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Thermal design of energy piles for a hotel building in subtropical climate: a case study in São Paulo, Brazil

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Case Study

Keywords
Energy piles
Micropile
Steel pile
Continuous flight auger pile

Abstract

The use of shallow geothermal energy through energy piles for the air-conditioning of buildings is increasing worldwide. This type of renewable energy technology is still not utilized in Brazil, where the hot dominating weather regions and the air cooling demand predominate. In this case of unbalanced heat transfer to the ground, the efficiency of the system may decrease with time due to the excessive heat injection into the soil. In order to investigate the possibility of an efficient application of this technology in São Paulo city, a balanced use of the ground for a ground-source heat pump (GSHP) system utilizing energy piles is evaluated in the present paper. Energy foundations were designed to meet the balanced heating and cooling loads (air conditioning and water heating) of a hypothetical business hotel building located in a site at the campus of the University of São Paulo, where thermal response tests (TRTs) were conducted on different types of energy pile. The number of energy piles required to supply the building thermal loads were estimated using the pile heat exchanger modelling software PILESIM 2.1 and compared with an analytical model prediction. The evaluations were done for three different types of pile tested at the site chosen for this study: micropiles, steel pipe, and continuous flight auger (CFA) piles. The results indicate that the ground heat extraction should be considered for the use of GSHP systems with energy piles in air cooling-dominated scenarios similar to the case studied here.

1. Introduction

Over the last twelve years, the consumption of electric energy for air conditioning in Brazilian residences has more than tripled, according to the Brazilian Energy Research Company (EPE, 2018). This growing demand for artificial air cooling causes negative impacts on the cost of electricity and environment. To mitigate this problem, the shallow geothermal energy using ground-source heat pump systems (GSHP) seems to be an environmentally friendly alternative to traditional air conditioning systems.

The GSHP system consists of a ground loop heat exchanger and a heat pump system (Lim et al., 2017), which allows the heat exchange between the ground and ambient temperature for cooling and heating of buildings. This system has been used for many years utilizing deep boreholes as ground heat exchangers; however, the additional cost of drilling deep boreholes has made this technology cost-prohibitive in some situations (Murphy et al., 2015). An alternative to this problem is the use of deep foundations as ground heat exchangers, commonly known as “energy piles”. Pile foundations, already necessary for structural support, when equipped with geothermal loops can be used for heat exchange operations, exploiting the near-surface geothermal energy (Sutman et al., 2020). Energy piles are constructed with pipe loops attached to the reinforcement cage for circulating heat-carrying fluid to facilitate soil–pile heat transfer.

In this context, heat exchanger piles were installed at the site of the CICS Living Lab, a building being built at the Campus of the University of São Paulo, in the urbane zone of São Paulo city. For this first use of energy foundations in Brazil, thermal response tests (TRTs) were conducted on three different pilot piles, constructed and tested to provide information for the design of the GSHP system that will be used in this building for space air cooling. However, the predominant thermal load demand of buildings in São Paulo is for ambient air cooling; and as mentioned in Zhang & Wei

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(2012), for cases of unbalanced heating and cooling loads the temperature of underground soil will gradually rise affecting the efficiency of the GSHP system. In cooling-dominated climates this imbalance can lead to an accumulation of heat in the ground, which decreases the coefficient of performance (COP) and increases energy consumption (Martins & Bourne-Webb, 2021).

Different strategies were proposed in previous studies to minimize this problem of heat accumulation of GSHP systems. Hybrid ground-coupled heat pump (GCHP) systems with domestic hot water (DHW) were investigated in Diao et al. (2010) to serve as a supplemental heat rejecter to alleviate the imbalance of ground thermal loads. Akrouch et al. (2020) suggested management strategies to active and/or deactivate groups of piles by zones, to prevent the increase of ground temperatures when dealing with unbalanced thermal loads. Martins & Bourne-Webb (2021) proposed the use of hybrid GSHP-NV systems (where NV means natural ventilation) to decrease cooling load imbalance in cooling-dominated buildings.

Therefore, considering the predominant air cooling demand of buildings in São Paulo city and in Brazilian regions of similar weather conditions, leading over time to an increase of the ground temperature, the current work was proposed to investigate a balanced application of a GSHP system to prevent this problem, by using energy piles for air cooling and to produce hot water daily.

This alternative operation mode of GSHP systems in cooling and heating process (to produce hot water) were investigated to provide a balance of ground temperature in Cui et al. (2008) and in Jalaluddin & Miyara (2012). In this case, the heat extraction from the ground also contributes to the increasing the heat exchange rate in cooling process. As suggested in Cui et al. (2008), in summer the system can operate in the heating mode for few hours to produce hot water when the cooling need is irrelevant or zero, and in the winter or when the cooling requirement is unnecessary, the main function of the system is to meet the hot water demand.

For the current study, a thermal design of energy piles for a hypothetical business hotel building located at the University of São Paulo campus was carried out using the results of ground thermal parameters and pile thermal resistance obtained from thermal response tests (TRTs) performed on three different types of energy piles at this site. This paper details the simulations procedure and results.

2. Case study description

2.1 Weather and soil conditions

The CICS Living Lab site, assumed for the case simulated in this paper, is located at the University of São Paulo (Figure 1) in São Paulo city (latitude: 23°33’15.8”S; longitude: 46°43’51.2”W), Southeast Region of Brazil, with annual average temperature of approximately 19.3-19.6 °C (maximum 24.9°C-25.2°C and minimum 15.5-15.8°C).

Figure 2 presents the soil profile at the CICS site, the results/ locations of standard penetration tests (SPT tests), and the variation of ground temperature with depth, obtained from temperature sensors installed in CFA piles by Pessin (2021). This figure illustrates the predominance of saturated medium dense slightly clayey sand, from approximately 4 to 16 m deep.

Pessin et al. (2022) determined the groundwater flow velocity of two sandy layers at the CICS site and found the

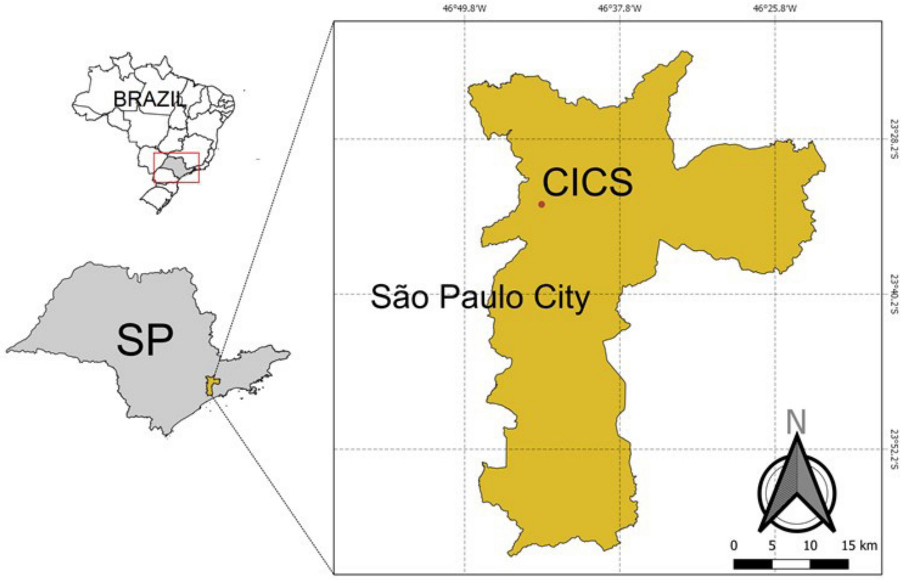

Figure 1. Location of the *CICS* site.

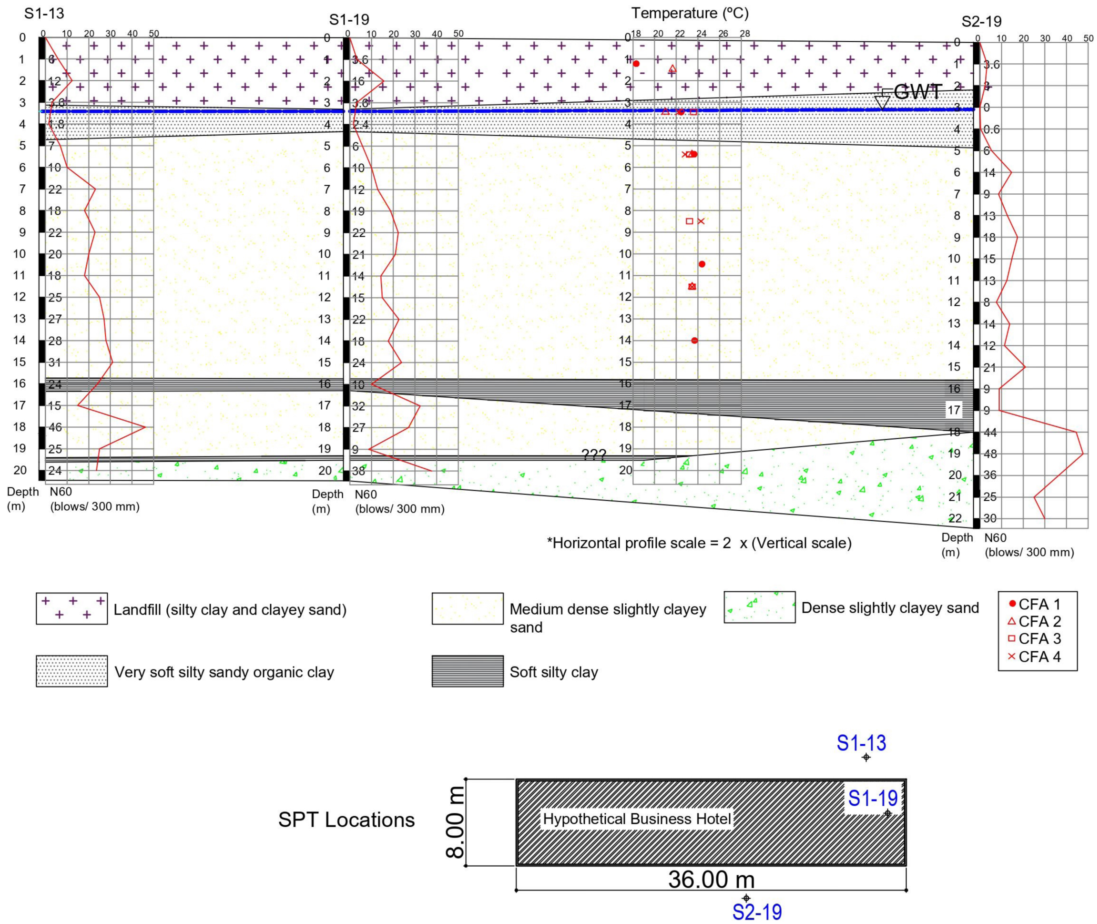

Figure 2. Soil profile, SPT tests results and locations, and ground temperature variations with depth.

Table 1. Characteristics of energy piles.

Type of energy pile	Diameter (m)	Pipe configuration in pile	Average length of piles (m)	Active length[a] of piles (m)
Micropile	0.35	U-shaped pipe	15	15
CFA pile	0.70	Triple-U	15	10.5
Steel pipe pile	0.24[b]	U-shaped pipe	20	20

[a]Active length = pile length equipped with pipes; [b]external pipe diameter.

highest values of flow velocity (from 0.05 to 0.2 m/day) for the uniform sand layer from 5 to 6 m deep. For the layer from 10 to 11 m deep, they observed a flow velocity of ~ 3.3×10^{-4} m/day. These values were adopted for the simulation conducted in this work.

2.2 Tested energy piles

Three different types of energy pile, constructed and tested at the CICS site, were assumed for the simulation performed for the hotel building thermal demand presented in this paper (for space cooling and hot water): micropile, continuous flight auger (CFA) pile, and steel pipe pile filled with grout. Figure 3 illustrates the dimensions and installation of the three types of energy pile, and Table 1 describes their geometrical characteristics. All piles were equipped with loops of high-density polyethylene (HDPE) pipes (inner diameter of 26 mm and outer diameter of 32 mm) for the heat exchange with surrounding soils.

The energy piles showed in Figure 3 were tested in previous investigations. Morais & Tsuha (2018) conducted a thermal response test (TRT) on the energy micropile ilustrated in Figure 3a. Later, Pessin (2021) carried out a TRT test on the CFA energy pile (Figure 3b), and Murari (2022) on the steel energy pile (Figure 3c). The details and results of the TRTs performed on these piles are described in these three mentioned studies. TRT tests provide thermal parameters used for simulation of GSHP systems, such as ground effective thermal conductivity, λ_{eff}, and the pile thermal resistance, R_b (Morais, 2019; Park et al., 2019).

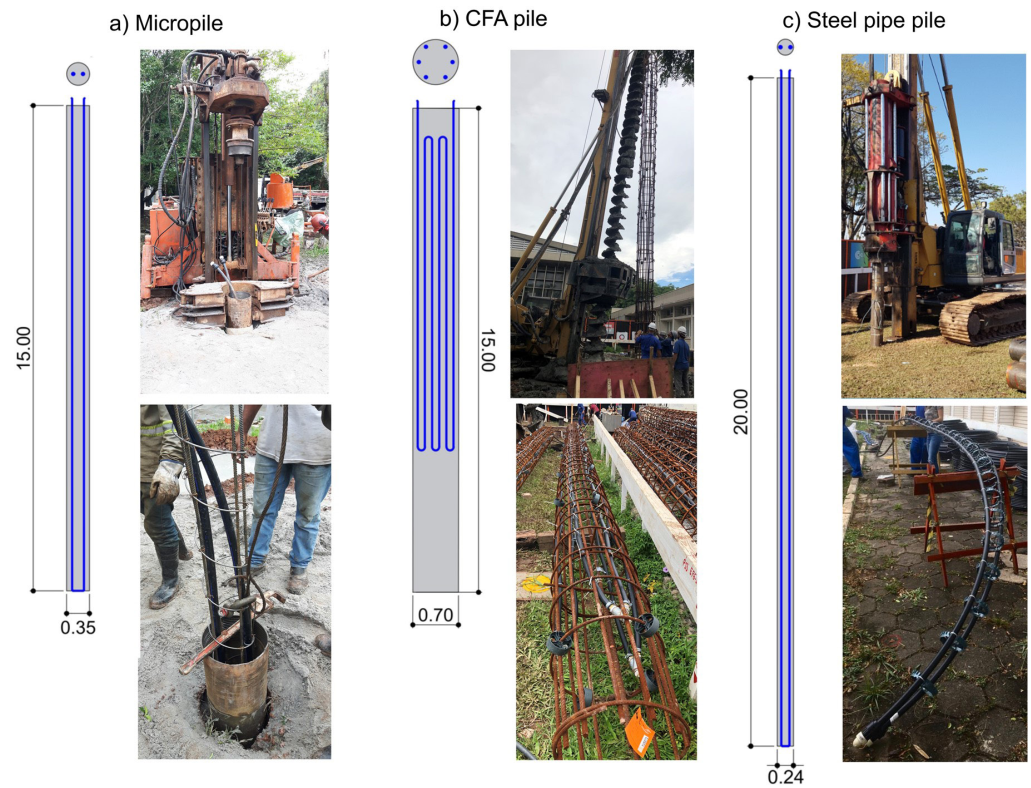

Figure 3. Dimensions and installation of energy piles at the CICS site: (a) micropile; (b) CFA pile; (c) steel pipe pile (dimensions in meters).

TRT is a field experiment for estimating the thermal parameters mentioned above; however, they cannot provide the actual thermal performance of heat exchanger pile in the real operating condition of GSHP systems. For this case, the thermal performance test (TPT) is the most suitable field test to evaluate the thermal performance (Park et al., 2019). Brandl (2013) suggests values of heat exchange rate for the pre-design of energy foundations and feasibility studies; however, for a more reliable estimation of the energy pile performance, a thermal performance test (TPT) was conducted on the CFA energy pile at the CICS site by Pessin (2021), to determine the heat rejection rate of a heat exchanger foundation element during the cooling operation for a building located at the test site.

In a TPT test the inlet fluid (water) temperature is kept constant using a heater system regulated by a temperature controller (You et al., 2014). The heat exchange rate was obtained by monitoring the outlet fluid (water) temperature while maintaining the inlet fluid temperature at approximately 35°C. Further details of the test equipment and experimental procedures can be found in Pessin (2021). As adopted in Park et al. (2016), for this test a mean flow rate of 9.3 l/min (measured by a turbine flowmeter) was used to provide sufficient temperature difference between the inlet fluid and the outlet fluid more than 2 °C. The TPT results are presented in Figure 4. The variation of heat exchange rate (q) showed in this figure was calculated by Equation 1:

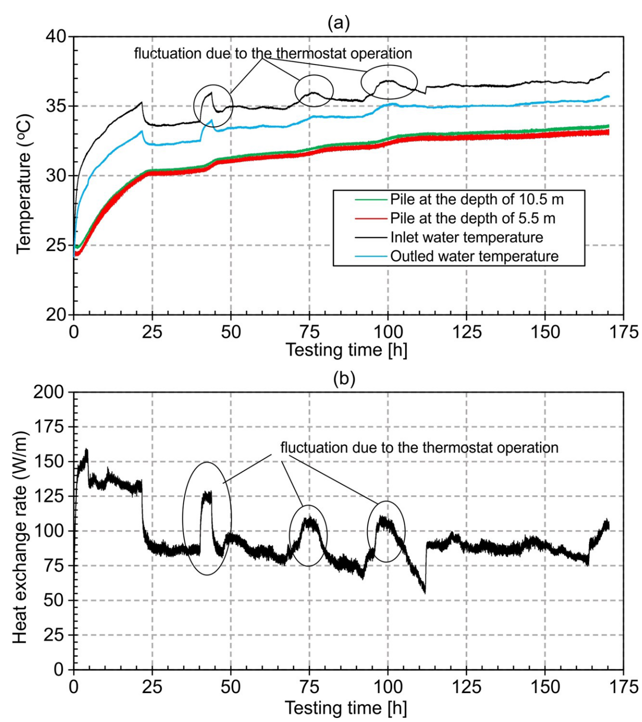

Figure 4. Variation of: (a) the fluid and pile temperatures; (b) of the heat exchange rate of the CFA energy pile over 175 h.

$$q = \frac{mc\left(T_{in} - T_{out}\right)}{L} \quad (1)$$

where, q is the heat exchange rate per pile active length (W/m); T_{in} is the inlet temperature of the fluid (K), T_{out} is the outlet temperature of the fluid (K), m is the flow rate of the fluid (kgs^{-1}), c is the specific heat capacity of the fluid (J kg^{-1}K^{-1}) and L is the pile active length (m).

Figure 4a shows that the after around 110 hours of heat rejection in the ground the pile temperature become almost constant. Figure 4b indicates that the heat exchange rate decreases significantly after few hours and tends to be constant (ignoring the fluctuations caused by the thermostat operation) with a value of approximately 85 W/m. This trend was also observed in a TPT test conducted in You et al. (2014) on a cement-fly ash-gravel (CFG) pile with 420 mm in diameter and 18 m in length. 2.3. Building and GSHP system description

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The building considered in this case study is a typical example of a business hotel in São Paulo city, with 20 floors and 12 rooms per floor, as illustrated in Figure 5. The occupancy schedule is defined as most of the occupation occurs from 06:00 PM to 08:00 AM and the main systems (lightning, air conditioning, and water heating) have their main demands on the same period.

Normally, the cooling demand of the building is supplied by a central water-cooling system composed of an electric chiller serving a set of fan coils with one fan coil for each room. The water heating demand of the building is supplied by a central water heating system composed of natural gas water heaters.

As mentioned previously in the text, one of the challenges of using GSHP systems is to balance the cooling and heating loads to control the variation of ground temperature with time. Therefore, the proposed system is composed of a set of heat pumps that provides the cooling and the heating demand for the hotel. Due to the superposition of the heating and cooling demand, it is necessary to include a water heated tank in the system. The temperature of such tank will be maintained by the set of heat pumps during the day (heat extraction from the ground), when there is a low cooling demand. During the night, the demand of heated water is supplied by the heated water tank and the cooling demand is supplied by the set of heat pumps (heat rejection into the ground).

A simplified schematic of the system for the cooling operation (Figure 6) and heating operation (Figure 7) is presented. To maintain a good efficiency and longer life cycle of the ground source heat pumps, it is important to balance the heating and cooling demand drawn from the ground. For the business hotel, the heating demand is much higher than the cooling demand, which imposes an unbalanced operation. To overcome this problem, the heating demand was split in such way that the heating and cooling demand of the heat pumps are similar to provide a balanced ground load. The remaining heating demand is provided by a set of natural gas water heaters.

3. Simulations using PILESIM 2.1

The program PILESIM 2.1 was used to study the long-term behavior of heat exchangers piles for a hypothetical building at the CICS site. This program was developed to simulate heating and cooling systems with energy piles or multiple borehole heat exchangers (Pahud, 2007). The long-term behavior of the energy piles for the building thermal demand was examined for a period of 20 years. Three different simulations were performed in order to validate the GSHP design for the three different foundation types tested at the CICS site.

3.1 Procedure description

The program PILESIM has been used extensively for the thermal simulation of heat exchanger pile systems. This program uses a modified finite difference method based on a version of the Duct Ground Heat Storage Method (DST) (Fadejev et al., 2017; Hellström, 1991; Martins & Bourne-Webb, 2021; Pahud, 2007) to perform thermal simulations and calculate the heat transfer from the ground to the thermal energy distributed in a building (Pahud, 2007).

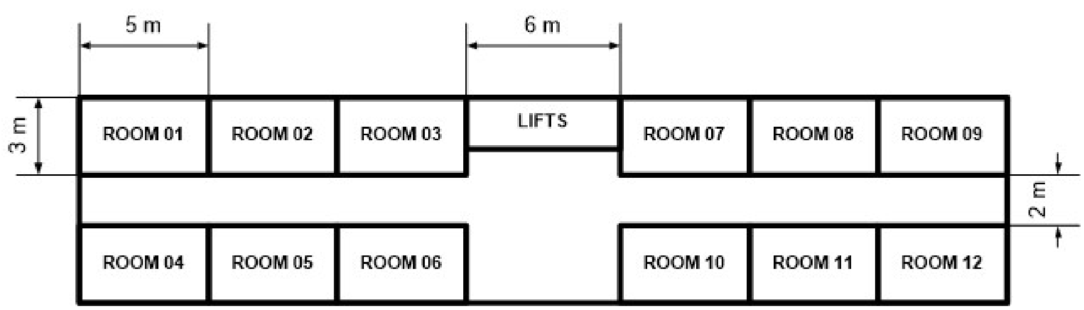

Figure 5. Simplified floor plan of a typical floor of the hotel building.

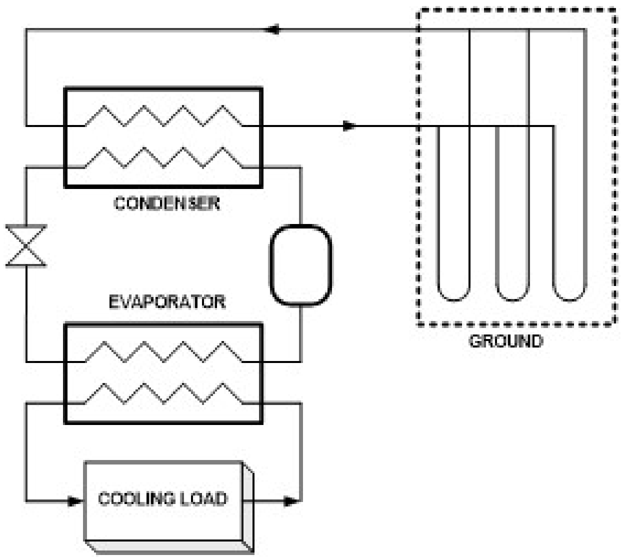

Figure 6. Simplified flow diagram (cooling operation).

The methodology used in this paper is illustrated in Figure 8. The hotel building was modelled using Energy Plus, an open-source tool for whole building simulations (Crawley et al., 2001) coupled with a TMY (Typical Meteorological Year) weather data file for the city of São Paulo. The outputs of such simulations are the hourly profile of the heating and cooling demand of the hotel. The estimated results are introduced as input for the simulations using the program PILESIM 2.1, which provides the thermal performance of energy piles, the thermal loads covered by the geothermal system, the COP values (for heating and cooling operations), the heat extraction and injection rates per meter pile, and the temperature of the ground surrounding the energy piles. This program provides results for each year of operation and over 20 years.

For the simulations using PILESIM 2.1, there are some assumptions that need to be considered for optimal use: (i) a relatively large number of energy piles; (ii) the energy piles

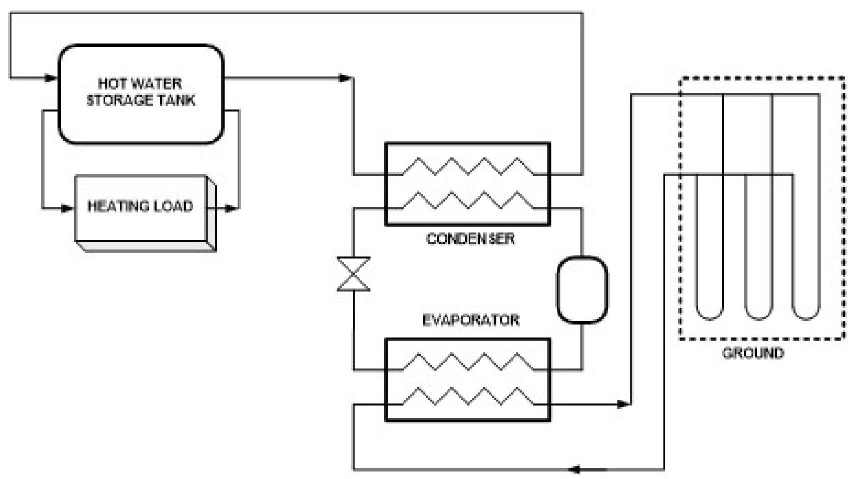

Figure 7. Simplified flow diagram (heating operation).

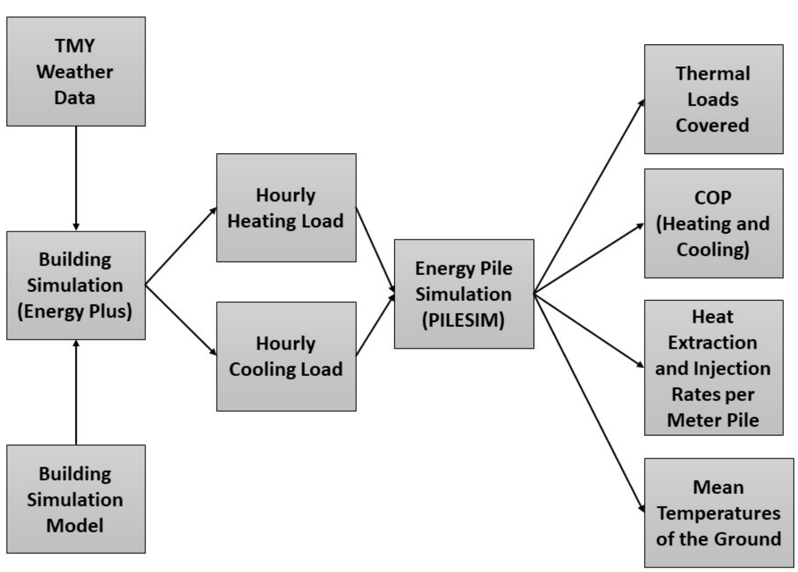

Figure 8. Schematic of the simulation methodology.

should be located in a regular spatial arrangement (a circular or squared area); (iii) the energy piles should have the same active length (Fadejev et al., 2017; Pahud, 2007).

According to the User Manual (Pahud, 2007), the input parameters to define a heat exchanger pile system is grouped in five main categories: (i) ground characteristics; (ii) energy piles parameters; (iii) ground-building interface specifications; (iv) heat pump and cooling machine data; and (v) loading conditions for heating and cooling. Additionally, it is necessary to specify the thermal properties of the soil layers in which the energy piles are installed (up to three layers can be specified). Moreover, it is possible to include the presence of a groundwater flow (if any) and the initial ground temperature before heat exchanges.

The three tested piles and the CICS site described above in the paper were used to characterize the energy foundations and the ground conditions for the simulations. For simplification, based on the soil profile presented in Figure 2, it was assumed that the topsoil layer, from 0 to 4.8 m, consists of a clayey soil with Darcy velocity of groundwater equal to 0 m/day. The second layer, from 4.8 to 10 m, is composed of sandy soil with the Darcy velocity of groundwater equal to 0.125 m/day, average value measured in Pessin et al. (2022) for the layer from 5 to 6 m. The third layer, from 10 to 20 m, is composed of a sandy soil with the Darcy velocity of groundwater equal to 3.3×10^{-4} m/day, based on the results of Pessin et al. (2022).

The soil thermal conductivity (layer from 0 to 20 m depth) for the current simulation was defined equal to 2.7 W/mK, based on the interpretation of the results of TRTs performed on a micropile and a steel pile filled with grout at the CICS site. Morais & Tsuha (2018) obtained a value of ~2.8 W/mK from the TRT conducted on a micropile (Figure 3a), and later, Murari (2022) found a value of ~2.6 W/mK from the TRT conducted on a steel pile (Figure 3c). The ground volumetric thermal capacity was adopted as 2.4 MJ/m^{3}K, based on the values suggested in Laloui & Rotta Loria (2020). The input parameters for the three types of energy piles evaluated are presented in Table 2. For all simulations, an active pile length (identical to the pile length) of 20 m was defined based on the driven resistance per pile recorded during steel pipe piles installation at the CICS site. The number of piles were defined in order to provide acceptable results of COP values and of heat rejection rate per meter pile (W/m), as the water heating demand can be complemented by the installation of natural gas water heaters.

For the present simulation it is necessary to include parameters related to the cellar (a non-heated space that separates the heated rooms from the ground below the building) and to the horizontal connected pipes, which are presented in Table 3.

The loading conditions for heating and cooling were obtained through EnergyPlus software for the standard business hotel, as presented in Figure 8. Loading conditions were determined based on heat demand, cold demand, and corresponding temperature levels. The parameters related to the heat pump and cooling machine thermal performances were calculated to ensure the best functioning of the system. A heat pump works with a refrigeration cycle which requires maintaining a higher condensing temperature (50 to 52 °C). To be able to reject the heat from the heat pump condenser, the inlet water temperature in the energy piles should be 45 °C in cooling operation mode. When the heat pump operates in the heating operation mode, the inlet water temperature in the energy piles should be 7 °C. These data were used as input to the simulations using PILESIM 2.1.

A limitation of the PILESIM program is that it only considers continuous cooling/heating operation for six months, and, for the current hotel building evaluated an alternative operation mode was assumed. Therefore, as the alternative operation mode increases the energy pile performance (Cui et al., 2008; Jalaluddin & Miyara, 2012), the results of the current simulation correspond to the most unfavorable operation mode.

3.2 Results

Long-term simulations performed with PILESIM 2.1 provided different results for the three types of heat exchanger piles evaluated. The simulations were carried out

Table 2. Energy piles parameters for simulation with PILESIM 2.1.

	Micropiles	CFA piles	Steel pipe piles
Diameter (m)	0.35	0.70	0.24
Number of piles	180	68	115
Average active length of piles (m)	20	20	20
Pile thermal resistance R_b (K/(W/m))[a]	0.13	0.04	0.10
Internal pile thermal resistance R_a (K/(W/m))[b]	0.39	0.40	0.34
Average spacing between piles (m)	1.20	2.10	1.50
Pipe configuration in pile	U-pipe configuration	U-pipe configuration	U-pipe configuration
Pipe number in a cross section of a pile	2	6	2
Pipe inner diameter (mm)	26	26	26

[a]Values obtained by Morais & Tsuha (2018), Pessin (2021), and Murari (2022) from the interpretation of TRTs; [b]Calculated by equations suggested in Hellström (1991), assuming an average typical thermal conductivity value for saturated concrete suggested in Loveridge (2012).

Table 3. Interface ground-building parameters.

Interface ground-building parameters	Input values for simulations
Room air temperature in building (°C)	24
Heigth of the cellar between rooms and ground (m)	0.60
Air change rate in the cellar (1/h)	0.00
Global-room cellar heat transfer coeficient (W/m^{2}K)	6.70
Insulation thickness between ground and cellar (m)	0.00
Concrete thickness between ground and cellar (m)	0.14
Lenght of the horizontal pipes on ground (m)	36.00

to predict the thermal behavior of the piles over 20 years. The outputs of the program (mean values for the period of simulation, for all scenarios adopted) are presented in Figures 9, 10 and 11.

The results of Figures 9 to 11 show that the average values of COP during 20 years of heating are the same for the three simulations using different types of piles, and the values of efficiency for the cooling are also similar. Most of the obtained values are within the ranges presented in Brandl (2006), which recommended GSHP systems with COP values ≥ 4 for economic reasons. Only the simulation for steel pipe piles presented a value of 3.9 for the average efficiency of the cooling machine (slightly smaller than the recommended value).

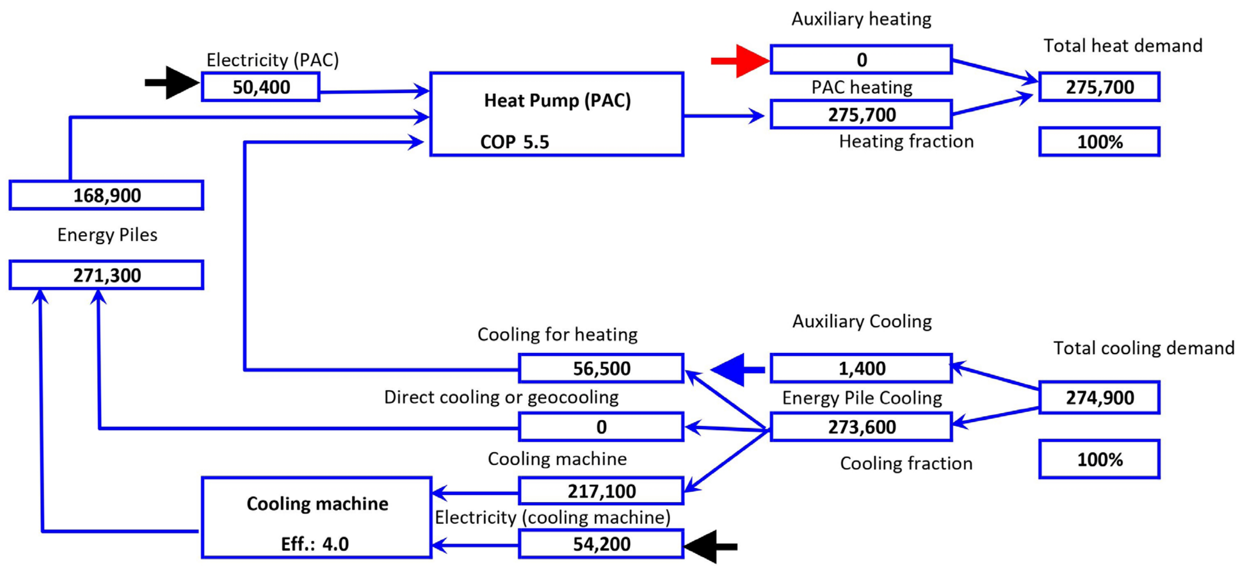

Figure 9. System heat balance in kWh/year (period of 20 years) for the system utilizing micropiles.

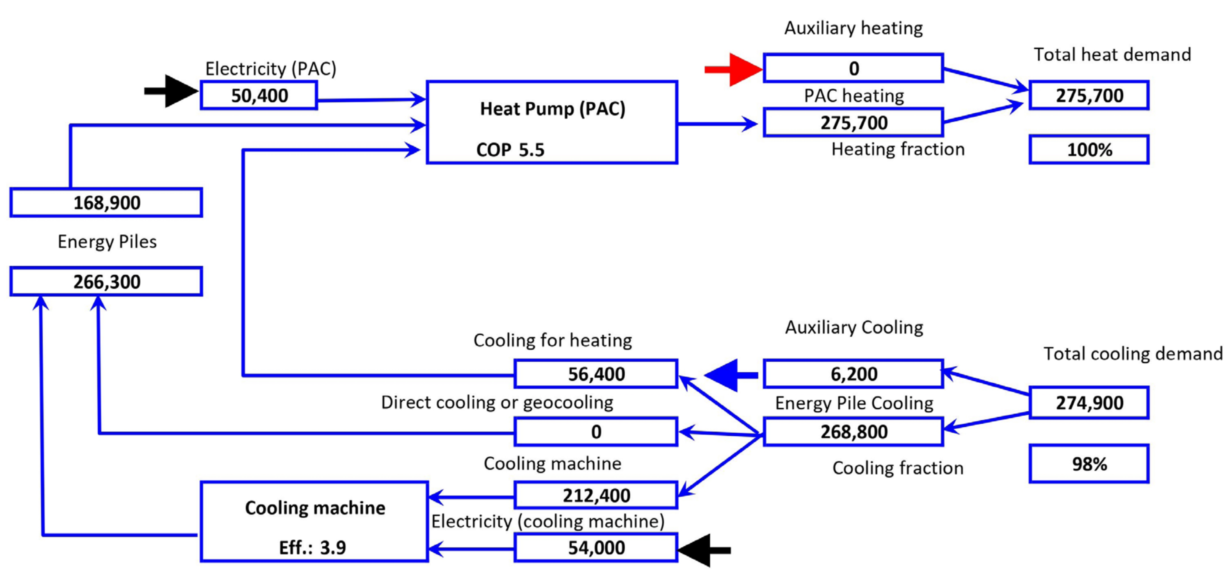

Figure 10. System heat balance in kWh/year (period of 20 years) for the system utilizing steel pipe piles.

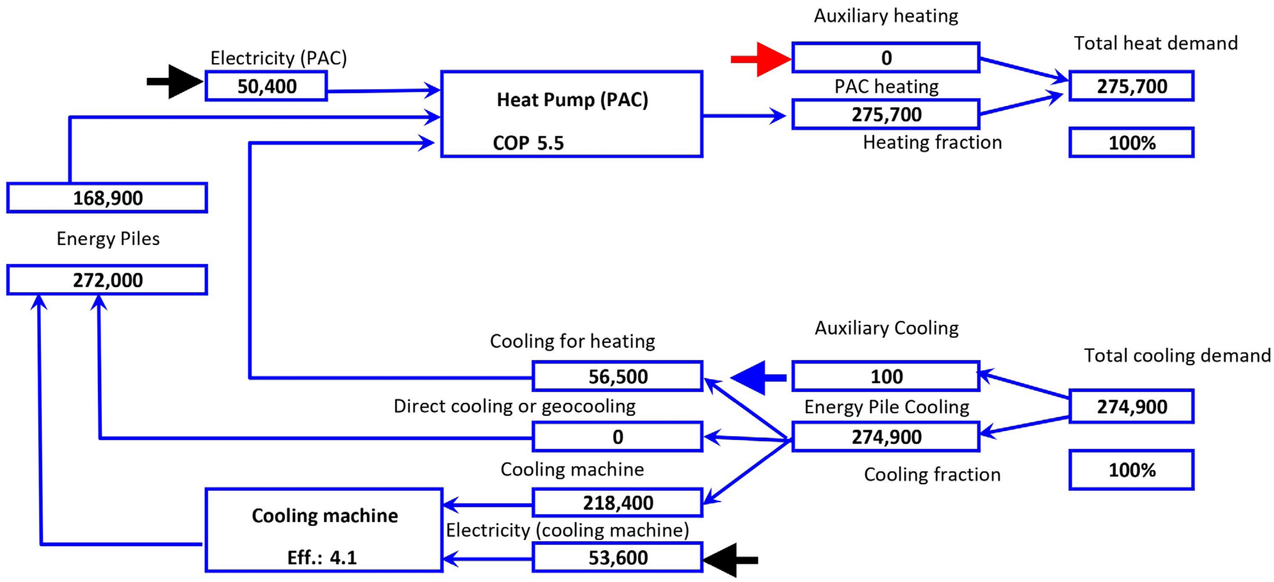

Figure 11. System heat balance in kWh/year (period of 20 years) for the system utilizing CFA piles.

Figures 9 to 11 also indicate the fractions of total heating demand covered by the heat pump and the fraction of the total cooling demand covered by the piles system and cooling machine. For the cases utilizing micropiles and CFA piles, 100% of the heating and cooling energies could be covered by the GSHP system, without the need for power provided by an auxiliary source. For the case with steel energy piles, the heating demand covered by the energy piles is 100%, while for cooling is 98%.

The program also provides results of the variation of the ground temperature during 20 years of operation of the GSHP system (Figure 12). The average initial ground temperature was about 23.8 °C; therefore, Figure 12 indicates an increase of approximately 11 °C in soil temperature after 20 years. This figure also shows that the ground temperature rises and remains practically constant after around 10 years of system operation. On the other hand, this increase does not seem to have affected the system efficiency, as in most cases the COP values are within the recommended range. Figure 12 also shows that the increase of ground temperature is slightly lower for the case of CFA piles. Probably it occurs because the number of piles in this case is reduced compared to the other two cases (Table 2).

On the other hand, as mentioned before in the text, the program PILESIM considers periods of six months of continuous operation (for cooling or heating demand), and the alternative cooling/heating mode proposed for the studied hotel building can alleviate the heat buildup in the surrounding soil. Jalaluddin & Miyara (2012) noted that the alternative operation mode provides a balance of ground temperature around the ground heat exchanger. Therefore, the results shown in Figure 12 correspond to the most critical condition for the ground, by considering a continuous operation mode. Probably for the hotel building proposed with an alternative operation mode the increase in ground temperature would be lower.

Additionally, the operation of energy foundations will cause temperature changes inside piles inducing additional stresses, which can affect the pile settlement. Therefore, the use an alternative cooling/heating mode appears to be less problematic for the foundation behavior, as in this case the variation of pile temperature would be reduced compared to the case of a continuous operation.

The average values of heat extraction and injection rates per meter of pile during 20 years of simulation are shown in Table 4. The heat injection and extraction rates per meter pile are higher for the CFA piles (larger pile diameter and larger heat exchange surface) and lower for the micropiles. The results for heat injection rates obtained for the cases of CFA and steel pipe piles are in good agreement with the recommendations of Brandl (2013) which suggested values of 40-60 W/m for piles with a diameter smaller than 0.5 m and 35 W/m^2 for piles with diameter greater than 0.6 m (for the CFA pile case the obtained value of 71 W/m corresponds to ~32 W/m^2). For the case of the system using micropiles, the values obtained are slightly lower than the recommended for piles with a diameter smaller than 0.5 m.

Additionally, the heat exchange rate recommended in Brandl (2013) for piles with diameter larger than 0.6 m is slightly lower than the value observed from the TPT test conducted on a CFA pile at the CICS site (Figure 4). Therefore, the suggested heat exchanger rate for the pre-design of energy foundations seems to be adequate for the current case study.

On the other hand, the heat extraction rates per meter pile for heating purposes are much higher compared to those obtained for cooling purposes. The values obtained for CFA piles case (135 W/m) and steel piles case (80 W/m) are

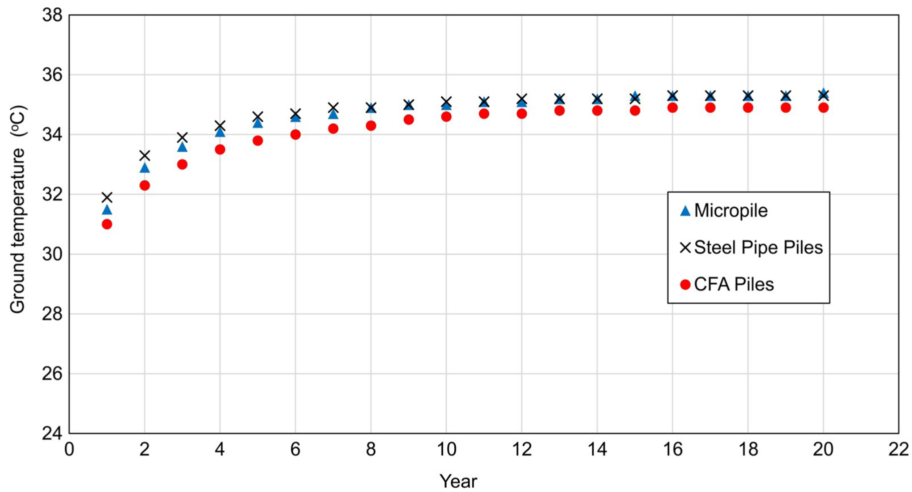

Figure 12. Variation of ground temperature during 20 years of the GSHP system operation.

Table 4. Results of simulations with PILESIM 2.1

	Micropiles	CFA piles	Steel pipe piles
Heat extraction rate per meter pile (W/m)	51	135	80
Heat injection rate per meter pile (W/m)	27	71	42

higher than those recommended by Brandl (2013) mentioned above. As shown in Table 4, only the values obtained for the micropiles case are within the recommended range (51 W/m). However, the main demand for the hotel building in São Paulo city is for space cooling, as the water heating demand can be complemented by other energy sources if the heat extraction using CFA and steel energy piles be not enough to the heating load requirement.

4. Comparison with analytical model

For comparison purposes, another estimation of the necessary length of energy piles for the GSHP system evaluated was done using an analytical model proposed by Ingersoll et al (1954 apud Kavanaugh & Rafferty, 2014). This model is based on the equation for the heat transfer from a cylinder buried in the ground, developed and evaluated in Carslaw & Jaeger (1947 apud Kavanaugh & Rafferty, 2014).

The first parameter that should be defined, besides the heating and cooling loads, is the coefficient of performance of the heat pump. This coefficient considers the efficiency of the heat pump and provides the actual amount of heat that should be rejected or extracted from the ground, as shown in Equations 2 and 3.

$$\frac{q_{cond}}{q_{lc}} = \frac{COP_c + 1.0}{COP_c} \tag{2}$$

where:

q_{cond}: heat pump condenser heat rate to ground [W];
q_{lc}: building cooling load [W];
COP_c: coefficient of performance (cooling mode).

$$\frac{q_{evap}}{q_{lh}} = \frac{COP_h - 1.0}{COP_h} \tag{3}$$

where:

q_{evap}: heat pump evaporator heat rate from ground [W];
q_{lh}: building heating load [W];
COP_h: coefficient of performance (heating mode).

The net annual heat transfer rate (q_a) is evaluated as the average between the q_{cond} and q_{evap} with the full-load hours in cooling ($EFLH_c$) and heating ($EFLH_h$), respectively, as shown in Equation 4.

$$q_a = \frac{q_{cond} \times EFLH_c + q_{evap} \times EFLH_h}{8760} \tag{4}$$

The equation for calculating the ground heat exchanger length for cooling is Equation 5:

$$L_c = \frac{q_a R_{ga} + q_{cond}\left(R_b + PLF_m R_{gm} + F_{sc} R_{gst}\right)}{t_g - \frac{ELT + LLT}{2} + t_p} \tag{5}$$

The equation for calculating the ground heat exchanger bore length for heating is represented by Equation 6:

$$L_h = \frac{q_a R_{ga} + q_{evap}\left(R_b + PLF_m R_{gm} + F_{sc} R_{gst}\right)}{t_g - \frac{ELT + LLT}{2} + t_p} \tag{6}$$

where:
F_{sc}: short-circuit heat loss factor between supply and return tubes in bore;
L_c: required bore length for cooling [m];
L_h: required bore length for heating [m];
PLFm: part-load factor during design month;
q_a: net annual average heat transfer to the ground [W];
R_{ga}: effective thermal resistance to the ground – annual pulse [m.K/W];
R_{gst}: effective thermal resistance to the ground – short pulse [m.K/W];
R_{gm}: effective thermal resistance to the ground – monthly pulse [m.K/W];
R_b: thermal resistance of bore [m.K/W];
t_g: undisturbed ground temperature [°C];
t_p: long-term ground temperature penalty caused by ground heat transfer imbalances [°C];
ELT: heat pump entering liquid temperature [°C];
LLT: heat pump leaving liquid temperature [°C].

The analytical model allows the design of the GSHP system in a simplified way, providing the pile lengths necessary to meet the energy demands. Table 5 presents the outputs of the analytic calculations.

The total pile length and shaft area values provided by the analytical model are similar to those of the simulations using PILESIM 2.1 for the micropiles and CFA piles cases. As illustrated in Table 5 and Figure 13, these values estimated using the program PILESIM 2.1were 10% higher for the micropiles case and 12% higher for the CFA piles case compared to the analytical model results. However, for the steel pile case, the values obtained using PILESIM 2.1 are 37% higher compared to those found by the analytical model.

The difference in total shaft area necessary between CFA piles and micropiles shown in Figure 13b can be explained by the difference in relative area ratio between the heat exchanger pipes and the pile shaft area (A_{pipe}/A_{pile}), illustrated in Table 6. During the GSHP system operation, the heat can be extracted or rejected in the ground by circulating a fluid (normally water) through the heat exchanger pipes. As presented in Table 6, for the CFA pile case the pipe area is 27% of the pile shaft area (ground contact area), while for the micropile case is only 18%. Therefore, a higher ground contact area (shaft area) is necessary for the micropile evaluated in this paper.

On the other hand, for the steel pipe pile case the relative area ratio is 27%, equal to the CFA pile case, and the necessary shaft area is around 60% of the value obtained for the CFA pile (see Table 5). Therefore, these results indicate that the relative area ratio is not the only influential parameter on the energy pile performance, and that the thermal performance is not directly proportional to the pile shaft diameter (for piles with the same values of A_{pipe}/A_{pile}).

The estimation of the pile shaft area needed to meet the required design pile load capacity for the hotel building simulated is not considered in the current evaluation of energy pile systems. For a conventional foundation design, the shaft resistance capacity for piles is proportional to the shaft area for a particular pile type. However, the results of

Table 5. Analytical model vs. PILESIM results.

Results	Analytical model			PILESIM program		
	Micropiles	CFA piles	Steel pipe piles	Micropiles	CFA piles	Steel pipe piles
Total pile length (m)	3249.5	1209.4	1676.2	3600	1360	2300
Total pile shaft area (m^2)	3573.0	2659.6	1263.8	3958.4	2990.8	1734.2

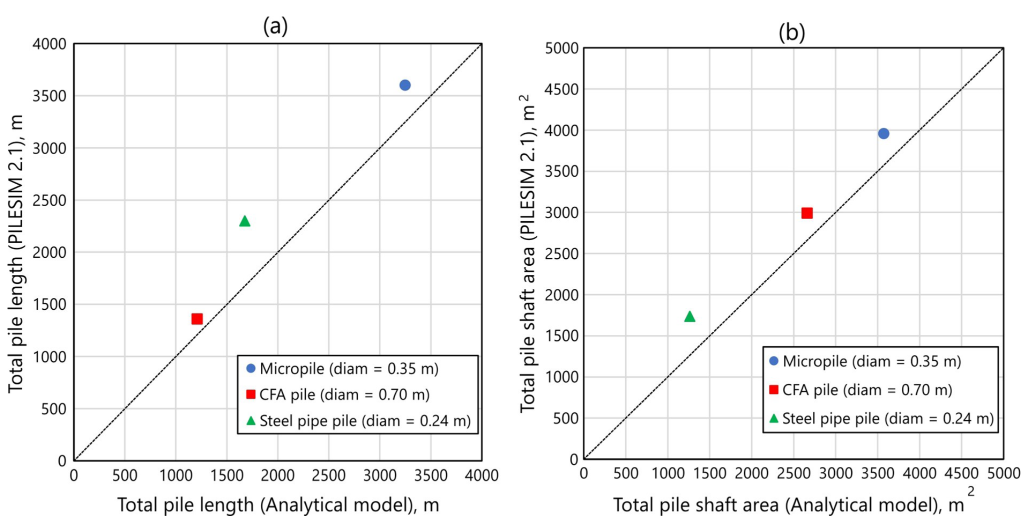

Figure 13. Results of (a) total needed pile length; (b) shaft area.

Table 6. Relative area ratio between the heat exchanger pipes and the pile shaft area (A_{pipe}/A_{pile}).

	Micropiles	CFA piles	Steel pipe piles
Pile shaft diameter (m)	0.35	0.70	0.24
Pipe external diameter (m)	0.032	0.032	0.032
Pipe number in a cross section of a pile	2	6	2
A_{pipe}/A_{pile}	0.18	0.27	0.27

needed shaft area to meet the thermal loads of a building shown in Figure 13 are independent of pile type (or installation procedure), while for the foundation design the values of unit skin friction (and needed shaft area) vary according to the pile type.

For a more economical application of energy pile systems, the total pile length (or shaft area) needed to meet the thermal loads should be lower than those needed to support the building mechanical loads. If the total pile length necessary for energy purposes is higher than the requirement for the foundation design, additional heat exchanger boreholes can be used to complement the building thermal demand.

5. Conclusions

The number and length of energy piles needed to meet the thermal loads demand of a hypothetical business hotel in São Paulo city were estimated using the program PILESIM 2.1 and by an analytical model. For the simulations, the ground and energy pile characteristics assumed were obtained from different studies carried out on the CICS site, located at the University of São Paulo campus. The simulations were carried out considering a continuous operation of the GSHP system; however, in the proposed case these systems operate in alternative operation mode, which increases the energy pile system performance as observed in previous studies.

The performance results obtained for the GSHP system using three different types of energy piles, considering the most unfavorable operation mode, show the feasibility of this technology in São Paulo city for a balanced demand of heating and cooling loads. However, further numerical and experimental studies are necessary to investigate the pile heat transfer in alternative operation modes for the climatic condition evaluated, to incentive the implementation of this renewable energy technology in regions of hot or warm climates.

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Declaration of interest

The authors declare that they have no financial interests or personal relationships that could have appeared to influence the study reported in this paper.

Authors' contributions

Letícia Menezes Santos Sá: conceptualization, Methodology, Formal analysis, Writing – original draft preparation. Alberto Hernandez Neto: formal analysis, Conceptualization, Writing - review & editing. Cristina de Hollanda Cavalcanti Tsuha: supervision, Funding acquisition, Writing - review & editing. Juliana Pessin: data curation, Writing - review & editing. Milena Cardoso de Freitas: data curation, Writing - review & editing. Thaise da Silva Oliveira Morais: Data curation, Writing - review & editing.

List of symbols

c	Specific heat capacity of the fluid
CFA	Continuous flight auger
$CICS$	Sustainable Construction Innovation Center
COP	Coefficient of Performance of the heat pump
COP_c	Coefficient of performance (cooling mode)
COP_h	Coefficient of performance (heating mode)
ELT	Heat pump entering liquid temperature
EPE	Energy Research Company
F_{sc}	Short-circuit heat loss factor between supply and return tubes in bore
$GSHP$	Ground source heat pump
$HDPE$	High density polyethylene
L	Pile depth
L_c	Required bore length for cooling
L_h	Required bore length for heating
LLT	Heat pump leaving liquid temperature
m	Flow rate of the fluid
PLF_m	Part-load factor during design month
q	Heat exchange rate per pile depth
q_a	Net annual average heat transfer to the ground
q_{cond}	Heat pump condenser heat rate to ground
q_{evap}	Heat pump evaporator heat rate from ground
q_{lc}	Building cooling load
q_{lh}	Building heating load
R_a	Internal thermal resistance of pile
R_b	Thermal resistance of the heat exchanger borehole/pile
R_{ga}	Effective thermal resistance to the ground – annual pulse
R_{gm}	Effective thermal resistance to the ground – monthly pulse

R_{gst}	Effective thermal resistance to the ground – short pulse
SPT	Standard Penetration Test
t	Time
t_g	Undisturbed ground temperature
T_{in}	Inlet temperature of the fluid
T_{out}	Outlet temperature of the fluid
t_p	Long-term ground temperature penalty caused by ground heat transfer imbalances
TPT	Thermal performance test
TRT	Thermal response test
TMY	Typical Meteorological Year
λ	Soil thermal conductivity
λ_{eff}	Subsoil effective thermal conductivity

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