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Numerical modelling of geothermal piles in tropical environment: group effect on heat dissipation

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Abstract. In tropical countries, geothermal piles are foundation elements that, besides providing structural support, dissipate heat from the internal environment of buildings to the foundation soil. Since foundations are usually composed of pile groups, the interactions among piles should be investigated also from the thermal efficiency standpoint. This paper presents a numerical model of a 5-pile group to study the influence of number and position of thermo-active piles on the heat transfer of the geothermal system. The numerical model was developed with ANSYS FLUENT and was validated with results obtained by Almeida [1] in his numerical model for a single pile. Results indicated that the thermal influence radius does not increase linearly with the number of thermo-active piles and that, in the limit, a group of piles may thermally behave as single pile. This study showed the importance of simulating heat transfer on pile groups for the improvement of geothermal foundations design, since the activation of all piles may lessen the thermal performance of the group.

Keywords: Geothermal piles. Numerical Modeling. Group Effects.

1 Introduction

A system of geothermal piles, also called Ground Source Heat Pump (GSHP), consists of a fluid, usually water, that circulates through a closed circuit of tubes (usually HDPE - high density polyethylene) inserted inside a foundation pile, allowing thermal exchange between the interior of the building and the subsoil, which is used as a deposit/source of thermal energy to optimize the operation of the heat pump responsible for the building's climatization [1]. Therefore, this system accumulates structural and heat exchange functions [2]. The use of geothermal piles for heating systems is widely used in European countries with severe winters, and in tropical countries, this technology may be used to dissipate the thermal energy of buildings into the subsoil [1].

The technical and economic feasibility of a geothermal system can be based on the heat exchange efficiency of the piles, measured by the difference between entry and exit temperatures of the circulating fluid. That difference results from the amount of thermal energy transmitted from fluid to pile and from pile to soil, and it can be measured by a Thermal Response Test (TRT), the main *in situ* test to obtain the thermal parameters of the soil necessary to design a GSHP system [3].

To support the load of a superstructure, piles are often used in groups [4]. In the case of geothermal piles, such groups can be divided into two classes: groups with widely spaced piles, in which piles are distanced enough to consider the response of each pile independent and comparable to the single pile case; and narrow spacing pile groups, where piles are so close that their individual responses are influenced by the thermal loads of neighboring piles. These interactions are manifested through the so-called "group effects" [5].

Much research has been devoted to group effects from a structural standpoint, however thermal loads involve effects different from those caused by mechanical loads [6]. Theoretical models and experimental procedures have been developed to describe the heat conduction process between the soil and a single heat exchanger pile, however the literature does not provide much information regarding the quantitative assessment of thermal interference phenomena for narrow spacing pile groups their effects on the overall thermal efficiency of the system [7]. In addition, most of the work on thermally induced effects on pile groups focuses on the mechanical rather than in the thermal response of piles. It is worth noting that no analysis or design of geothermal piles can be considered complete without addressing the behavior of piles as single and group elements [8], therefore the effects of temperature variations of a pile on those around it must be considered [9].

Bourne-Webb et al. (apud Caulk et al. [10]) emphasize the need for advanced finite element models, in addition to field studies, to improve the design guidelines for geothermal piles. The existing guidelines, developed by the GSHPA (Ground Source Heat Pump Association), focus on "best practices" for dimensioning and installation [10], and do not necessarily consider the interaction factor between the piles of a group as a criterion for dimensioning thermo-active piles [9]. Where pile groups are installed following only structural spacing requirements, the radial temperature distribution and heat flow should be known, since overlapping thermal fields between adjacent piles due to group operation can result in decreased performance of the geothermal system [7].

2 Thermal interaction in pile groups

Sousa Júnior [3] evaluated, by numerical modeling, the thermal efficiency of different configurations of pile groups inserted in a tropical soil in Brasília City (Brazil) by understanding the thermal interaction between piles of different groups and their influence on the heat exchange. Results showed that an increase in spacing (s), due to an increasing in diameter (s = 3D), corresponded to less interaction between the heat bulbs and, consequently, higher thermal efficiency of the group, since a greater spacing increases the volume of soil occupied by the group, ensuring greater heat changes with the volume of soil around the piles. For D = 0.6 m the interaction between the temperature bulbs was practically nonexistent.

The improvement of thermal efficiency of pile groups with the increase in pile spacing was also reported by Kong et al. [11]. Sanner, Mands and Sauer (apud Kong et al. [12]) recommended distance of at least 4.0 to 4.5 m between two piles to avoid reducing the thermal performance of the system. Orozco [13] showed that the optimal spacing depends on the available thermal storage capacity of the surrounding soil and the piles' parameters (diameter, length, thermal properties). For s < 1D, the bulb formed around two piles was found to work as an "equivalent pile". Similar effect was noted by Silvani et al. (apud Laloui and Di Donna [9]) in a model of nine piles in which equal temperature was imposed on all piles. For s = 3.2D, Orozco [13] observed a division into two thermally distinct regions separated by a transition zone, i.e. two thermal bulbs, and, for s = 8D, there was total thermal separation between the piles. The heat exchange rate per pile length stabilized at s of approximately 6D.

Extending these studies, Sousa Júnior [3], Salciarini et al. [7], Kong et al. [11] and You et al. [14] analyzed the pile location inside the group. Sousa Júnior [3] showed that, when the heat bulbs of piles fixed in foundation blocks intercept, the difference of temperature between the soil and the pile decreases, the decrease in the temperature gradient results in a reduction of heat exchange and, consequently, the thermal efficiency is also reduced. The more nearby piles interact, the lower the efficiency of each pile, therefore the center pile has the worst result. Kong et al. [11] added that, after the central pile, the piles with greatest loss in heat exchange are the lateral piles, followed by the corner ones. The central pile becomes almost ineffective in a stationary regime, since the temperature gradients around it are insignificant, while the external piles only exchange heat with the soil external to the pile group.

In general, the geometric arrangement of foundation piles is determined only by the structural requirements of the building [15]. Abdelaziz [4] alerts that, although the typical pile spacing of 3D at foundation engineering practice ensures minimal mechanical interaction between adjacent piles, it may not be sufficient to minimize the thermal interaction. The spacing between geothermal piles can be increased by increasing the grid spacing or reducing the number of piles available to support the building. This solution may not be economic, since the mechanical capacity of each individual pile would need to be increased by increasing the pile diameter or length. An alternative solution would be to selectively alternate some piles in the grid as geothermal piles, maintaining the spacing of the original grid and increasing the spacing of the geothermal piles, since not necessarily all piles in a geothermal foundation must be thermo-active [7]. Thus, the number of piles that will support the building is maintained, but the number of geothermal piles is reduced, and it may not be sufficient to meet the building's thermal demand.

It is also important that the spacing between geothermal piles be as uniform as possible (well distributed spatial arrangement) to avoid significant local changes in soil temperature, which may have implications for the piles' structural integrity [15]. For You [14], a line layout is the most effective measure to increase the heat exchange. The approach that best meets the building's structural and thermal needs must be selected with these limitations in mind.

3 Numerical modeling

The simulations were developed using the student version of ANSYS FLUENT. The first step was to create a simplified model, geometrically similar to that developed by Almeida [1], in order to validate it for a single pile.

Simplifications were adopted: the U-tube was not modeled, the convective exchange of temperature with the air above the soil surface was not considered and the heat source is the whole pile. Once satisfactory results were obtained for a single pile, the model evolved for a group of 5 piles (4 piles around a central pile).

The input parameters of the numerical model are summarized in Tab. 1 and were obtained from the TRT test performed at the Polytechnic School of São Paulo University (EPUSP), described by Morais and Tsuha [16] and previously used for the calibration of the numerical model by Almeida [1]. The values adopted are those for which the geothermal system reached stability conditions in the TRT.

Table 1. Numerical model input parameters

Parameter	Value
Diameter of soil domain (m)	6.00
Length of soil domain (m)	18.00
Pile diameter (m)	0.35
Pile length (m)	15.00
Undisturbed soil temperature (K)	297.33
Ambient temperature (K)	301.15
Geothermal pile temperature (K)	305.60
Soil thermal conductivity ($W.m^{-1}.K^{-1}$)	2.82
Soil specific thermal capacity ($J.kg^{-1}.K^{-1}$)	1578.90
Concrete thermal conductivity ($W.m^{-1}.K^{-1}$)	2.00
Concrete specific thermal capacity ($J.kg^{-1}.K^{-1}$)	1000.00

Two border conditions are present in several references and were also adopted in this model: a distance of 3 m from the center and bottom of the thermo-active pile to limit the model domain, and constant undisturbed temperature at the limiting surfaces of the soil domain [1]. The temperature of the geothermal pile interior was adopted as equivalent to the temperature at the concrete/soil interface obtained at the TRT and, finally, the soil domain is adiabatic, i.e. all phenomena occur inside the concrete and soil system.

The following assumptions, presented as widely used and well-founded by Almeida [1], were also adopted:

- Soil is an infinite, isotropic and homogeneous medium, so that geotechnical and thermal parameters do not vary within the limits of the domain;
- The initial temperatures in the subsoil (prior to the thermal flow provided by the geothermal system) and in the piles are constant along depth;
- The heat transfer occurs in the radial direction and the vertical heat transfer (along the axis relative to the pile length) is negligible;
- The physical mechanism of heat transfer in soils is conduction, governed by Fourier's Law, as thermal flows by convection and irradiation are negligible when compared to the heat rate transmitted by conduction;
- There is heat exchange between at the interfaces of the concrete and the soil domains;
- The temperature variation does not change the density and saturation and, consequently, the thermal conductivity and the thermal capacity of the soil; nor the density, thermal capacity and thermal conductivity of the concrete.

Sousa Júnior [3] notes that the operation of a geothermal pile causes the formation of a bulb-shaped region, influenced by the pile heating, which indicates that the heat transfer is not just radial. However, results prove the validity of neglecting the vertical heat transfer along the pile length. Another consideration is that the precision of the solution is highly dependent on the number and distribution of elements in the mesh, so that better results are obtained as the refinement and computational cost increase. The use of a student license, limited to 512,000 nodes, did not allow a good refinement in all simulations, however, the results were satisfactory.

Once the model was validated for a single geothermal pile, the edge piles were inserted, so that the numerical model now has a central pile and 4 equidistant edge piles, forming a group of 5 identical piles. The typical pile spacing used in foundation engineering practice (3D) was used as the center-to-center distance between the central pile and the edge piles, and a 3-m distance from the center of the edge piles was adopted to define the soil domain boundary, similar to the case of a single pile. This geometry was chosen for its simplicity and symmetry.

Five cases were simulated, with different quantity/position of the thermo-active piles in the group, in order to evaluate the influence of these variables on the thermal performance of the group. The cases studied can be identified in Fig. 1.

4 Results and discussions

4.1 Validation

The longitudinal temperature distribution profile was compatible with that obtained by Almeida [1], however, the simplification adopted by not modeling the U-tube and the circulating fluid, i.e. using the whole pile as a heat source, resulted in a much higher heat input in the model than would happen in reality. The total heat transfer rates at the concrete/soil and soil limit interfaces resulted around 60% higher than those obtained by Almeida [1]. The ratio between the heat transfer rates at the concrete/soil and the soil limit interfaces, however, was practically equal, as shown in Tab. 2.

Table 2. Results for total heat transfer rate per interface

Interface	Model developed by Almeida [1]	Model developed in this research	Percentage variation between models
Concrete/soil	474.63 W	762.31 W	61%
Soil limit surface	722.63 W	1193.53 W	65%
Ratio between interfaces	0.66	0.64	-

In addition, the soil regions thermally affected by the pile heating were compared through the concept of thermal influence radius, defined by Fare (apud Almeida [1]) as the distance measured from the pile center, at half its length, to the point on the ground whose temperature is changed by 1K with respect to its undisturbed temperature. A thermal influence radius of 2.05 m was obtained, 10% lower than that obtained by Almeida [1].

The simplified numerical simulation brought qualitative results (spatial distribution of temperatures, configuration of heat bulb, thermal efficiency) satisfactorily close to those from a more detailed and complex model. Therefore, the proposed numerical model can be considered adequate for the objective of a parametric study on geothermal pile groups.

4.2 Study cases

The radial (plane Z=7.5m) and longitudinal (plane XZ) distributions of temperatures as a function of the amount of thermo-active piles in the group for the five study cases can be identified in Fig. 1.

Before discussing the results, two points should be highlighted:

- Once the constant temperatures inside the geothermal piles and at the lateral limit of the model are imposed as boundary conditions, the program distributes the temperatures in the available space. Thus, an increase in the model radius would cause the influence radius to increase. This aspect should be further verified by numerical modeling and field measurements.
- The same temperature was considered for the interior of all geothermal piles, regardless of the number of thermally active piles. In a model without this simplification, the heat source of the system would be the circulating fluid inside the active piles, and the heat exchanges between fluid and tube, and tube and concrete, would result in lower temperatures in the soil/pile interface.

The temperature distributions in Fig. 1 indicate that the more piles are thermally activated, the greater the influence between piles, creating a non-linear overlap of effects, so that the group behaves as an "equivalent pile". The influence radius of the group increases as more piles are activated, from 1 to 4 piles, and no difference was observed between the influence radius of 4 or 5 activated piles (Fig. 2).

Figure 3 shows that the total heat transfer rate (quantity of heat that is transferred from the piles to the soil per time unit, $\dot{Q}$) increases, but at ever smaller increments, for each new active pile. This can be explained by the decrease in heat flux (total heat transfer rate per unit of area perpendicular to the flow for all thermo-active piles, $\dot{q}$), caused by the thermal interactions as more piles are activated. The percentual increments of total heat transfer rate ($\Delta\dot{Q}$) and reduction of heat flux ($|\Delta\dot{q}|$, in absolute value since it is a reduction, i.e. a negative value) for each new active pile are shown in Tab. 3. The heat flux and total heat transfer rate at the interface of the non-active piles with the surrounding soil are practically null, since the heat received by the pile surface facing the active piles passes through the pile and leaves it through the surface facing the soil limit. The balance is practically null except for the heat loss inside the pile.

The thermal efficiency of the pile group was evaluated by the relation between the heat flux loss and the increase in the total heat transfer rate: the arrangement is considered more efficient the smaller this relation. A hierarchy based on that efficiency is presented in Tab. 3.

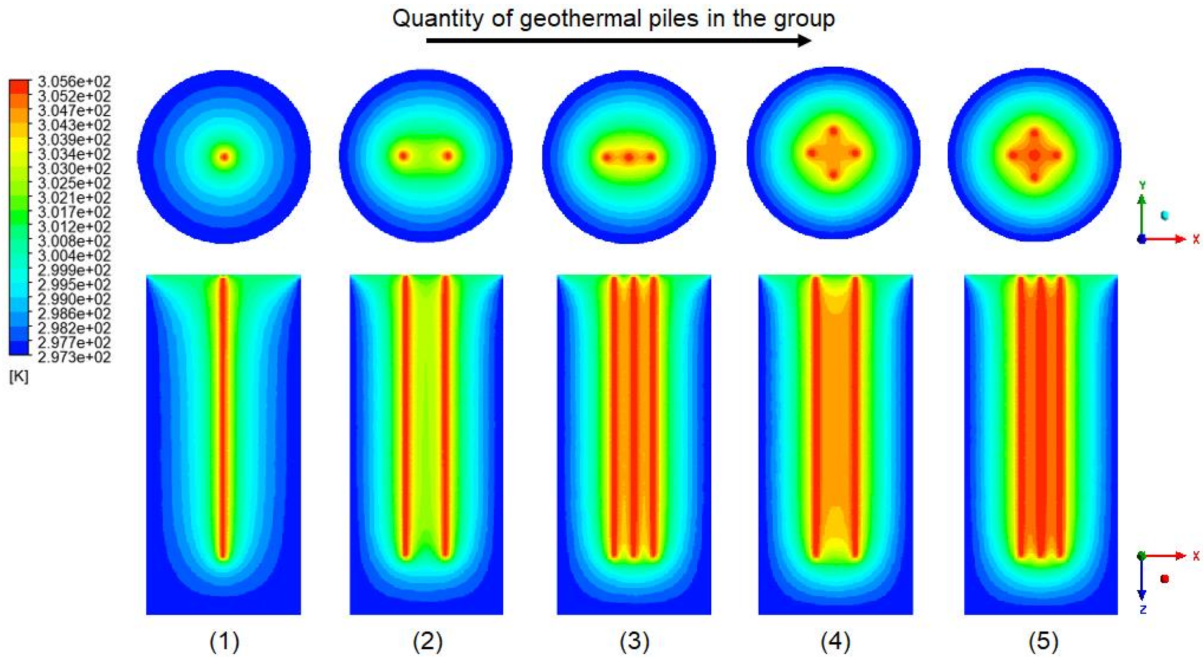

Figure 1. Results of radial (Z=7.5m) and longitudinal (Plane XZ) temperature distribution as a function of the number of thermo-active piles in the group
(1) only the central pile is thermo-active; (2) 2 diametrically opposed thermo-active piles; (3) a line of 3 thermo-active piles; (4) only the 4 edge piles are thermo-active; (5) all piles are thermo-active

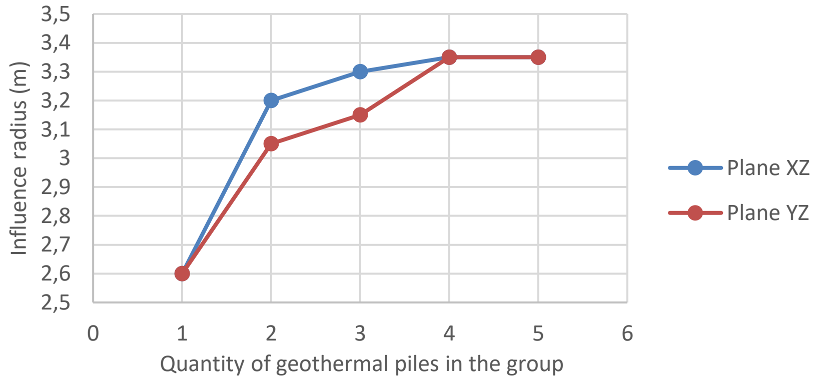

Figure 2. Variation of the influence radius with the number of thermal piles per plane

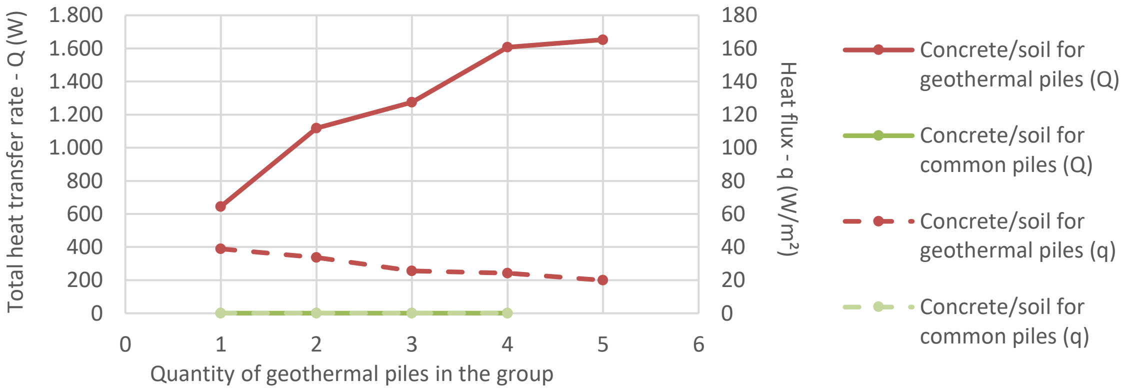

Figure 3. Variation in the total heat transfer rate and heat flow at the concrete/soil interfaces

Table 3. Relation between loss of heat flow and gain of total heat transfer rate

Variation in the quantity of thermo-active piles	$\Delta\dot{\boldsymbol{Q}}$ (W)	$\lvert\Delta\dot{\boldsymbol{q}}\rvert$ (W/m²)	$\lvert\Delta\dot{\boldsymbol{q}}/\Delta\dot{\boldsymbol{Q}}\rvert$	Efficiency hierarchy
0-1	100%	0%	0.00	*****
1-2	73%	13%	0.18	***
2-3	14%	24%	1.74	**
3-4	26%	5%	0.21	****
4-5	3%	18%	6.33	*

$\dot{Q}$: total heat transfer rate; $\dot{q}$:heat flux.

The results in Fig. 1 showed that once the edge piles are active, the activation of the central pile has little relevance in altering the group temperature distribution. This can be explained considering that the central pile, being the more subject to interactions, may become ineffective, as remarked by Kong et al. [11]. From that, it can be inferred that, for a narrow spacing group, when the external piles are active, the activation of the internal piles is preferably dispensable, depending on the building's thermal demands. In this case, besides not increasing the influence radius, the active internal pile increases the temperature inside the group domain, which reduces the thermal gradients and, consequently, the thermal exchanges in that region. The capacity of exchanging heat of the soil will be better used the further apart the thermo-active piles are.

As for the influence radius, Fig. 2 shown greater increment when the configuration of thermo-active piles is changed from a line (case 3) to a cross (case 4). The cross layout of thermally active piles takes the heat exchanges to larger distances, but it is not necessarily more efficient, as shown in Tab. 3. The thermally affected region tends to constancy after a certain quantity of thermo-active piles within the same area, and the addition of a new thermally active pile, besides not increasing the thermally affected region, also decreases the heat flux (less efficient system). This can be observed in the increase from 2 to 3 piles, and from 4 to 5 piles. In addition, Tab. 3 shows that, in terms of efficiency, it is preferable to have a line arrangement of the geothermal piles in the group, and do not activate the central pile, to ensure greater spacing between the heat exchanging piles. A solution to avoid losing efficiency would be to increase the distance between the geothermal piles. Greater spacing results in less interaction between heat bulbs and also, in a greater volume of soil to exchange heat, consequently increasing the efficiency of the group.

The proposed model considered a constant temperature in the whole pile, based on the temperature of the concrete/soil interface obtained at the TRT for a single pile, whereas a geothermal pile would receive a constant temperature from the circulating fluid. The results show that the more thermo-active piles in the group, the lower the heat flux. Thus, by activating a greater number of piles, there would be less thermal exchanges, and, therefore, a lower temperature would be expected at the concrete/soil interfaces than that obtained for a single pile. Thus, the results allowed a mostly qualitative analysis for heat exchanges.

The use of a geothermal pile group is justified by the higher total heat transfer rate. Although there is a decrease in heat exchange per area (heat flux), activating more piles increases the thermally affected area until a certain number of piles. For example, Fig. 3 shows that the highest total heat transfer rate is obtained by the group with 5 thermo-active piles, however, the heat flux is the lowest, and the influence radius does not change from that obtained for the group with 4 thermo-active piles, as shown in Fig. 2. Allowing to state that it is preferable to activate only the group's edge piles, unless the distance between edge piles and internal piles is sufficiently large so that the thermal interaction between them is small. Analyzing the results of Fig. 2 and Fig. 3 together, it is possible to notice that in case 2 the piles are far enough so that the group radius of influence increases by 19% while the heat flux decreases only 13%, in relation to case 1; but when activating a third pile between them, it has an increase of only 3% for the radius of influence against a decrease of 24% on heat flux, what justifies the preference by not activating the group's central pile.

5 Conclusions

The numerical analysis of an integrated system of a group of 5 geothermal piles in different configurations was carried out to study the influence of the increase of heat transfer as a function of number and location of thermo-active piles.

The numerical model was developed using ANSYS Fluent and based on the preliminary results and conclusions of the model developed by Almeida [1]. The model was validated from the experimental results of the TRT conducted at EPUSP campus by Morais and Tsuha [16] and the numerical results of Almeida [1].

Results of the pile group study indicated that the thermal influence radius does not increase linearly with the number of thermo-active piles and that, at the limit, a group of piles can behave thermally as a single pile, whose equivalent diameter depends on the position and number of active piles in the group. The use of pile groups eliminates the need to design large piles to increase the heat transfer area and, consequently, the dissipation of thermal energy.

This study showed the importance of simulating the heat transfer of pile groups to improve the design of geothermal foundations, since the activation of all piles decreases the group thermal performance, which would be maximum in a scenario of widely spaced piles, what may not be the best scenario in structural terms.

A next step of this research could be the modeling of radially equidistant cylindrical surfaces in order to evaluate the total heat transfer rate as a function of the radial distance to the center of the group. In addition, the diameter of a single pile with thermal effects equivalent to that of the group as a function of the number and position of active piles should be investigated. Other groups of piles commonly designed in practice, as well as the effect of the circulating fluid and the movement of groundwater, are also possible scenarios to be developed for the study of heat transfer in groups of geothermal piles.

Finally, as highlighted by Rotta Loria and Laloui [5], there is a lack of field data for heat exchanger pile groups operating for periods compatible with practical applications, the performance of these tests is of paramount importance to obtain more reliable models regarding the prediction of the group thermal performance and the soil thermal response.

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