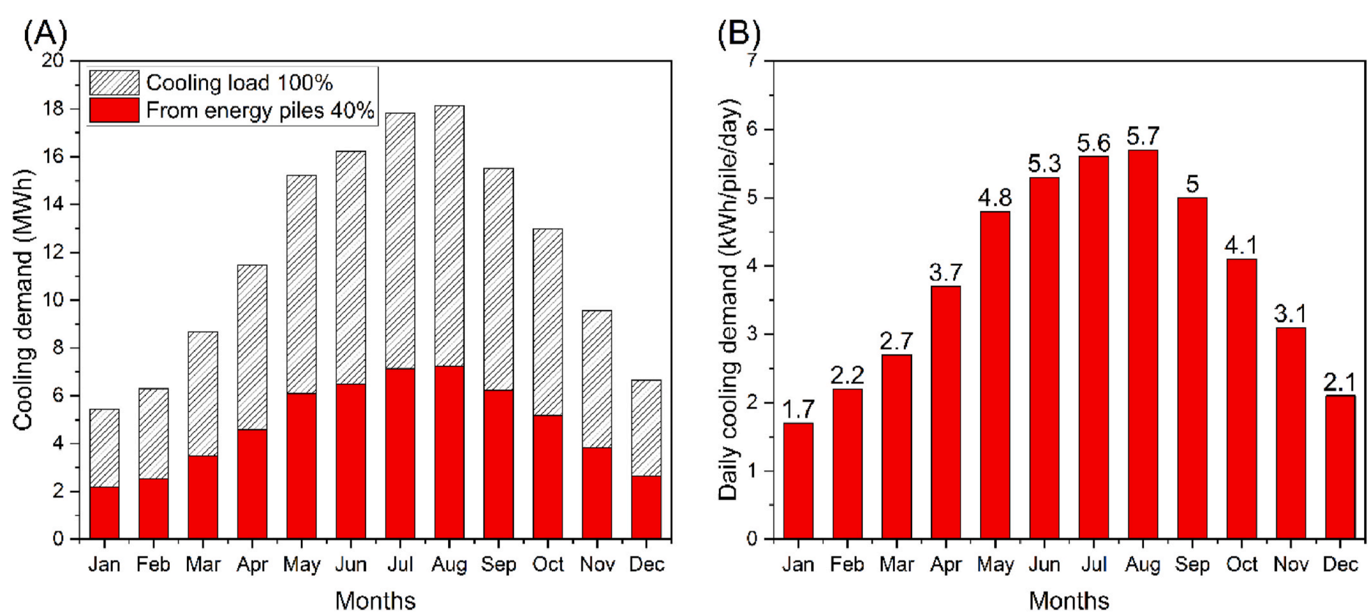

Fig. 5. (A) Total cooling load for the case study of a building in Dubai, with the targeted 40 % of its total cooling load through its energy foundation (B) The implemented daily cooling demand per energy pile for the case study.

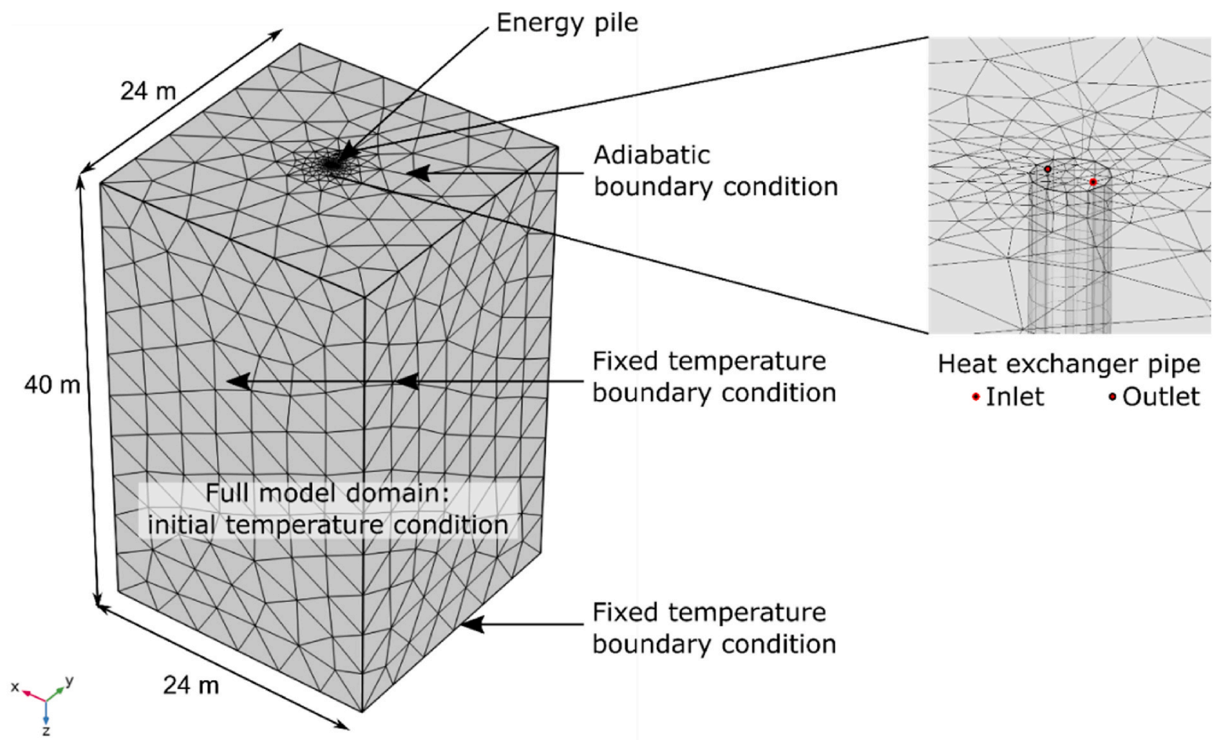

Fig. 6. 3D numerical model setup including applied initial and boundary conditions and meshing for one energy pile of the case study in Dubai.

Table 3
Model parameters used in the thermal analyses.

	Parameter	Value	Unit
HCF	Fluid	Water	
	Flow velocity	1.0	m/s
	Thermal conductivity	f(T)[b]	W/(m·°C)
	Density	f(T)[b]	kg/m^3
	Specific heat	f(T)[b]	J/(kg·°C)
Ground	Temperature	30	°C
	Thermal conductivity	Varying over depth[c]	W/(m·°C)
	Density	1537	kg/m^3
	Specific heat	961	J/(kg·°C)
Pipe	Inner diameter	25.4[a]	mm
	Surface roughness	0.0015	mm
	Wall thickness	3.25	mm
	Thermal conductivity	0.42	W/(m·°C)

[a] *Unless specified otherwise.*
[b] *Same functions as specified in Table 1.*
[c] *See Fig. 5.*

flux across this boundary. The mesh used for the computation is also shown in Fig. 6 and was composed of 39738 tetrahedral elements, 864 pyramids, 592 prisms, 1140 triangles, 864 quads and 592 edge and vertex elements to mesh the pipes in the energy pile.

Table 3 provides a summary of the model parameters used in the simulation. The model is capable of considering the real operation of the heat pump, by considering a daily cycle as previously explained in the modelling framework in section 2. In this framework where it is targeted to provide 40 % of the cooling demand using the energy foundation, this means that after the heat pump switches off, auxiliary means provide cooling for the building.

4.3. Results

The behaviour of the system is initially analysed for one year. Results in terms of temperature of the heat carrier fluid at the pipe outlet over time are presented in Fig. 7. On a daily basis, the temperature at the outlet of the geothermal pipes increases as the heat pump turns on and cooling energy is extracted. After the daily cooling demand is reached, the heat pump turns off and the outlet temperature decreases. The highest outlet temperatures are observed when there is the highest cooling demand, in the month of August. After August, a decrease in the outlet temperature can be seen. Due to the continued heat injection, the temperature does not come back to the initial value at the beginning of the year. An increase of the outlet temperature of 3.20 °C is found over a time period of one year, with the outlet temperature being 33.20 °C at the end of the year. The pattern shows that the strongest increase or decrease in the outlet temperature occurs at the start of each month, after which a slower increasing or decreasing trend can be seen. This is caused by the change of the energy demand at the start of each month. The outlet temperature remains within the limit of the maximum allowed temperature for the heat pump during the evaluated time period of one year, thus showing the potential for using energy piles to provide cooling energy but needs to be explored further on a longer time scale.

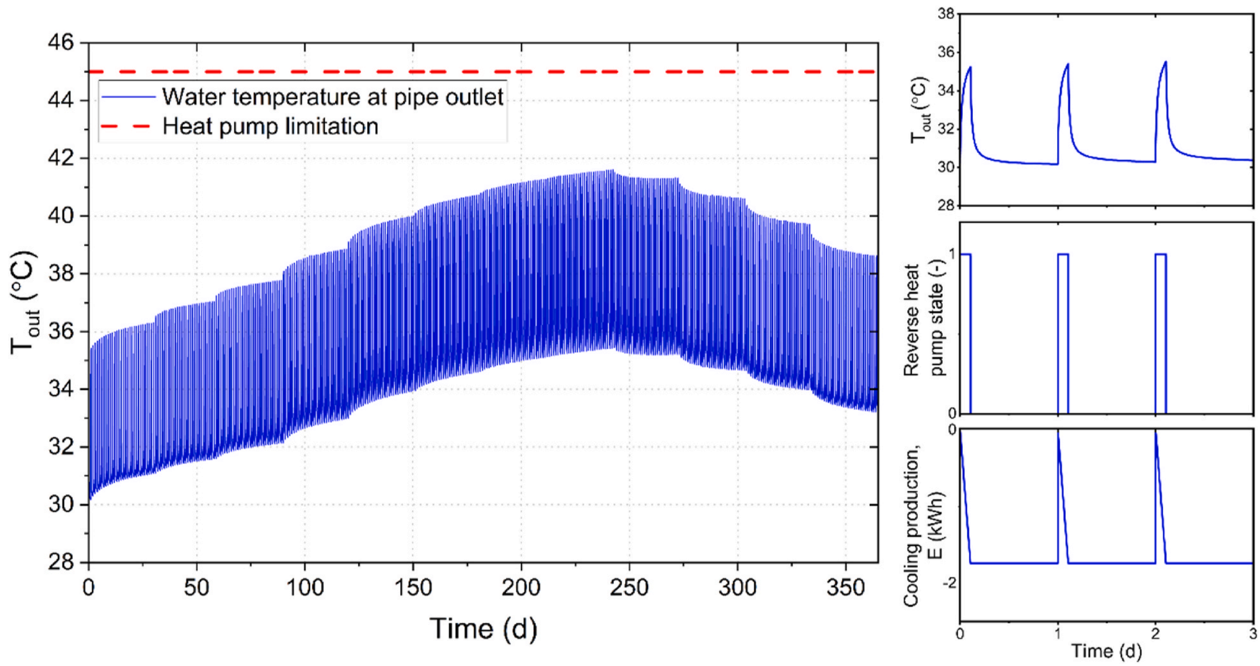

Fig. 7. (Left) One-year modelling results (Right) zoom in on the daily pattern for the first three days of the simulation.

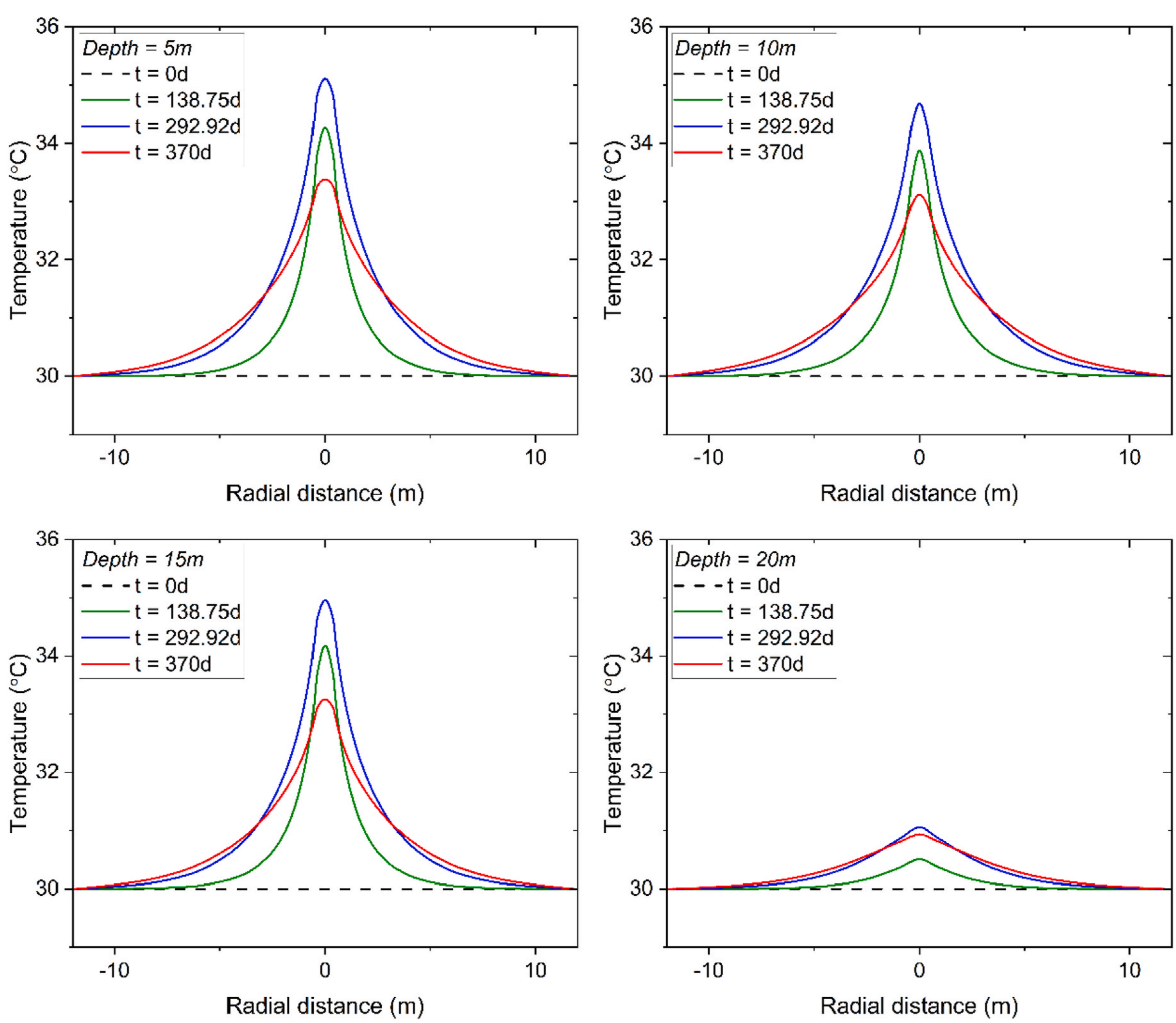

Fig. 8. Radial temperature distribution around the energy pile at different depths and moments in time.

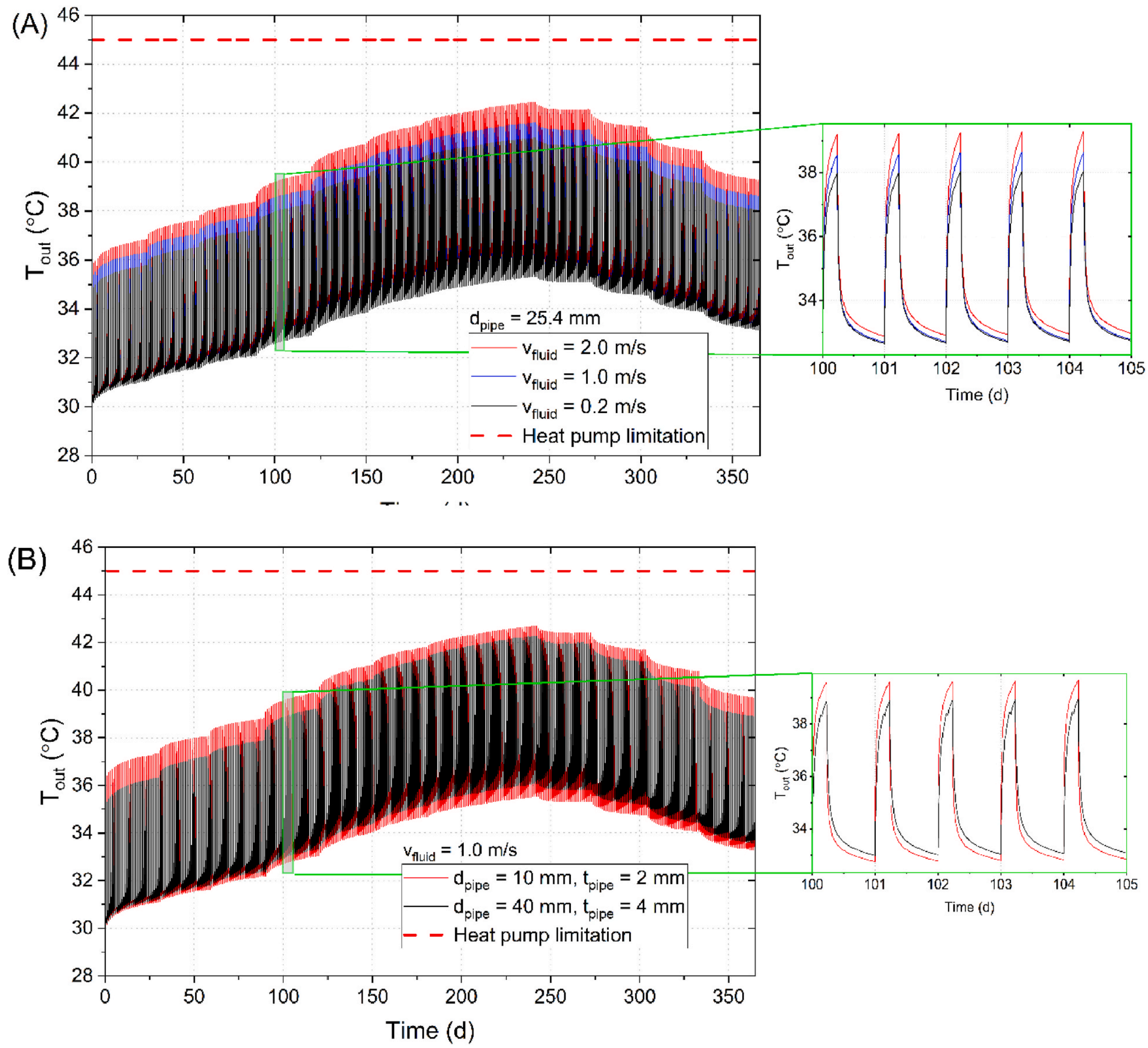

Fig. 9. Sensitivity analysis of (a) the fluid flow velocity and (b) pipe characteristics internal pipe diameter and wall thickness.

Another important aspect for the system to function sustainably over time is the influence that geothermal activation of the foundation has on the soil temperature surrounding the energy pile. To provide insight in this factor, Fig. 8 presents the radial temperature distribution at different depths and different moments in time, compared to the initial undisturbed ground temperature. The extraction of cooling energy through the use of the energy pile is increasing the soil temperature in a zone surrounding the energy pile. The highest temperatures are found at the position of the pile, with similar patterns over time at 5, 10- and 15-m depth. At a depth of 20 m, which resembles the bottom of the foundation pile, the increase in temperature is smaller than at the other positions, the reason for it being that in this cross section there are no pipes with the heat carrier fluid. The zone of influence, defined as where the temperature differs from the initial ground temperature of 30 °C, gets wider after a longer time period of cooling energy extraction. At the end of one year the diameter of the zone where the temperature increase is larger than 0.5 °C is approximately 12 m, which shows the influence the energy pile has on the ground temperature. It should thus be noted that when there is a pile spacing within this zone of influence, interaction effects have to be accounted for in the design of energy piles for cooling purposes. This effect becomes even more important on longer time scales.

4.3.1. Sensitivity analysis pipe diameter and HCF flow velocity

The one-year analysis is repeated for different heat carrier fluid flow velocities and internal pipe diameters characteristic of real applications with the objective of showing the possible range of variation in the results through these design parameters. The HDPE pipes used in energy piles commonly have a diameter range between 10 and 40 mm with a variation of the wall thickness between 2 and 4 mm [6] and for the fluid flow velocity in the pipes a range from 0.2 to 2.0 m/s is evaluated.

The influence of the two design parameters is shown in Fig. 9A and B. For the full range of fluid flow velocities between 0.2 m/s and 2.0 m/s, while using a pipe diameter of 25.4 mm with a wall thickness of 3.25 mm, the limitation of the heat pump in terms of outlet temperature is respected. Using a lower HCF flow velocity results in lower values of the outlet temperature compared to higher flow velocities. The heat pump limitation is also respected for the different pipe characteristics analysed, using a flow velocity of 1 m/s. Using a pipe diameter of 10 mm with a wall thickness of 2 mm leads to a larger amplitude in the daily outlet temperature variation compared to the pipe with an internal diameter of 40 mm and a wall thickness of 4 mm. Using a lower flow velocity or a wider internal pipe diameter both decrease the volumetric flow rate in the ground heat exchanger pipes, $\dot{V}$, and thus cause similar

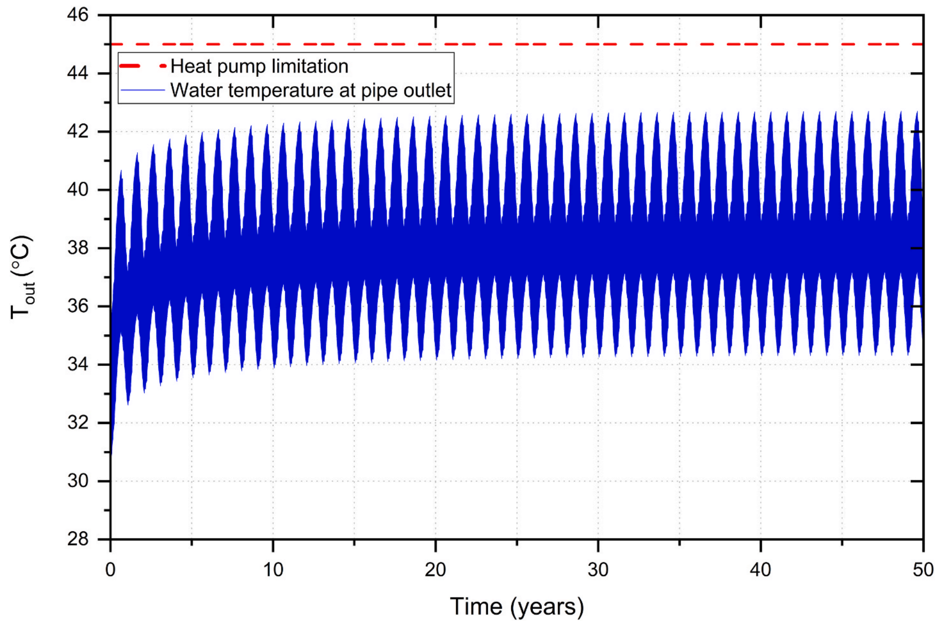

Fig. 10. Outlet heat carrier fluid temperature over a time period of 50 years.

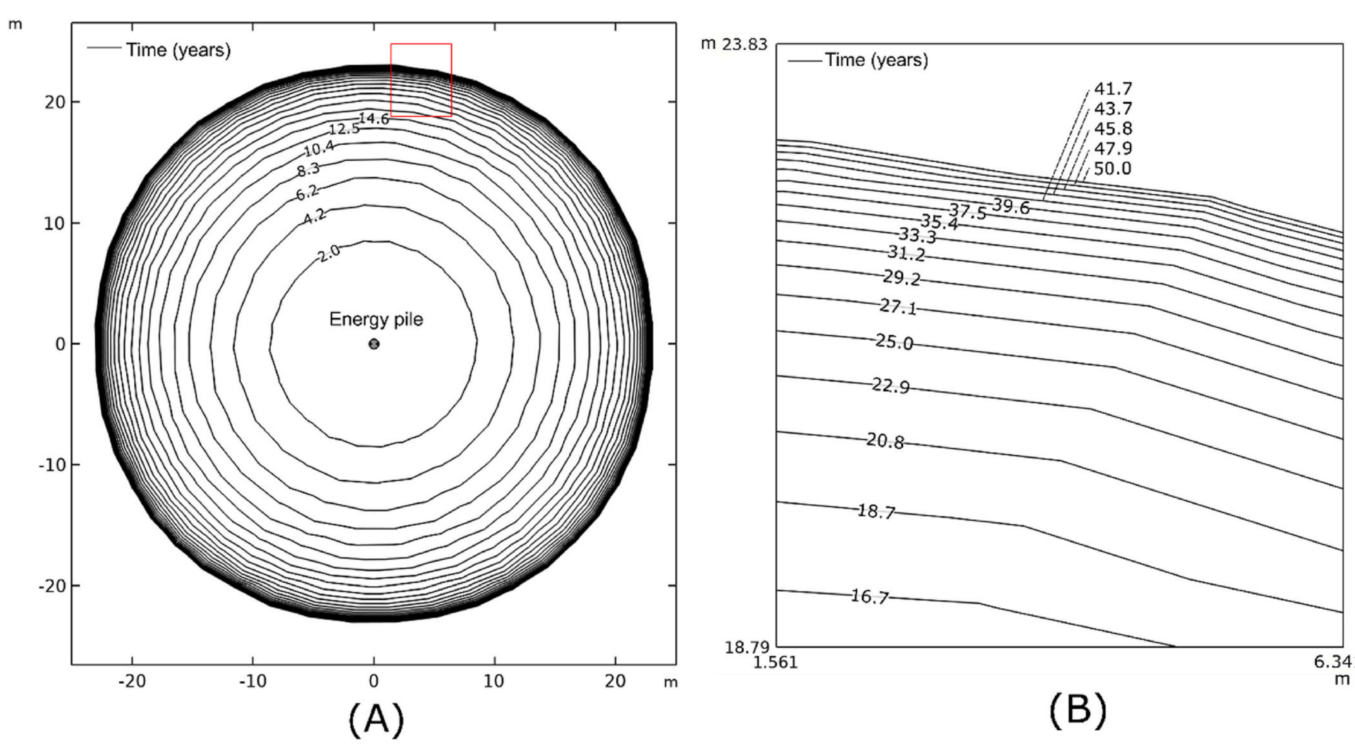

Fig. 11. (a) Top view of the energy pile with progression of the zone in which $\Delta T \geq 0.5$ °C over time. Contour lines indicate the time in years. (b) Zoomed view on section indicated in red in (a).

behaviour in the results, lowering the maximum outlet temperature obtained. It should be noted that altering the value of the flow velocity impacts the systems operating cost and optimization of this variable should be done considering pumping costs and limitations.

4.3.2. Long-term performance

For the case study evaluation over a longer time period, the heat pump power is imposed directly on the line elements in the model to simulate the functioning of the heat pump [20]. The soil domain in the numerical model is enlarged to avoid the influence of the boundary conditions on the solution during the long-term evaluation. The soil domain used for the long-term model analyses has a height of h = 2L, and widths of x, y = 80m. A mesh with 47093 elements is used in the computations.

The model is used to assess the system's energy performance over a 50-year period, and Fig. 10 illustrates how the outlet water temperature changed during this time. The strongest increase in outlet temperature is found in the first years of use of the energy pile. After this initial response, there is a lower rate of increase. A stabilizing trend of the temperature is observed in the long-term behaviour. The outlet

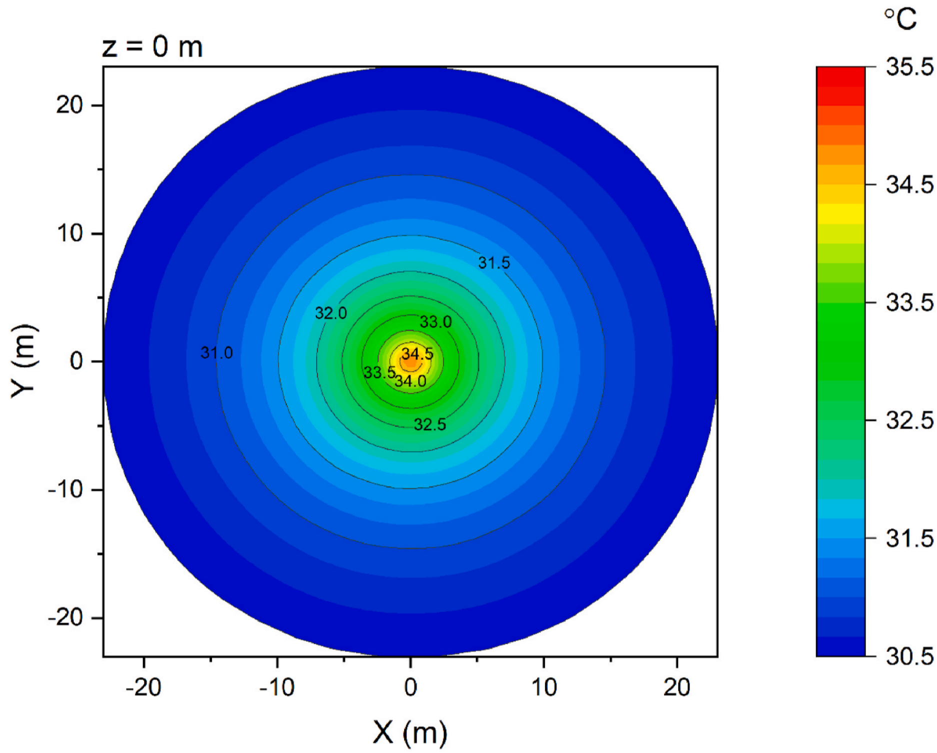

Fig. 12. Soil temperature distribution after 50 years of cooling energy extraction.

temperature remains within the capacity range of the heat pump over the full time period and thus the heat pump limitation is respected. It is, however, important to realize that influences of the internal pipe diameter and HCF flow velocity are not accounted for in this long-term performance.

The influence of long-term cooling energy extraction on the soil temperature around the energy pile is also evaluated. Fig. 11 shows the progression over time of the zone around the energy pile in which the temperature increase with respect to the initial soil temperature is higher than 0.5 °C. The figure shows that the radius of this zone around the energy pile increases with time and reaches a value of 23 m after 50 years of cooling energy extraction. The plot also shows a stabilizing trend in the expansion of this zone over time, with the contour lines lying closer together after a longer time period.

Fig. 12 presents the influence of 50 years of cooling energy extraction on the soil temperature distribution at the end of this time period, at the surface level. Temperatures near the energy pile are highest, around 35 °C and a lower temperature increase is found at a larger distance from the energy pile. The highest increase in soil temperature after 50 years over the whole domain is found at the pile-soil interface and is 6.1 °C at depth of 3.8–6.3 m on the sides where the pipes are located closest to the interface. Figs. 11 and 12 present further insight to the increase of soil temperatures surrounding the geothermally activated foundation pile, following 50 years of energy extraction, and provide insight into the scale at which the soil temperature is affected. This is an important factor to account for when calculating energy pile group interaction effects and is further discussed below in section 5.2.

5. Discussion on the case study results

It is essential to consider certain factors during the interpretation of the results presented in this study.

5.1. Model verification

The numerical model and the framework implemented in this study could only be validated based on one published experiment. The model is able to adequately capture the evolution of the outlet temperature over time. It is crucial to further validate the modelling approach with additional experimental data, and caution should be exercised in the interpretation of the results until this is accomplished.

5.2. Pile group effects

The results presented in section 4 are obtained by assessing only cooling extraction by one energy pile. For a building with a pile spacing wider than the zone of influence, it is thus shown that 40 % of the energy demand of this building can be provided through geothermally activating the foundation. However, for buildings with piles located closer to other piles also interaction effects due to pile group behaviour should be considered. A higher increase in soil temperature can be expected in zones where this zone of influence overlaps for different piles, due to their mutual influence at the same time. This will also influence the performance of the system. The effects of the thermal interference of piles on the performance of the system over one year is assessed for the presented case study according to an infinite pile group approach, similar to Ref. [27]. The effects were quantified to be within 10 % of outlet temperature increase at the end of the year for an infinite pile group with a spacing of 6.75 times the pile diameter, which means that the 40 % cooling energy can still be provided for this timeframe. A pile spacing of 6.75D (5.4 m) is possible for the available surface of the building considered in this case study. In other cases where this might not be feasible and a shorter spacing or grouped piles under a cap have to be implemented higher interaction effects and thus a larger increase in outlet temperature can be expected.

Akrouch et al. [10] suggested that management strategies to activate and non-activate groups of energy piles could improve the performance of the system while dealing with the unbalanced thermal load. Working with these activated and non-activated groups of piles will limit the influence of the interaction effect. However, working with these management strategies also means that higher cooling energy demands should be implemented for individual energy piles to still cover sufficient cooling energy extraction.

5.3. Groundwater flow and environmental limitations

Another component that is not included in this study is potential groundwater flow. Groundwater flow was not expected for the evaluated case study of Dubai and thus is not accounted for in this study. In regions with hot-dominated climates and groundwater flow, this is an important aspect to consider. When present, groundwater flow is expected to have a positive influence on the results through the cooling effect it has on the increasing soil temperatures around the energy pile.

These increasing soil temperatures can in some locations also be a limitation for the use of energy piles for cooling extraction purposes. Local environmental guidelines might pose a limitation of the maximum temperature disturbance that can be caused. The maximum allowable soil temperature limitation is likely determined by the location of implemented energy piles, as different ecosystems are capable of dealing with different temperature variations.

6. Conclusions

This paper presents an analysis of the long-term behaviour of cooling energy extraction with energy piles in Dubai with the goal to improve the understanding of using this technology in hot-dominated climates for space cooling purposes. After validating the modelling framework with a published experiment, a 3D numerical model is used to assess a case study in Dubai. It was targeted to provide 40 % of the cooling energy demand of a building through its energy foundation. Based on the results of this study the following conclusions are drawn.

- Due to the unbalanced energy demand for this case study an increase in heat carrier fluid and soil temperatures over time is found. This increase is highest in the first years of the analysed time period and the rate of increase slows down over time. Both these components show stabilization behaviour over time, thus suggesting the viable use of this technology even under these conditions.
- The numerical results based on an isolated energy pile suggest that for the analysed building 40 % of the total cooling demand can be provided with the energy piles foundation over a time period of at least 50 years. Within this time period, the limitation imposed by the heat pump functionality in terms of the heat carrier fluid temperature is respected.
- Overall, it can be concluded that there is potential for energy piles can help provide cooling energy in hot-dominated climates, where space cooling is often one of the main energy consumers. Limitations that should be considered in this evaluation are in terms of the inlet temperature to the heat pump or environmental restrictions in soil temperature.

CRediT authorship contribution statement

Sofie ten Bosch: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Elena Ravera:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Lyesse Laloui:** Conceptualization, Resources, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: the second author works at GEOEG – an engineering firm developing energy geostructures. The third author holds shares of GEOEG.

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