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Laboratory experimental and numerical thermal response tests in thermal piles prototypes in tropical soil

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Article

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Abstract

This paper provides preliminary results on geothermal energy piles (GEPs) for the thermal climatization of structures founded on the typical tropical unsaturated soil of the central region of Brazil. The research employed a series of prototype simulations of a thermal pile embedded into a calibration chamber with compacted unsaturated soil. It closely simulates the behavior of a (prototype) section from real scale GEPs founded in the geotechnical media of the region, in terms of compactness, mineralogy, water content and thermal variables. One of the on-going thermal tests was numerically simulated with a Multiphysics commercial software to calibrate a model and expand the results to possible scenarios of distinct (laboratory) GEP performance. The analyses will base future simulations of typical foundation layouts for large-scale structures founded on tropical soils of the region to verify the thermal energy efficiency under average operational conditions. Besides the known limitations of this research, still at early stage, an initial assessment was achieved to design shallow geothermal systems for local conditions.

1. Introduction

Greenhouse gas emissions produced by fossil fuels are causing a slow change in the climate's conditions. Air conditioning systems in superstructures demand a considerable amount of the existing carbon-related energy sources, which are non-renewable. Many developed countries have addressed Shallow Geothermal Energy (SGE) as a renewable source of energy worthy of investment and development. SGE refers to the exploitable thermal energy in the shallow subsurface of the earth, using ground source heat pumps to exchange ground heat and provide sustainable energy to superstructures. These energy systems can provide cooling to buildings, helping reduce harmful gas emissions (Brandl, 2006). They can also be useful to agro-industrial structures, possibly to be employed in storage rooms, animal sheds, and other living or working structures largely present within Brazil's Midwest agribusiness frontier.

For instance, storage barns must be refrigerated in this industry to keep crops from germination or deterioration processes, being mostly mainly being used during harvesting season. Other structures that must also be refrigerated are residential living quarters. Feasibility of SGE usage for the region has not yet been assessed. Still, to provide a sustainable solution, one must initially understand its potential to be implemented into local conditions and know how to design it to provide heat loads usually demanded by common/existing structures.

Hence, this paper focuses on the potential use of energy piles to climatize barns, agricultural, industrial or residential quarters/deposits through the exchange of heat with the typical, mostly unsaturated tropical soil of the Brazilian Midwest region (Figure 1).

The agribusiness in this central region is vital. It competes in a worldwide range, which could initially allow the implementation of clean, sustainable energy systems that are uncommon in Brazil. They are also relatively expensive to implement, given the lack of companies, technology, personnel, and expertise.

As most of the needed energy is supplied from the ground, the SGE system contributes to the cost-saving operation of the superstructure, besides decreasing the release of greenhouse gases into the atmosphere (a critique which is made to large-scale meat producer farms of the Brazilian Midwest regarding methane emissions). Notice that in the COP26, Brazil has compromised itself to cut off all methane emissions by 2050, which is not a simple task.

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Figure 1. Brazilian states and Midwest region: the agribusiness frontier for exportation of commodities.

Nevertheless, there are certain minimum requirements for the installation of SGE systems, as an abundant array of previous publications has already been ascertained in the literature, especially in the last 5 years or so (for instance, Akrouch et al., 2015; Di Donna et al., 2016; Olgun et al., 2017; Salciarini et al., 2017; Rotta Loria et al., 2018; Sani et al., 2019; Sani & Singh, 2020; Bourne-Webb & Bodas Freitas, 2020; Cunha & Bourne-Webb, 2022, among others).

Unsaturated soils are also rarely considered as a thermal medium for heat exchange. However, experience has shown that the SGE system works, besides decreasing heat exchange efficiency (Ahmadipur & Basu, 2016; Akrouch et al., 2016; Sani et al., 2018). It seems, however, that the typical laterized tropical soils of the midwest region of Brazil have special features that may render them more feasible for SGE exploitation, as an abundant presence of iron and aluminum oxides. From pedogenetic aspects of their formation, this mineralogical characteristic increases their overall thermal conductivity (Bandeira Neto, 2015; Orozco, 2016; Sousa Júnior, 2017). Of course, this poses an extra challenge to the design but nevertheless encourages further research in this direction.

Efficiency in SGE systems also depends on other variables. For instance, stable ground temperature over seasons is inevitable for sustainable long-term heat exchange operations. A geothermal heat exchange system is considered balanced when the heating and cooling demand is approximately the same. When the heating or cooling demand is greater than the other, there is a nonsymmetrical energy expense, and the whole system becomes unbalanced. Generally speaking, in the majority of the Brazilian regions, the operation of ground source heat pump (GSHP) systems would be unbalanced, as the cooling demand might be higher than the heating one throughout the year. Thus, the geotechnical medium can gradually heat up and lose efficiency for thermal storage. In the case of GEPs, the increase in axial stress and strain is observed (Akrouch et al., 2014; Murphy et al., 2015; Abdelaziz & Ozudogru, 2016). This phenomenon can be explained by the difference in the thermal expansion coefficients of the pile and the soil, and end restraints, as demonstrated by Goode III & McCartney (2015). This is certainly another challenge for design.

Therefore, before full application within local geotechnical, environmental and thermal constraints, research must be done to understand how SGE systems can operate daily, either at short and large time frames, considering the existing unsaturated medium local temperatures. So, with prototype tests that simulated a GEP section immersed into a compacted soil "representative" of the region, and thermal variables derived from both laboratory tests and empirical correlations, it was possible to gather information on a "normal" GEP operation that served to calibrate a thermal model for subsequent numerical simulations.

Distinct working scenarios for heat flow production by an isolated energy pile were numerically evaluated by a Multiphysics commercial software, considering several external variables as flow, fluid inlet temperatures, and pipe configurations. Steady-state conditions were assumed in the parametrization, with distinct time frames of heat production.

The exercise proved valuable to grasp an initial understanding of potential capabilities for exploiting thermally active piles into local structures. It is theoretically feasible, experimentally valid, and possibly operational. However, further validation is mandatory to broaden the knowledge to real scale and time conditions.

Energy demand in the region is undoubtedly existent. The sustainable appeal is strong, but the implementation of this technology still depends on other factors yet to be matured, as the availability of technology, design companies and contractors, governmental policies and funding, public awareness, and large-scale experimental research. Actually, lots of research.

2. Materials and methods

2.1 Geothermal properties and geotechnical characterization of the soil

The soil used in this research was collected in the Geotechnical Experimental Field of the University of Brasilia (UnB), Darcy Ribeiro Campus located in the Federal District (DF), in August 2019. The reason for the choice of the collection site was due to the fact that the soil collected is characteristic of the entire DF and the vast knowledge of the geotechnical characteristics of the soil due to the numerous researches developed in this experimental field, which can be cited the works of Guimarães (2002), Silva (2007, 2009), Fuji (2012), Borges (2014), Queiroz (2015), among other works developed in the Graduate program in Geotechnics at UnB.

Table 1 shows, in summary, the main geotechnical parameters obtained in the characterization tests. This is a soil whose specific weight of grains is 27.32 kN/m^3.

2.2 The prototype and compression soil in the chamber

The prototype was executed and concreted in a compacted soil within the chamber with average soil moisture content of 20%, void ratio of 0.8, porosity of 44%, and dry unit weight of 13.6 kN/m^3 (as shown in Figure 2a). The soil was compacted into 12 sequential layers to simulate "average" conditions of the tropical soil of the Federal District of Brazil, where the University of Brasília geotechnical research site is located (home base of the studies presented here).

The compaction process was carried out by layering with a manual compactor with a 16 × 16 cm^2 square socket, weight of 10.73 kg, drop height of 27.5 cm, and 513 strokes per layer, evenly distributed over the 12 soil layers. This procedure has enabled a total compaction energy of approximately 2353.6 kN.m/m^3 (24 kgf.cm/cm^3). These specifications allowed the compacted specific weight, density, and other soil variables to "approach" those conditions found in the field deposit, normally derived via previous laboratory data and parameters estimated by traditional SPT correlations at this site. The chosen soil moisture content was the lower possible in the dry range of the curve that permitted the desired dry unit weight with a homogeneous compaction (Figure 3).

Table 1. Main geotechnical characterization parameters of the tropical soil analyzed.

Parâmeter	*WL* (%)	*WP* (%)	*IP (%)*	*Gs*	SUCS
	41	24	17	2,76	CL-ML

2.3 Thermal parameters of the soil

The parameters of the compacted soil were defined by empirical methods that relate the thermal conductivity (λ_{soil}) and the specific heat capacity (*Cp*) with geotechnical variables of the layer as porosity, degree of saturation, mineralogy, and granulometric distribution. This was done because thermal tests of the local soil deposit, or the compacted soil samples, have not been performed yet at this stage of the research.

The 1 m of compacted soil layer along the GEP prototype was divided into 12 distinct layers according to compaction procedures carried out during sample preparation. Lu et al.'s (2007) methodology was employed to derive the average thermal conductivity of each layer, considering the thermal conductivities of the minerals that form this soil, the porosity, and the respective degree of saturation of the layers.

The thermal conductivity parameter for each layer is related to the (bulk) thermal conductivity of a laterized soil strata within the first 4 m of the research site ($\lambda_{mineral}$), since this is the zone where the soil sample was extracted. Although differences are expected, the superficial soil characteristics from the site, at this depth range, do not change considerably with depth (up to the 8 to 10 m transition zone before the typical regional saprolite of slate.

The mentioned (bulk) variable represents the bulk thermal conductivity of the minerals of this zone, as a whole,

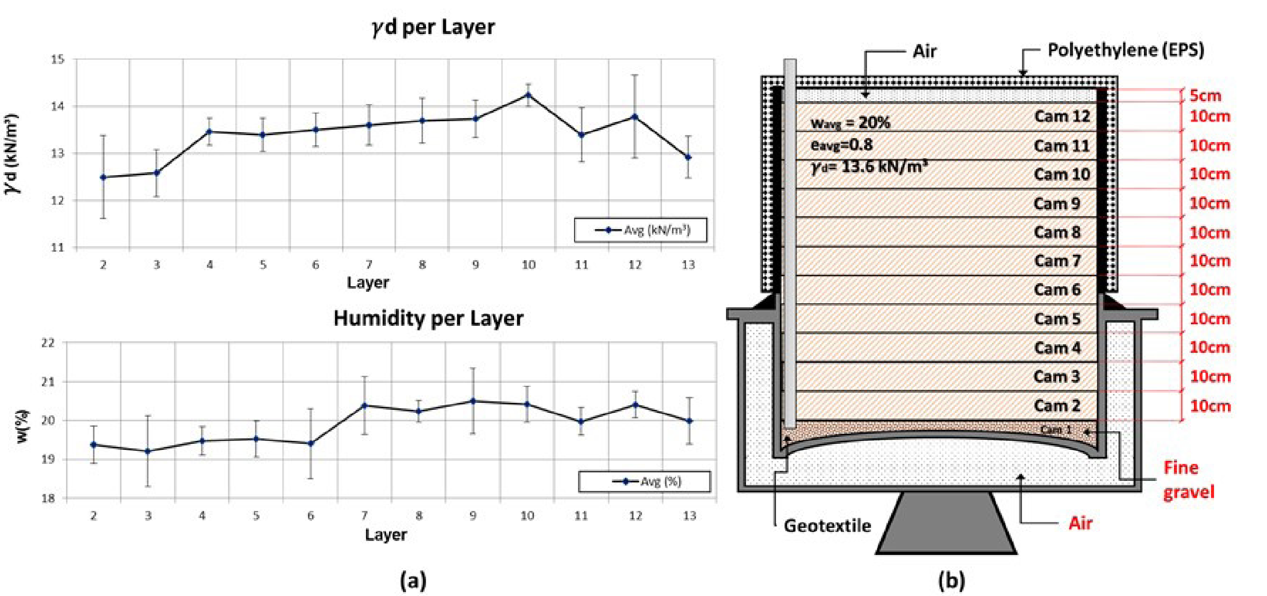


Figure 2. (a) Soil moisture content and dry unit weight distribution per layer; (b) 12 soil layer distribution in the calibration chamber.

in accordance with their relative percentage within the soil mass. This percentage was defined with X-ray diffractometric tests by Rodrigues (2017), i.e., exemplifying, this author has determined the following amounts of minerals for this soil: 34.9% of quartz, 34.6% of gibbsite, 22.1% of kaolinite, 6.6% of hematite, and few (< 1%) percentages of other minerals. A bulk value of 3.94 W/m.K was derived and used in Lu et al.'s (2007) method to estimate each layer's average thermal conductivity (λ).

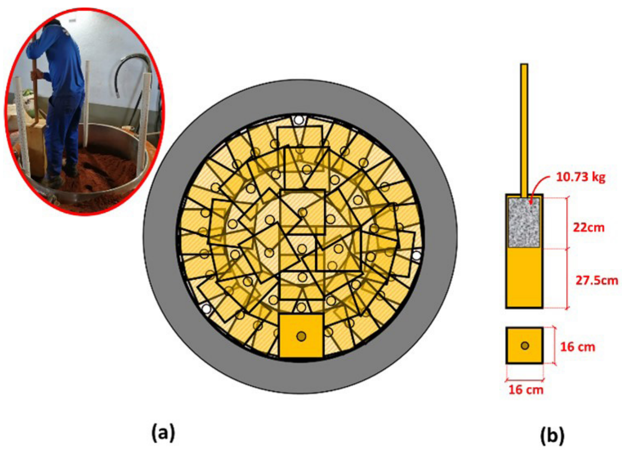


Figure 3. (a) uniformly distribution of compression per layer in the chamber; (b) compactor dimensions and weight.

The specific heat capacity in J/kg.K was derived by the model of Johansen (1975), taking into consideration the dry unit and the specific apparent weight of the soil, the density of the water, the soil water content, and the volumetric heat capacity of the water (as 4.18×10^6 J/m^3.K).

2.4 Thermal response test machine and calibration chamber

In order to calibrate the numerical model and to understand the behavior of the GEP prototype under heat exchange conditions, an initial setup test was performed inside a thermally insulated testing chamber (as shown in Figure 4). The dimensions of this cylindrical chamber were 1.1 m in diameter by ~1 m in height.

The developed prototype of the geothermal pile was 1 m long and 20 cm in diameter, with internal HDPE exchanger tubes of 19,05mm in external diameter into an overall 1U loop configuration. The tubes were uniformly distributed along the steel reinforcement cage of the GEP. Thermo sensors were installed at distinct compacted layers surrounding the pile to check the all-around temperature. Those dissipated along the chamber radius at distinct points in the compacted layers (see Figure 5).

Figure 6 shows the basic schematic of the plant of the home-based TRT machine developed by the Arduino platform. It is a closed circuit with water circulation overflow

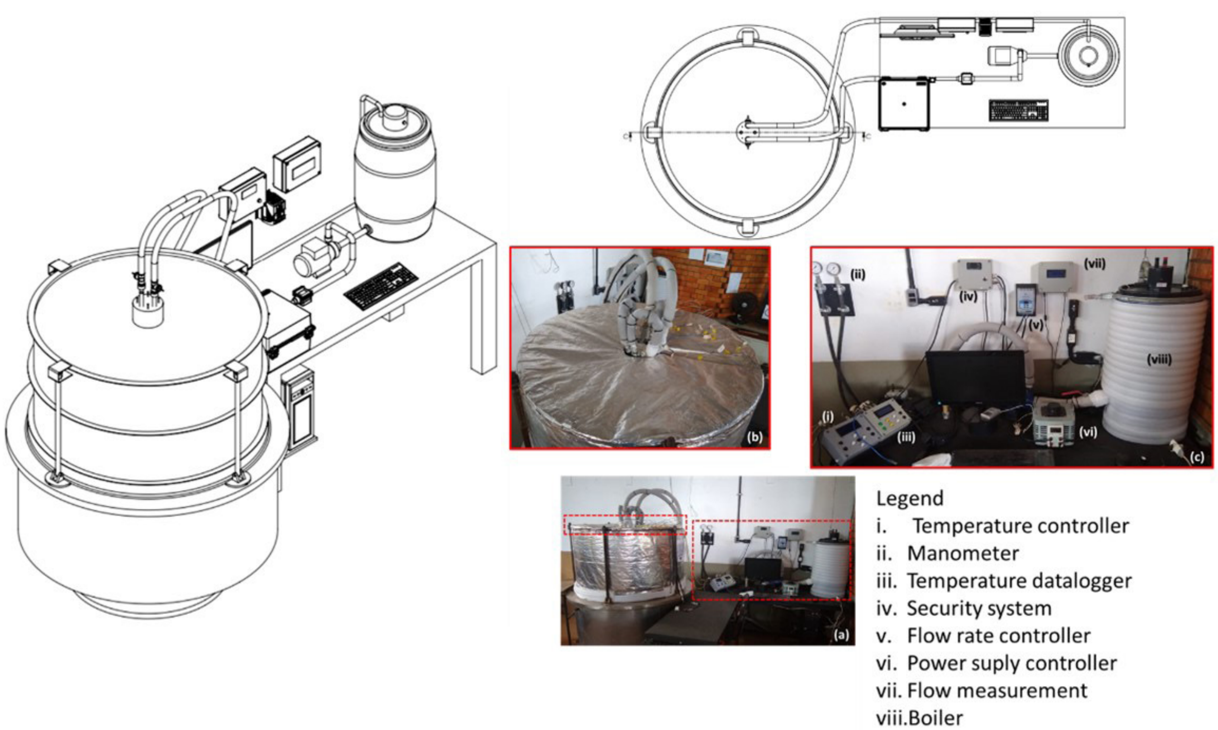


Figure 4. (a) Overview of the thermal response test machine and the calibration chamber. (b) thermal response test machine details, and (c) superior view of the calibration chamber.

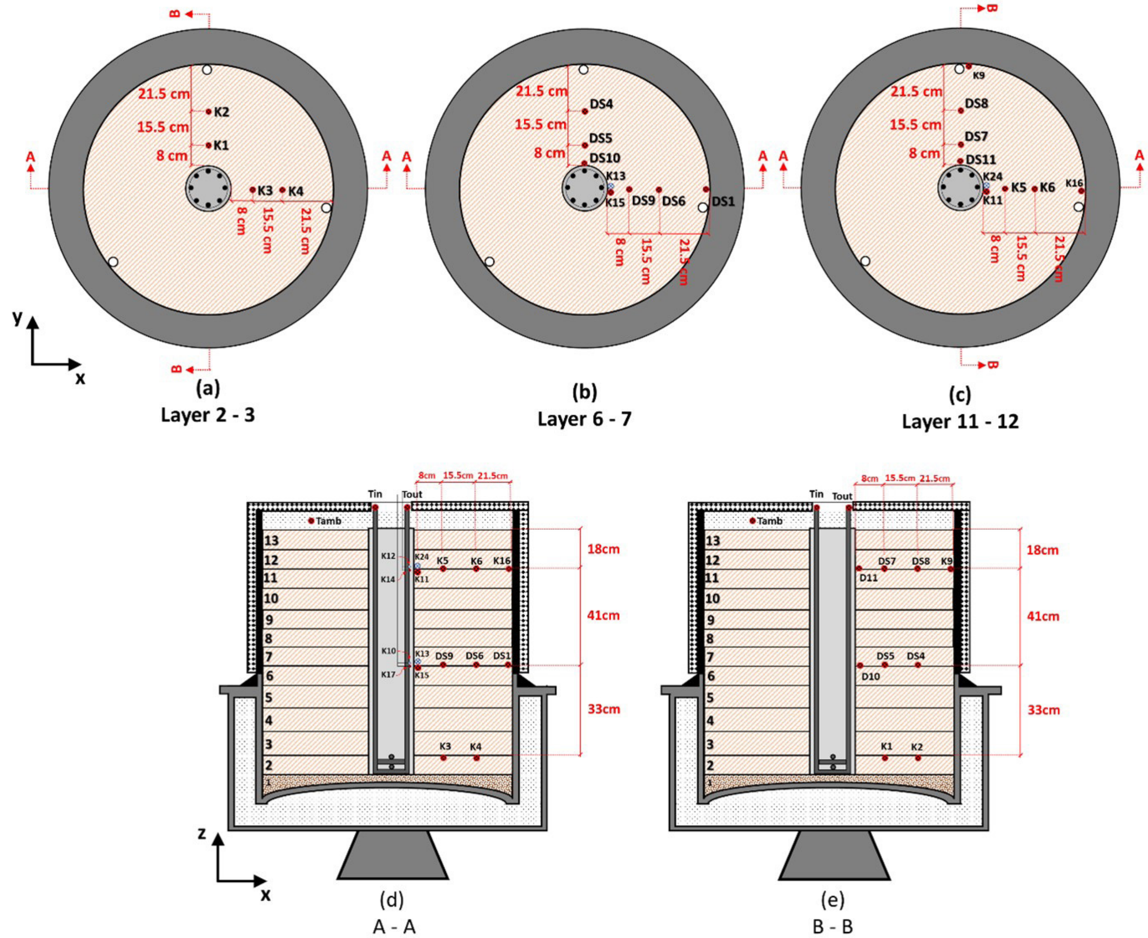


Figure 5. Temperature sensors radially distributed in the thermal chamber: (a) layer 2-3; (b) layer 6-7; (c) layer 11-12; (d) section A-A; (e) section B-B.

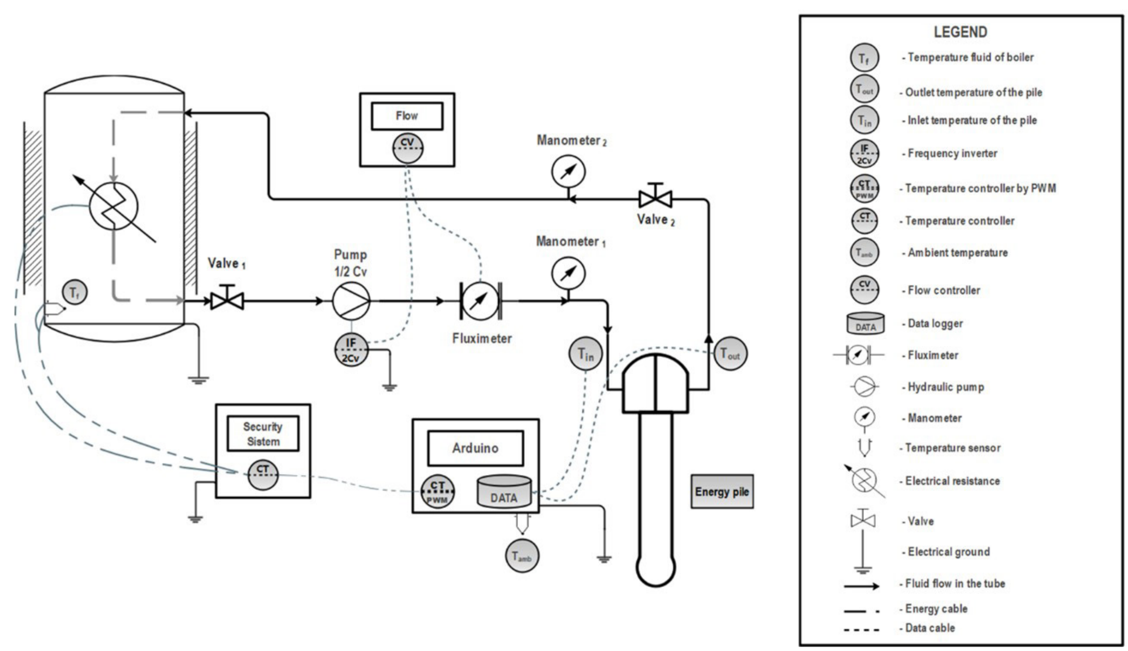


Figure 6. Hydraulic plant diagram of the developed thermal response machine.

and heating, both controlled in the machine. The flow control was performed by a frequency inverter installed in the pump circuit. The power control was done through a voltage variator coupled with a true RMS Wattmeter.

The inlet and outlet temperatures are collected by a data acquisition system developed by the Arduino platform and the flow measurement system. A safety system was also developed to protect the machine against overheating and eventual power failures.

Figure 7 presents the picture of the U tube configuration of the prototype of the geothermal pile with the thermal couplers installed in the external tube surface and in the pile/soil surface of the bore of the pile.

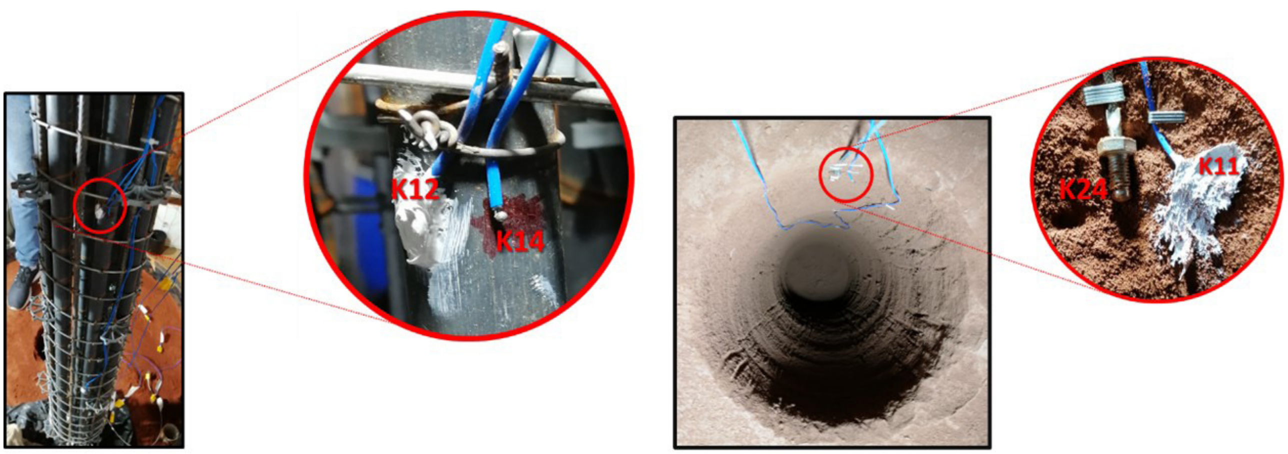
2.5 Thermal tests in calibration chamber

The thermal response test in the chamber was performed on the prototype of 1U configuration, a constant flow rate of Q = 3.06 L/min and electrical power of heating machine of 150 W, turbulent regime, soil moisture at the beginning of the test was approximately 16.10%, subject to a thermal power of heat exchange of 106 W/m.

The prototype thermal response test results can be seen in Figure 8a and analysis of the test by the linear source method (as shown in Figure 8b).

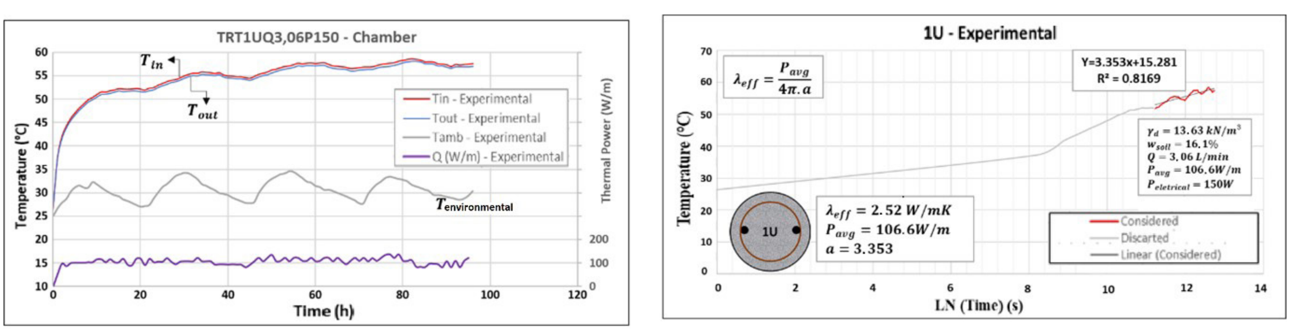
It is worth noting that the thermal power of heat exchange is relatively high since the average recommendation of heat exchange is between 60 and 80 W/m. In this case, it was chosen to initially analyze a situation of heat exchange at the industrial level.

It is known that the thermal conductivity estimated by the Line Source method is not an accurate estimate for the situation in question since the slenderness of the prototype is well below that recommended by the method to consider an infinite linear source. Therefore, to lessen some of the inaccuracies, a numerical model was calibrated to estimate with greater precision and accuracy the thermal conductivity of the soil analyzed.



(a) (b)

Figure 7. (a) sensors installed on the wall of the prototype pipe before concreting; (b) sensors installed on the wall of the concrete/soil interface of the prototype.



(a) (b)

Figure 8. (a) experimental results in the thermal chamber for calibration; (b) analysis results by the infinite linear source method of the TRT test.

During the TRT test, temperature data were collected in space and time from the entire thermal chamber throughout the test. Figure 9 shows the development of the temperature bulb during the trial heating phase of the test.

It can be seen that there was very little temperature increase for test times above 50 h. It was also observed that the temperature bulb reached the chamber walls with border interference.

This situation is not ideal, but a thermal interference of approximately 6 °C of difference in relation to the initial temperature was observed, which can be considered a relatively low variation compared to the maximum temperatures on the wall of the pile (approx. 50 °C).

2.6 Numerical software

Commercial software based on the finite element method, denominated COMSOL Multiphysics v.5.2, was employed in calibration and parametric simulations. It is ideal since it offers specific modules that simulate heat transfer and the flow regime inside the heat exchanger pipes. Moreover, it is quite flexible in terms of boundaries, geometric conditions, and input parameters. It has a friendly output, easy to follow.

For instance, the "heat transfer in solids" module calculated the heat conduction between the concrete pile and surrounding soil. The convective heat between heated fluid and pile wall, or within the circulating system's fluid, adopted the "non-isothermal pipe flow" module to fully complement the heat phenomena process.

The step-by-step analysis procedure was given by:

- Geometry modeling: in this step, the 3D dimensions of the soil domain, piles, and pipes were specified. The assumed geometry and limits of the model were the same as those used in the experimental test. The soil domain was modeled in a cylindrical shape with a diameter of 1.10 m and height equal to 1.08 m, similar to what was adopted in the lab. (as in Figure 2). Figure 10 depicts the adopted final mesh of the problem;
- Material properties: in this step, the properties of water, concrete, and soil were specified, as for instance the soil's specific mass (ρ_{soil}), thermal conductivity (λ_{soil}), and specific heat capacity (C_p), as previously defined in the present paper;
- Non-isothermal pipe flow convection parameters: pipe properties were inputted as shape, internal diameter, wall roughness, and thermal conductivity (λ_{pipe}). The friction factor between inner surface and fluid was estimated with the Colebrook-White equation (Colebrook, 1939), according to COMSOL's recommendations. Initial values of atm. pipe pressure, fluid inlet/outlet positions, and inlet temperatures around 55 ºC at a constant heat rate of 97 W/m were then defined;
- Heat transfer in solids conduction parameters: Initial soil and pile temperatures (T) were given, and eventual variations tried out;
- Mesh configuration: type of element and density. All three types of elements were tested (tetrahedral, prismatic, and hexahedral), and the tetrahedral type was used given its accuracy versus running time. The density of elements has also increased from pipe/pile outwards. The final mesh (Figure 10) respectively adopted 94, 14671, and 22312 elements for pipes, pile, and soil;
- Simulation time: normally of 50 h of system's flow. Note that the numerical simulations lasted 96 h, beyond the minimum duration recommended by CEN/TC 341 (CEN, 2011).

$$Q_L = C_w \cdot \rho_w \cdot q_{in} \left(\frac{T_{in} - T_{out}}{L_p} \right) \quad (1)$$

where

C_W – specific heat capacity of water (4182 J/kgK);

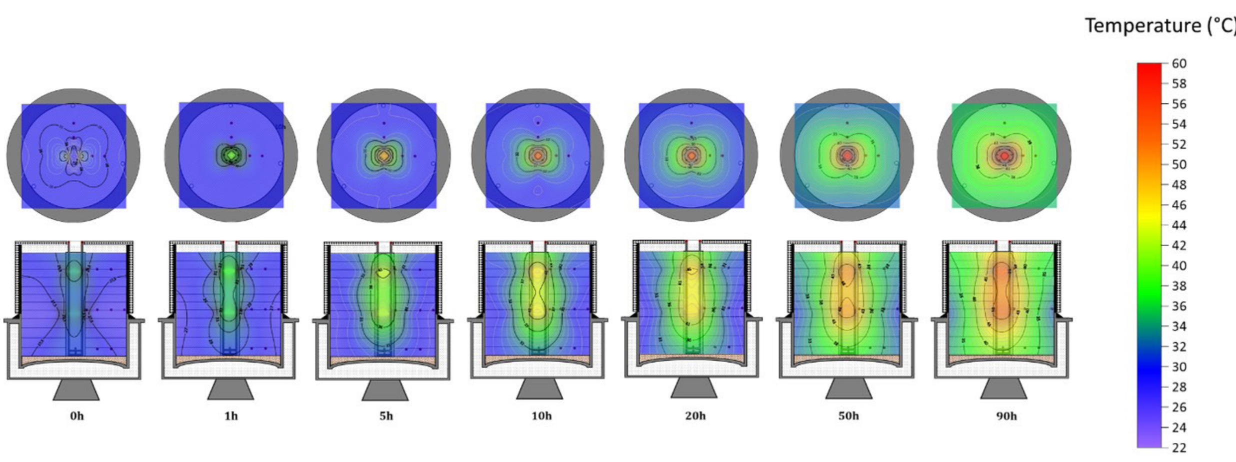


Figure 9. Temperature bulb advancement in the thermal test chamber of prototype 1U-Q3.06-P150.

ρ_W – water density (1000 kg/m^3);
q_{in} – water flow rate (m^3/s);
T_{in} – Inlet temperature (K);
T_{out} – Outlet temperature (K);
L_p – Pile length (1 m).

3. Results and discussion

3.1 Calibration of numerical model in thermal chamber

Calibration was performed by inputting previous parameters into the software discretized mesh and running the problem for 96 h of total time. The initial soil temperature of the chamber was about 29.0 °C, water inflow at 3.06 L/min was also adopted, the experimental heat flux by energy pile was calculated about 105.11 W/m.

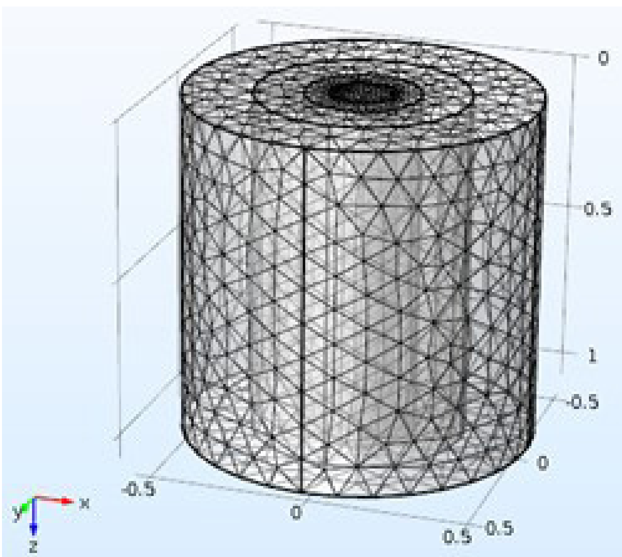


Figure 10. Mesh configuration adopted for numerical analyses.

During the TRT test, temperature data were collected in space and time from the entire thermal chamber throughout the test. Figure 11a shows the development of the temperature bulb in space and time during the trial heating phase.

Figure 11b shows that for a condition of only 1.0 m lengths, there is considerable boundary influence from the upper and lower ends of the chamber. This has led the analyses in this research to focus on the middle of the prototype, where there are the least possible boundary influence effects in the experiments and results.

The inlet and outlet temperatures of the numerical model were determined linearly, following a linear fit of the data obtained from the experimental tests (as seen in Figure 12).

The calibration was evaluated by comparing the experimental versus simulated thermal energy efficiency ΔT, or inlet/outlet temp at about the same heat flux per meter of the pile. Differences can be seen in in Figure 13.

As it can be clearly noted, the differences between the results were reasonably low, suggesting that the numerical modelling was able to simulate the thermal phenomena reasonably well, besides some minor limitations.

Some of them relate to the boundary conditions of the calibration chamber. Indeed, the boundary was not fully exempt from the pile's thermal influence and from external temperature changes in the laboratory. Moreover, DS1 and K16 temperature sensors (Figure 4) were clearly tampered.

Unfortunately, the chamber was limited in size, and insulation problems were noticed after such tests. Boundary effects are therefore present in both compared results,

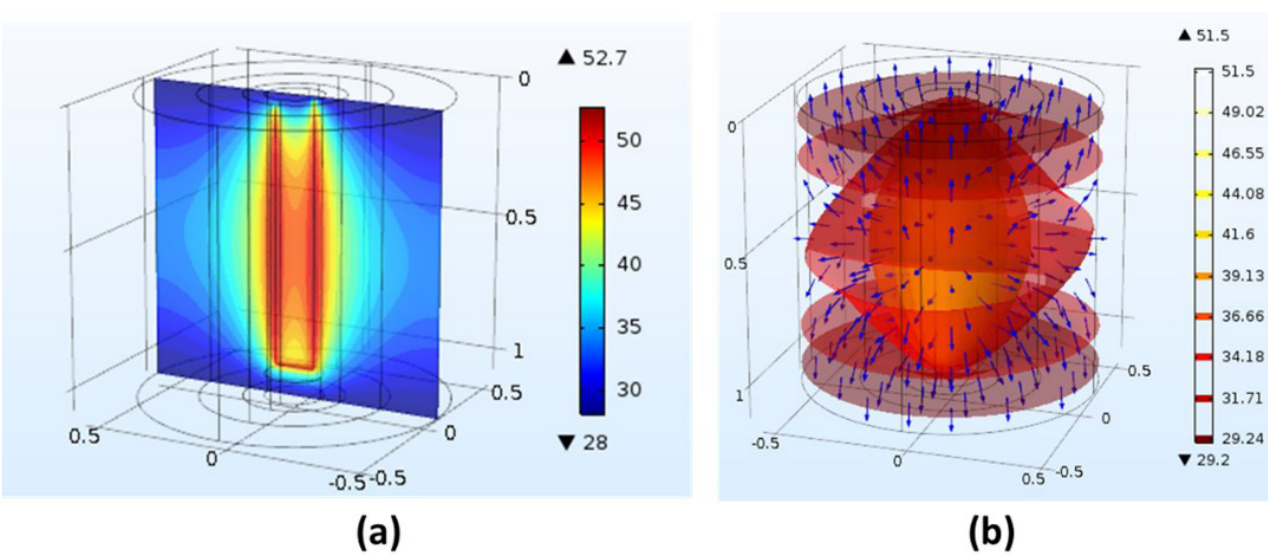


Figure 11. (a) temperature contours (°C) for a longitudinal cross-section of model pile at 96 h of thermal loading; (b) direction of heat flux after 96 h of testing.

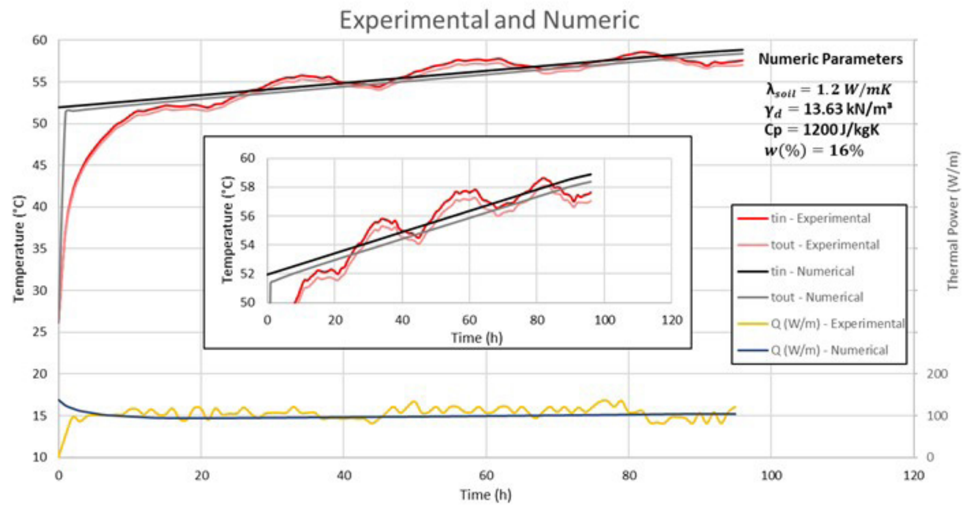


Figure 12. Comparison of experimental and numerical data from model calibration of thermal response test results.

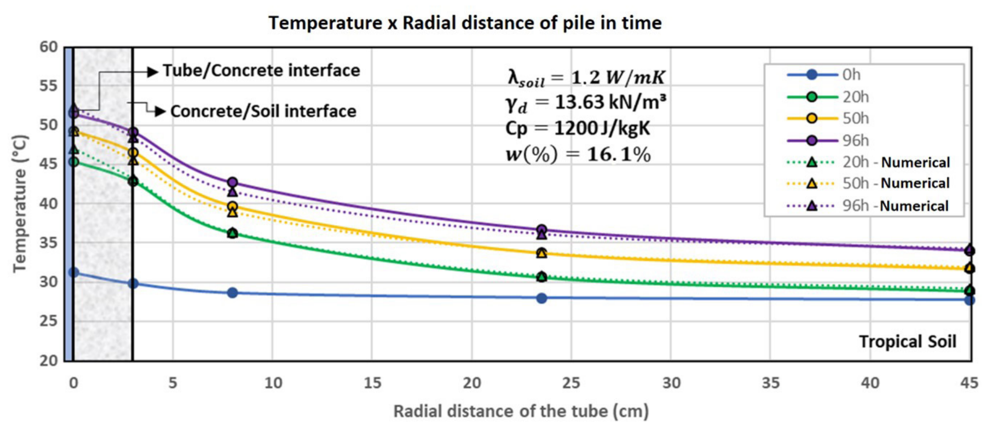


Figure 13. Comparison of experimental and numerical data from model calibration of space and time soil thermal distribution.

which does not invalidate the comparison for most of the chamber sensors (inner section), but must be properly dealt with in future experimental procedures. This aspect will be commented on later.

3.2 Parametric analysis

Numerical simulations were performed for 4 configurations of pipe arrangement in the pile prototype analyzed in the laboratory. From the calibration in 1U (as seen in Figure 11), analyses were performed in three more distinct configurations (2U, 3U, and 4U). In each configuration, the heat flux dissipated by the prototype was verified. The thermal conductivity in each situation was estimated too.

Figure 14 shows the graphs with the results of numerical simulations of the TRT tests for the 4 configurations of the studied prototype. In all configurations, the slope of the temperature line versus the natural logarithm of time remains constant, not suffering any variation with the configuration of tubes in the pile since the fluid flow rate inside the tubes remained constant in all configurations.

Although it is not ideal for analyzing a TRT with a prototype pile whose slenderness is much lower than that recommended by the standard. For the line source method to be accurate, the analyses were performed in such a way as to show that there is no variation in the slope of the regression line as a function of the configuration, which allows us to see that the variation of the effective conductivity of the prototype in the chamber was dependent only on the thermal flux dissipated in this same apparatus.

Due to the increase in the number of tubes, with the established configurations, the time and length of water circulation in the tube increased, which has allowed the observation of the increase in the inlet and outlet temperature variation in the tube as a function of its configuration. In addition, the heat exchange surface area of the tube increases. Consequently, the heat flux over the pile increases in the same proportion. This can be seen in Figure 15, which shows the variation between the inlet and outlet temperature of the prototype and the variation of heat dissipated to the ground for the configurations studied in each presented graph.

Observing Figure 16, one can notice a significant increase in the heat flux dissipated in the prototype from 1U to the 2U configurations. Going from 96.76 W/m to 155.63 W/m of heat exchanged an increase of approximately 60.9% in heat exchange from 2U to other configurations (3U and 4U). Moreover, the heat exchange rate increase from 3U to 4U is practically the same (around 14%).

This information becomes quite useful when determining the best cost/benefit of using tubes per pile. For this situation, for instance, increasing the length of 50% of the tube (from 2U to 3U) becomes unfeasible since the gain in the heat exchange rate in the prototype increases to only 13.8%. However, when increasing the length of the tube from 1U to 2U, one notices a considerable gain in the heat exchange rate in the tested prototype analyzed, allowing the perception that the 2U configuration has the best cost-benefit compared to the other simulated scenarios.

This paper showed the thermal behavior of a prototype pile heat exchanger in tropical soil, subjected to different

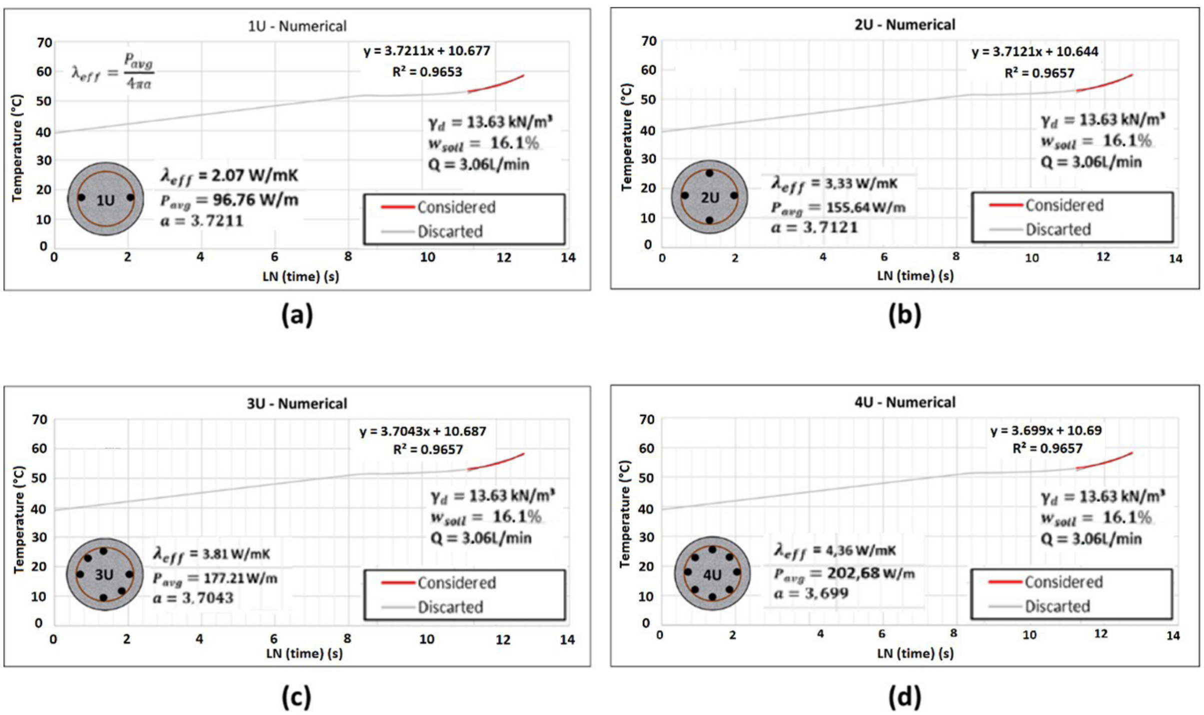


Figure 14. Thermal conductivity analysis by the line source method for configurations: (a) 1U; (b) 2U; (c) 3U; (d) 4U.

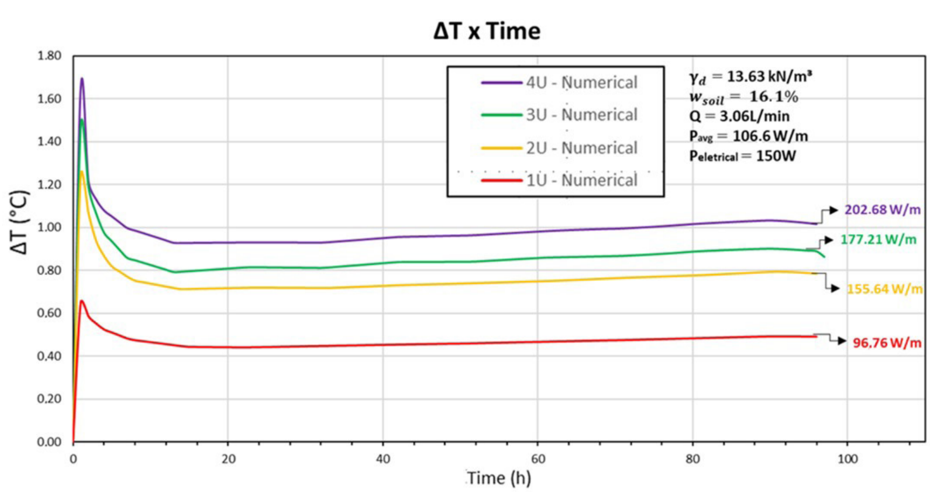


Figure 15. Variation of inlet and outlet water temperature in the prototype with test time.

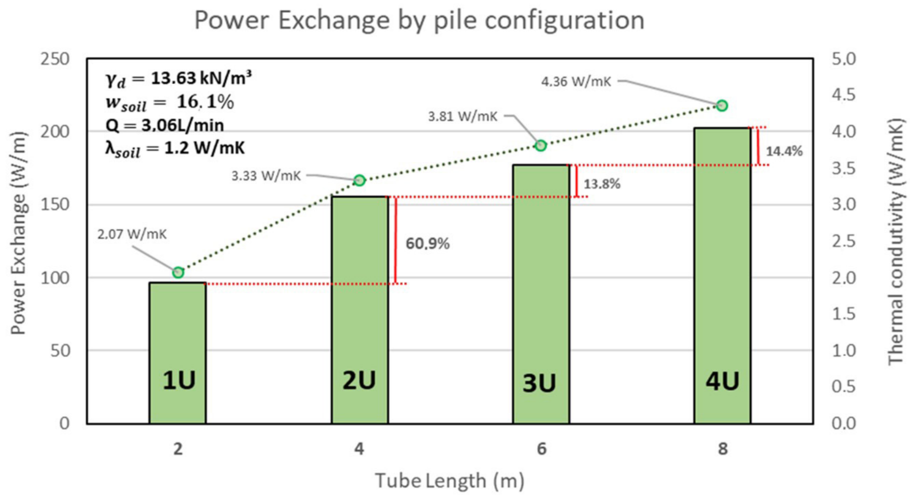


Figure 16. Cost benefit analysis for the best pile configuration analyzed.

configurations. There is still little work in Brazil developed in this line of research, especially in unsaturated tropical soil. This motivated the research groups of the Geotechnical Postgraduate Program of the University of Brasilia (GPFees and Geofluxo) to contribute to the development of this field of research nationwide.

4. Conclusions

The paper has provided preliminary results from on-going research that has employed a series of prototype simulations of a thermal pile embedded into a calibration chamber, with compacted unsaturated soil from a laterized deposit. The analyses will hopefully base future simulations of typical foundation layouts for large-scale structures founded on tropical soils of the region. This research is therefore an initial step on this direction.

Based on the analyses performed in this paper, it could be concluded that:

- After 50 h of testing, it is noticed that the regime of temperature increase over time is practically stationary, and the test can be analyzed with the equations from a stationary point of view (as can be seen in Figure 13);
- The angular coefficient derived from the analyses of the TRT simulations is independent of the configurations tried out in this paper. On the other hand, the heat flux dissipated by the prototype on the ground varies considerably depending on the configuration studied, being most efficient in the 2U condition and least efficient in the 3U and 4U configurations;
- The variation of the effective thermal conductivity of the prototype as a function of the pipe configuration in the analyzed heat exchanger pile prototype depends only on the variation of the heat flux dissipated from the prototype to the ground. This variation is, therefore, independent of the slope of the line source method analysis (as can be seen in Figure 14);
- Increasing the tube contact area increases the heat flux dissipated in the heat exchanger;
- The thermal response machine allowed the successful development of laboratory tests, which made it possible to develop relatively low-cost equipment to be reproduced by the academic community – especially for the special conditions of the soil in the mid-west region of Brazil.

It can be concluded that, besides the known limitations of this on-going research, still at an early stage, an initial assessment was achieved regarding some of the critical parameters to design heat exchanger pipes and piles immersed in the tropical unsaturated soil of the Federal District of Brazil. Perhaps with proper due modifications, the results gathered in this research will be of importance to start designing shallow geothermal systems to exchange heat loads with local superstructures, taking into account the specific local conditions of the region. The development of the whole technology, involving heat pumps, secondary superstructure refrigeration systems, and an integrated design, will eventually follow such initial steps.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Charles Pereira Chaves: conceptualization, Data curation, Visualization, Writing – original draft. Juan Camilo Silva: conceptualization, Data curation, Methodology, Supervision, Validation, Writing – original draft. Renato Pinto da Cunha: Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Final Review, Resources, Software. André Luis Brasil Cavalcante: supervision, Validation, Software, Resources, Writing – review & editing.

List of symbols

cm	Centimetres
Cp	Thermal capacity
Cw	Specific heat capacity of water
Gs	Specific gravity of the soil
HDPE	High-density polyethylene
IP	Plastic index
J	Joule
K	Kelvin
Kg	Kilogram
L_p	Pile length
m	Linear meter
m^2	Square meter
m^3	Cubic meter
P_{avg}	Thermal power average per meter
$P_{electrical}$	Electrical power
Q	Flow rate
q_{in}	Water flow rate
RMS	Root mean square
SUCS	*Soil unified classification system*
T_{in}	Inlet temperature
T_{out}	Outlet temperature
TRT	Thermal Response Test
W	Watts
WL	Liquid Limit
WP	Plastic Limit
w	Soil moisture content
γ_d	Dry unit weight of the soil
λ_{soil}	Soil thermal conductivity
λ_{pipe}	Thermal conductivity of the pipe
$\lambda_{mineral}$	Mineral thermal conductivity
ΔT	Temperature difference (inlet and outlet)
a	Angular coefficient
ρ_{soil}	specific mass of the soil
ρ_W	Water density λ_{eff} Thermal conductivity
°C	Celsius degree

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