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Case study on the design of horizontal geothermal heat exchangers in residual clayey soil in southern Brazil

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Case Study

Keywords

Horizontal ground heat exchanger
Slinky configuration
Clay soil
Geothermal system design
Low-enthalpy energy

Abstract

Shallow geothermal systems based on ground source heat pumps constitute an energy-efficient solution for space heating and cooling; however, their application in Brazil remains limited, particularly with respect to horizontal ground heat exchangers installed in residual soils. This paper presents a case study on the analytical design of a horizontal Slinky-type ground heat exchanger intended for the thermal conditioning of a 25 m^2 experimental test room located in Maringá, Paraná, southern Brazil, operating approximately 40 h per week. The subsurface profile is composed of residual clayey soil derived from basaltic bedrock, whose geotechnical and thermal properties were determined through laboratory and in situ investigations. The design was carried out using an analytical methodology specifically developed for horizontal geothermal systems, which accounts for seasonal ground temperature variations, soil thermal conductivity and diffusivity, and peak building thermal loads. The results reveal a pronounced asymmetry between operating modes, with a required pipe length of approximately 306 m for summer cooling and 126 m for winter heating. A compact horizontal Slinky configuration was adopted to satisfy site constraints while maximizing heat exchange per unit area. Sensitivity analysis indicates that soil thermal conductivity is the dominant parameter governing exchanger length, followed by thermal diffusivity and heat pump performance. The findings highlight the importance of site-specific thermal characterization and the use of appropriate design methodologies for horizontal geothermal systems in subtropical and residual soil environments.

1. Introduction

Low-enthalpy geothermal energy is commonly used for building climate control and domestic hot water heating, through ground source heat pump (GSHP) systems, which enable thermal energy between the ground and the built environment. The most efficient and cost-efficient configuration is the closed-loop system, where a working fluid circulates though high-density polyethylene (HDPE) pipes, transfer of heat via conduction. This configuration requires a heat pump unit to extract or reject heat between the subsurface and the conditioned space (Brandl, 2006; Sani et al., 2019).

According to Brandl (2006), a closed-loop geothermal system is composed of three main components: the primary system (ground heat exchanger), the secondary system (building thermal distribution system), and the heat pump unit (Figure 1). The primary system consists of heat exchange elements embedded in the ground, which may be installed either horizontally or vertically depending on site conditions and design requirements. These elements can also be integrated into structural foundation components, such as energy piles, and their main function is to exchange heat with the subsurface in order to provide heating or cooling to buildings, as well as to infrastructure elements such as pavements, tunnels, bridges, and other civil structures (Brandl, 2006). Horizontal configurations offer the advantage of simpler installation, whereas vertical systems are often adopted when surface area is limited.

The secondary system comprises a closed network of pipes installed within the building, typically embedded beneath floors or within walls and ceilings. Its role is to distribute the thermal energy exchanged with the ground, either supplying heat extracted from the subsurface to warm the indoor environment or removing excess heat from the building and releasing it back to the ground (Sani et al., 2019). In addition to buildings, this system can also be applied in infrastructure such as bridges, roads, and airport runways for de-icing purposes.

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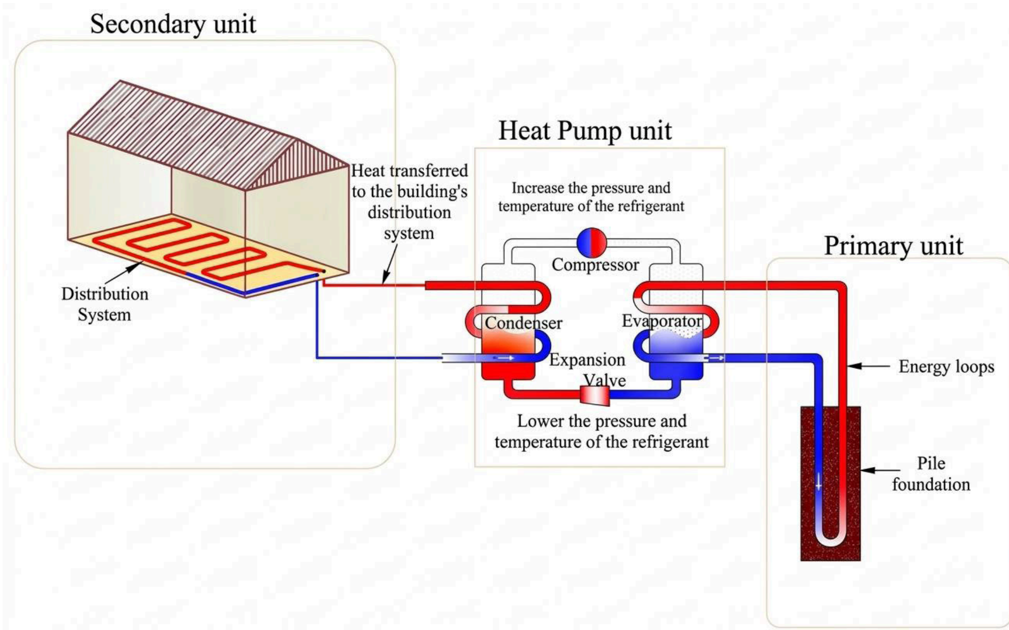

Figure 1. Geothermal heat pump system (Sani et al., 2019).

The heat pump unit is responsible for transferring thermal energy between the primary and secondary systems, using a circulating fluid within polyethylene pipes to reach the temperature levels required for space heating or cooling. As described by Sani et al. (2019), its main components include the evaporator, condenser, compressor, and expansion valve. As emphasized by Neto (2015), the heat pump does not generate thermal energy but rather transfers it from one location to another with high efficiency.

The design of geothermal heating and cooling systems is a technically demanding task, particularly in regions with heterogeneous geological conditions and significant variability in environmental factors affecting ground heat transfer (Kavanaugh & Rafferty, 2014; Tang & Nowamooz, 2020; Shi et al., 2022). These factors include incident solar radiation, precipitation, urban shading, air temperature variations, and evapotranspiration, all of which directly influence the ground's thermal regime and its effective thermal conductivity and capacity over time.

According to Shi et al. (2022), the relative impact of these factors on the long-term performance of shallow geothermal systems is still not fully understood, nor is it clear which environmental variables should be prioritized in predictive design models. This uncertainty reinforces the need for site-specific methodologies that incorporate local geotechnical and climatic conditions into the system design.

Moreover, as highlighted by Kim et al. (2018a), horizontal ground heat exchangers (GHEs) should not be designed using the same criteria as vertical borehole systems. While vertical systems are installed at depths where seasonal thermal fluctuations are attenuated, horizontal GHEs are subject to near-surface temperature variations, making them more sensitive to environmental dynamics. This condition demands greater attention to factors such as soil type, installation depth, soil moisture content, and pipe configuration, especially when employing compact layouts such as the Slinky coil arrangement.

In Brazil, the application of low-enthalpy geothermal systems remains limited in both residential and commercial contexts. Despite the country's broad range of soil types and a climate conducive to renewable energy solutions, the absence of national technical standards, limited availability of regional geotechnical and thermal soil data, and low awareness among designers and engineers continue to hinder the broader adoption of geothermal systems. Studies by Costa (2012), Tonus (2023), and Visintin (2023) underscore the untapped potential for shallow geothermal technologies in Brazil, particularly in urban areas with constrained space. Tonus (2023), for instance, emphasizes the need for accurate thermal characterization of tropical soils and the careful selection of appropriate design methodologies, warning that poor knowledge of subsurface thermal properties can result in overdesigned or underperforming systems.

Within this context, it is essential that horizontal and vertical ground heat exchanger systems be treated separately during the design phase, employing methodologies tailored to their distinct thermal behaviors and accounting for local environmental and geological constraints to ensure technically sound and energy-efficient solutions.

Accordingly, this study presents a case study on the design of a horizontal Slinky-type ground heat exchanger intended for the thermal conditioning of a 25 m^2 experimental test room located in Maringá, Paraná, southern Brazil, with an operational schedule of approximately 40 hours per week.

The primary objective is to evaluate the applicability of an analytical design methodology for horizontal geothermal systems in residual clayey soils under subtropical climatic conditions, integrating site-specific geological, geotechnical, and thermal data. An analytical approach proposed in the literature is applied to estimate the required pipe lengths under different seasonal operating conditions, with particular emphasis on the influence of soil thermal properties, system efficiency parameters, and installation constraints. The results aim to support preliminary design decisions and contribute to the advancement of shallow geothermal applications in the Brazilian context.

2. Case of study

This study addresses the design of a shallow geothermal system intended for the thermal conditioning of a 25 m^2 test room to be implemented in an experimental field adjacent to the Senai Institute of Innovation in Structural Engineering (Instituto Senai de Inovação em Engenharia de Estruturas), in Maringá, Paraná, southern Brazil. The room is designed to represent a typical commercial occupancy, accommodating two occupants and two personal computers, and is intended to operate under controlled indoor conditions for approximately 8 hours per day, totaling about 40 hours of operation per week. The room is oriented 34° southeast relative to the solar azimuth at sunrise, a configuration that directly influences solar gains and internal thermal loads.

Peak thermal demands for the conditioned space were estimated at 3048 W under summer conditions and 1696 W during winter. These design loads constitute the basis for the sizing of the thermal conditioning system, ensuring compliance with indoor thermal comfort criteria. To meet these demands, the proposed system is composed of three coupled subsystems: (i) a heat pump unit responsible for active heat extraction and rejection; (ii) a secondary distribution circuit, consisting of polyethylene piping embedded within the floor and wall elements to promote internal heat transfer; and (iii) a primary geothermal subsystem, comprising horizontal ground heat exchangers (GHEs) installed within the shallow subsurface. The present work focuses exclusively on the design and sizing of this primary geothermal subsystem.

The proposed installation site is located in an open area between buildings, where the ground surface is directly exposed to solar radiation throughout the day. Figure 2 presents a plan view of the study site, situating the test room and defining the available area for the installation of the horizontal ground heat exchanger within the surrounding built environment. As illustrated in Figure 3, the site is expected to experience variable solar incidence from morning to afternoon, resulting in pronounced diurnal fluctuations in surface heating and shading patterns. These conditions influence the near-surface ground thermal regime and define the surface thermal boundary conditions adopted in the geothermal design.

From a climatic perspective, the region exhibits a humid subtropical climate, characterized by precipitation concentrated in the summer months and a well-defined dry season during winter. Mean monthly rainfall ranges from 50 to 150 mm, and daily maximum air temperatures frequently exceed 23 °C. These climatic conditions induce seasonal variations in soil moisture content and ground temperature, which are critical factors governing heat transfer processes in shallow geothermal systems.

The local subsurface profile consists predominantly of residual clayey soils derived from basaltic bedrock. These materials typically exhibit low thermal conductivity and heat diffusivity, particularly under unsaturated conditions. Consequently, the thermal properties of the soil were explicitly incorporated into the analytical design approach used to estimate the required pipe length for the horizontal Slinky-type ground heat exchanger under different seasonal operating scenarios. The geotechnical and climatic characteristics described herein therefore establish the boundary conditions and input parameters adopted in the analytical methodology presented in the following section.

2.1 Geological context of Maringá

The municipality of Maringá is situated on the Third Paraná Plateau, in the northern region of the state of Paraná, southern Brazil. Geologically, the area lies within the Phanerozoic Paraná Sedimentary Basin and is predominantly underlain by volcanic rocks of the Serra Geral Group, formed by extensive continental fissural eruptions during the Mesozoic Era.

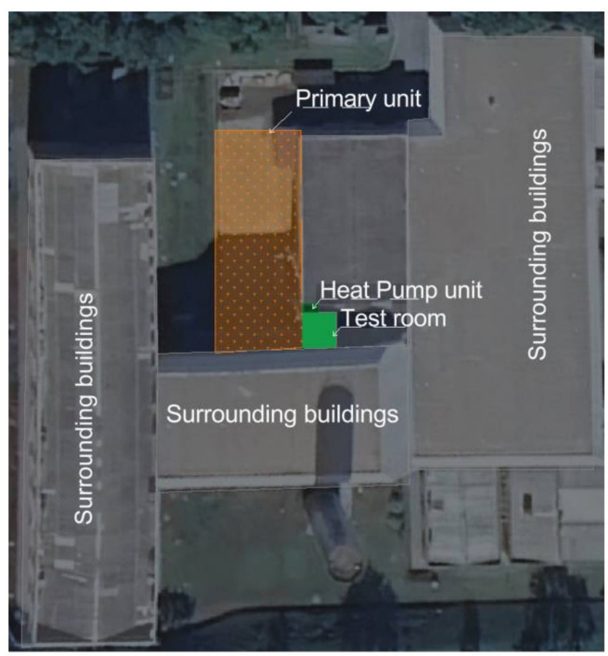

Figure 2. Plan view of the experimental site showing the location of the test room, the available area for the horizontal Slinky-type ground heat exchanger (primary unit), and the surrounding buildings.

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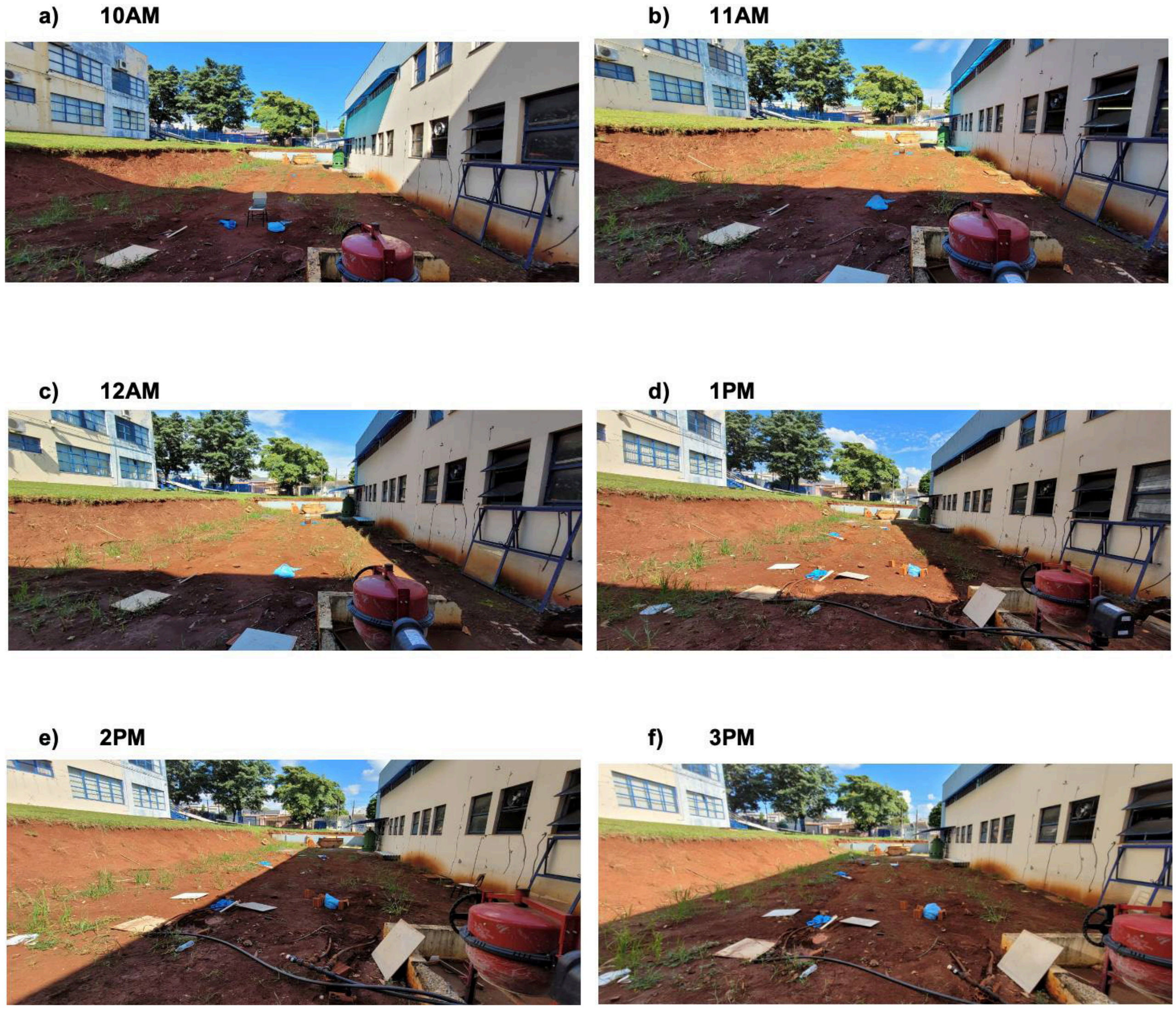

Figure 3. Solar exposure of the proposed installation site at different times of the day (Adapted from Visintin, 2023). (a) 10:00 AM; (b) 11:00 AM; (c) 12:00 PM; (d) 1:00 PM; (e) 2:00 PM; (f) 3:00 PM

Two main stratigraphic units of this group are present in the region. The Paranapanema Formation comprises massive pahoehoe basalt flows with well-developed columnar jointing, featuring compact cores and brecciated flow tops. The Pitanga Formation, in turn, consists of thinner, more vesicular basaltic flows, often rubbly and compound in nature, locally interlayered with sandstones and siltstones of volcanic or epiclastic origin.

Geochemical analyses conducted by Valore (2020) indicate that the basalts in the area are enriched in titanium dioxide (TiO_2), strontium (Sr), silica (SiO_2), barium (Ba), zirconium (Zr), and titanium (Ti), pointing to an evolved tholeiitic composition with mineralogical signatures relevant to thermal conductivity assessments.

In the northern and northeastern portions of the municipality, eolian sandstones of the Goio-Erê Formation, belonging to the Caiuá Group, are also observed. These sandstones are fine to very fine-grained, predominantly composed of quartz, feldspar, and iron oxides, and often exhibit cross-stratification and ripple marks, indicating deposition under high-energy wind conditions.

Furthermore, recent unconsolidated deposits associated with Quaternary alluvial sediments, classified as part of the Recent Sediments Formation, are found in the northern sectors of the municipality, representing zones of active or past sedimentary reworking and posing important considerations for near-surface thermal behavior and soil compaction properties.

2.2 Geotechnical characterization

Three disturbed soil samples were collected at a depth of 0.60 m, and in situ density tests were performed at a depth of 1.50 m, corresponding to the planned installation depth of the horizontal ground heat exchangers. Each disturbed sample was obtained using a spade and a manual auger, following standard geotechnical sampling procedures.

Laboratory tests were conducted to determine the grain size distribution, Atterberg limits, and specific gravity of soil particles, in accordance with ABNT NBR 7181 (ABNT, 2016c), ABNT NBR 6459 (ABNT, 2016a), ABNT NBR 7180 (ABNT, 2016b), and ABNT NBR 6508 (ABNT, 2014), respectively. The results indicate a soil with high clay content, ranging from 54.0% to 75.0%, with silt contents of up to 14.2% and minor sand fractions. The plasticity index varied between 4.0% and 7.0%, while the specific gravity of soil solids ranged from 2.73 to 2.83 g/cm^3 (Table 1).

Based on the grain size distribution, the material was classified as silty clay according to the Shepard classification system (Shepard, 1954). According to the Unified Soil Classification System (USCS), as adapted in ABNT NBR 6502 (ABNT, 2022), the soil was classified as low-compressibility silt or low-plasticity organic soil (ML–OL). Additionally, using Skempton's activity criterion, the material was identified as inactive clay, with activity values (*PI*/clay fraction) lower than 0.75.

Field density tests were carried out in accordance with ABNT NBR 9813 (ABNT, 2016d), and the results are summarized in Table 2. The moisture content remained consistently high, with values close to 32%, suggesting favorable conditions for heat transfer, as increased water content generally enhances soil thermal conductivity. The void ratio ranged from 1.16 to 1.25, while porosity values exceeded 53%, indicating a loose soil structure that may influence thermal behavior. The dry density ranged from 1.24 to 1.30 g/cm^3, reflecting a highly porous clayey soil, which may limit thermal diffusivity despite the beneficial effect of moisture.

3. Desing methodology

The design of the primary shallow geothermal system is structured as a sequential and deterministic procedure, in which the thermal demand is progressively translated into the geometric definition of the ground heat exchanger, as summarized in Figure 4. Although soil temperature, moisture content, and degree of saturation may vary seasonally, the adopted design approach considers peak thermal loads, which are assumed to be representative of approximately 1% of the annual operating period and therefore govern the system capacity.

The procedure starts with the definition of the thermal loads, including peak heating and cooling demands for summer and winter conditions, as well as the net annual heat exchange. These loads constitute the primary input to the sizing process and define the required heat transfer rate between the ground and the circulating fluid.

Subsequently, three sets of parameters are defined in parallel: pipe characteristics, soil thermal properties, and heat transfer fluid properties. Pipe characteristics include the inner and outer diameters and the flow regime, expressed by the Reynolds number, which controls convective heat transfer inside the pipe. Soil properties comprise thermal conductivity, thermal diffusivity, and the undisturbed ground temperature, which govern conductive heat transfer in the surrounding medium. The heat transfer fluid is characterized by its thermal conductivity and the Nusselt number, which are used to quantify convective heat exchange at the fluid–pipe interface.

Based on these parameters, the thermal resistances of the system are evaluated, including the internal convection resistance of the fluid, the conductive resistance of the pipe wall, and the conductive resistance of the surrounding soil.

Table 1. Laboratory testing results (Adapted from Visintin, 2023).

	Sample 1	Sample 2	Sample 3
Specific Gravity of Soil (g/cm^3)	2.83	2.82	2.73
Liquid Limit (*LL*)	49%	48%	48%
Plastic Limit (*PL*)	43%	41%	44%
Plasticity Index (*PI*)	6%	7%	4%
Sand	5.5%	5.3%	7.3%
Silt	12%	14.2%	10.6%
Clay	54%	75%	74.8%

Table 2. In-situ density test result (Adapted from Visintin, 2023).

Property	Sample 1	Sample 2	Sample 3
Natural bulk density (g/cm^3)	1.64	1.71	1.65
Dry density (g/cm^3)	1.24	1.30	1.25
Moisture Content	31.53%	31.93%	31.79%
Void ratio	1.25	1.16	1.23
Porosity (%)	55.5	53.67	55.18

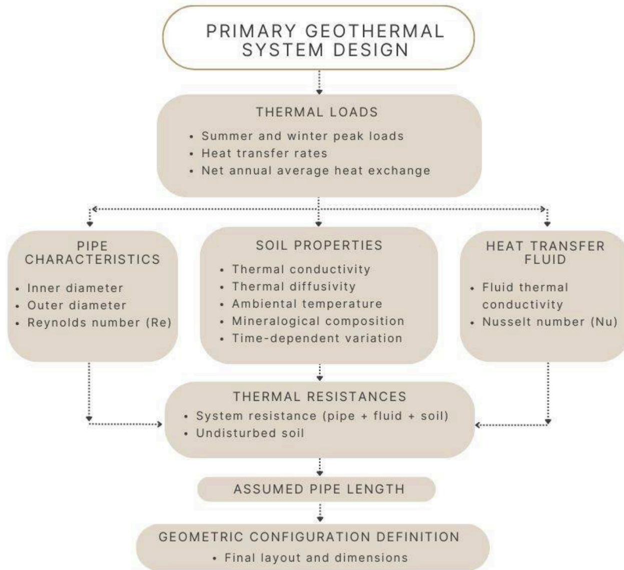

Figure 4. Flowchart of the design process for the primary geothermal system, highlighting input parameters and thermal interactions (Adapted from Visintin, 2023).

The soil is assumed to be semi-infinite, homogeneous, and isotropic, with constant thermal properties, and heat transfer within the ground is considered to occur exclusively by conduction, in accordance with Fourier's law. The undisturbed soil condition is adopted as the reference boundary state.

From the total thermal resistance and the imposed peak thermal loads, an initial required pipe length is determined. This length corresponds to the minimum ground heat exchanger extension necessary to satisfy the heating and cooling demands of the test room under design conditions. Finally, this value is used to define the geometric configuration of the primary system, including the final layout and dimensions of the geothermal heat exchanger.

For vertical geothermal systems, many analytical design methods assume a relatively stable subsurface thermal regime and therefore do not explicitly account for temperature variations induced by surface conditions. In contrast, horizontal ground heat exchangers are installed at shallow depths and are directly influenced by surface boundary conditions, such as solar radiation, ambient air temperature, longwave thermal radiation, and shading effects (Kim et al., 2018b; Visintin, 2023). These factors introduce pronounced temporal and spatial variations in ground temperature, resulting in more complex thermal boundary conditions.

To address these limitations, Kim et al. (2018a) developed an analytical design method specifically for horizontal ground heat exchangers by modifying the equation originally proposed by Kavanaugh & Rafferty (1997) to incorporate seasonal variations in ground temperature. The modification reflects the fundamentally different thermal behavior of shallow horizontal installations, in which the ground thermal regime is strongly governed by atmospheric forcing and soil–atmosphere heat exchange processes. Unlike vertical systems, where heat transfer is primarily controlled by the geothermal gradient and occurs at the borehole wall and surrounding grout, horizontal systems experience significant near-surface thermal fluctuations due to their shallow installation depth. Consequently, the modified formulation treats the horizontal pipe itself as the effective heat exchange element embedded directly within the soil, allowing these fluctuations to be explicitly represented.

This approach provides a more physical description of heat transfer under shallow subsurface conditions and forms the analytical basis for the sizing of the horizontal Slinky-type ground heat exchanger adopted in the present study. Accordingly, the required pipe length to meet the cooling demand can be calculated using Equation 1.

$$L_{(c,h)} = \frac{q_a R_{ga} + q_{(lc,lh)}\left(\dfrac{COP_{(c,h)} \pm 1}{COP_{(c,h)}}\right)\left(R_p + PLF_{(mc,mh)} R_{gm} + F_{sc} R_{gd}\right)}{T_{(H,L)} - \dfrac{T_{in} + T_{out}}{2}} \tag{1}$$

The parameter q_a represents the net average annual heat exchange between the ground and the system, while q_{lh} and q_{lc} denote the building's peak thermal loads during heating and cooling periods, respectively. The coefficient of performance (*COP*) of the heat pump governs how these building loads are translated into heat exchanged with the ground. In cooling mode, the total heat rejected to the ground is given by $q_{lc}(COP_c+1)/COP_c$, whereas in heating mode the heat extracted from the ground is calculated as $q_{lh}(COP_h-1)/COP_h$.

The part-load factor (*PLF*) accounts for the system's operational efficiency during the design period, while the short-circuit loss factor (F_{sc}) represents thermal interaction between the supply and return pipe legs. The thermal resistance of pile is described by R_b, while R_{ga}, R_{gm}, and R_{gd} correspond to the effective ground thermal resistances associated with long-term (annual), medium-term (monthly), and short-term (daily) heat pulses, respectively. The thermal resistance of a pipe with circular cross section is represented by R_p.

At the installation depth of a horizontal ground heat exchanger, the ground temperature reaches its seasonal maximum and minimum values, denoted by T_H and T_L, respectively. The inlet (T_{in}) and outlet (T_{out}) fluid temperatures, defined by the system designer, establish the operating temperature range under summer and winter conditions. Their average value, $(T_{in}+T_{out})/2$, is assumed to represent the mean fluid temperature circulating through the system.

Ground temperature variation with depth has been investigated using analytical formulations that differ in complexity and intended application. Early theoretical developments by Carslaw & Jaeger (1959) established a general solution for heat conduction in a semi-infinite medium, forming the basis for describing subsurface temperature diffusion. Subsequently, Kusuda & Achenbach (1965) extended this framework by proposing an analytical expression that relates ground temperature to both depth and time, explicitly accounting for periodic variations in surface temperature and enabling the representation of seasonal thermal behavior in the subsurface.

From a design-oriented perspective, Brandl (2006) introduced an alternative formulation aimed at practical engineering applications. Instead of explicitly solving the governing heat conduction equations, this approach represents ground temperature as a harmonic response to surface temperature fluctuations, with an exponential decay over depth governed by mixed Cauchy or Neumann boundary conditions. Although simplified, the method captures the dominant physical mechanisms controlling near-surface thermal behavior and provides an efficient means of estimating initial ground temperature profiles for the sizing of shallow geothermal systems (Equation 2).

$$T_g\left(y,t\right) = T_{med} - T_{amp} e^{-|y|\sqrt{\frac{\pi}{p\alpha}}} cos\left[\frac{2\pi\left(t-tc\right)}{t} - |y|\sqrt{\frac{\pi}{p\alpha}}\right] \tag{2}$$

In this expression, T_g represents the ground temperature (°C) at a given depth and time; T_{med} denotes the mean annual air temperature (°C), serving as the baseline for thermal variation; *Tamp* is the annual amplitude of air temperature (°C), which captures the extent of seasonal fluctuations; *y* corresponds to the depth below the ground surface (m), influencing the attenuation of temperature oscillations; α is the thermal diffusivity of the soil (m²/s), characterizing the soil's ability to conduct and store heat; *t* indicates the time (s) at which the temperature is being evaluated; *p* is the period of the thermal cycle considered (s), typically corresponding to one year; and *tc* refers to the time elapsed since the beginning of the year until the occurrence of the lowest air temperature (s), which helps align the phase of the temperature wave with actual climatic conditions.

3.1 Design considerations

The design of the ground heat exchanger was established based on a consistent set of initial conditions and simplifying assumptions. These parameters were selected to ensure the representativeness of the thermal response of the soil–pipe system and the reliability of the numerical simulations.

The heat exchangers were assumed to be installed at a depth of 1.5 m below the ground surface, representative of shallow geothermal applications. Soil thermal conductivity was estimated using the empirical formulation proposed by Lu et al. (2007), while thermal diffusivity was calculated as the ratio between soil thermal conductivity and volumetric heat capacity. The initial ground temperature distribution was defined using the harmonic temperature fluctuation method, allowing the estimation of maximum and minimum undisturbed ground temperatures over the annual cycle.

Water was adopted as the circulating fluid due to its well-established thermophysical properties and widespread application in shallow geothermal systems. High-density polyethylene (*HDPE*) pipes were specified for the heat exchanger, with internal roughness values provided by the manufacturer and used in the evaluation of the internal flow regime. The system was designed for a service life of 10 years.

Regarding operational conditions, the test room was assumed to operate 8 hours per day, 5 days per week, representing a typical occupational usage pattern. The analysis period considered cumulative operating times corresponding to the defined service life, including extended scenarios to account for thermal inertia effects in the ground.

Table 3 presents the complete set of geometric, thermal, hydraulic, and operational parameters adopted in the design of the horizontal ground heat exchanger.

3.2 Thermal loads and system operation

Consequently, to properly size the ground heat exchanger, input data related to the thermal demands of the secondary system were considered. These include the peak heating and cooling loads, determined based on the thermal resistance of the construction materials of the test room, as well as the room orientation with respect to solar incidence and the monthly average outdoor air temperatures. The peak cooling load was estimated as 3048 W, while the peak heating load was 1696 W. When adjusted by the heat pump's *COP*, resulted in corrected peak loads (q_{cond} and q_{evap}) of 3683 W and 1376 W, respectively (Table 4).

Table 3. Horizontal ground heat exchanger design parameters (Adapted from Visintin, 2023).

Category	Properties	Unit	Value
Heat Exchanger Depth	Installation depth	(m)	1.5
Soil Thermal Properties	Soil thermal conductivity	(W/mK)	1.5
	Soil volumetric heat capacity	(Ws/m^{3}K)	4831929
	Soil thermal diffusivity	(m^2/s)	3.1 x 10^{-7}
Undisturbed Ground Temperature	Maximum undisturbed temperature	(^{o}C)	25.62
	Minimum undisturbed temperature	(^{o}C)	19.5
Heat Transfer Fluid	Fluid thermal conductivity	(W/mK)	0.61
	Nusselt number (*Nu*)		76.66
Pipe Characteristics	Inner diameter	(m)	0.026
	Outer diameter	(m)	0.032
	Reynolds number (*Re*)		12273
Analysis Parameters	Simulation period	(years)	10
	Daily operating hours	(hrs)	8
	Annual operating days (*T1*)	(days)	7300
	Extended period (*T2* = *T1*+30 days)	(days)	7330
	Enhanced operating scenario (*T3*)	(days)	7330.334

Table 4. Project load data (Adapted from Visintin, 2023).

Summer load	3048	W
Winter load	1696	W
Heat rejection rate from heat pump condenser do ground (q_{cond})	3683	W
Heat extraction rate from ground to heat pump evapotator (q_{evap})	1376	W
Annual net heat transfer to ground (q_a)	327.59	W
Partial load factor during design month (PLF_m)	0.31	-

Based on these values, the heat transfer rates for the condenser and evaporator were established. In this study, the heat pump operates with a coefficient of performance (*COP*) of 5.3 in heating mode and 4.5 in cooling mode. The equivalent full-load hours were calculated according to Brazilian Ergonomic Regulation NR-17 (Brasil, 2020), which defines the thermal comfort range for indoor occupational environments as 20–23 °C for sedentary activities. This range was adopted as the reference for sizing the ground heat exchanger, ensuring that thermal comfort requirements are met under typical office conditions.

3.3 Soil thermal resistance calculations

The design of the horizontal ground heat exchanger was carried out using the methodology proposed by Kim et al. (2018a), which incorporates the system's thermal loads, soil thermal properties, and operational parameters to determine the required pipe length. The thermal resistances of the system were calculated considering the fluid-to-pipe resistance, pipe wall resistance, and soil-to-pipe resistance.

Additionally, soil thermal resistance parameters (f_{of},f_{o1}, f_{o2}, G_f, G_1, G_2) were determined to account for the transient thermal interaction between the soil and buried pipes over different time scales.

Using these parameters, the effective thermal resistances at annual (R_{ga}), monthly (R_{gm}), and daily (R_{gd}) scales were computed to properly size the heat exchanger and evaluate system performance under different operational scenarios. The thermal resistances and soil parameters adopted in the analysis are summarized in Table 5.

4. Analysis and results

Using the method proposed by Kim et al. (2018a) for horizontal exchangers, the required pipe lengths to meet the thermal demands were calculated: 306.7 m for summer (*Lc*) and 125.8 m for winter (*Lh*).

The trench configuration depends on the available construction area. For the test room, the trench was limited to 17.5 m in length and 0.6 m in width (Figure 5). Given this constraint, a Slinky layout was chosen to optimize the installation area. To determine the number of trenches, Equation 3 by Kim et al. (2016) was used, along with the geometric parameters listed in. As a result, three heat exchangers were deemed necessary to meet the test room's thermal demands (Table 6).

$$L = NL_l + 2PN + \frac{\pi d}{2} + d \tag{3}$$

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Table 5. Design considerations (Adapted from Visintin, 2023).

	Properties	Unit	Value	Notes
Primary geothermal system resistance	Fluid-to-pipe thermal resistance (R_{film})	mK/W	0.01	Resistance from fluid to pipe wall
	Pipe wall thermal resistance (R_{tube})	mK/W	0.08	Heat conduction through pipe wall
	Soil-to-pipe thermal resistance (5m layer) (R_s)	mK/W	0.46	Resistance from surrounding soil to pipe wall
	Thermal resistance of the pipe (R_p)	mK/W	0.55	Sum of pipe and fluid resistances
Soil thermal resistance parameters	f_{of}	-	3141.37	Annual Fourier number
	f_{o1}	-	13.00	Monthly Fourier number
	f_{o2}	-	0.14	Daily Fourier number
	G_f	-	0.71	Annual ground thermal response function
	G_1	-	0.28	Monthly ground thermal response function
	G_2	-	0.06	Daily ground thermal response function
	Effective annual thermal resistance (R_{ga})	mK/W	0.29	Effective annual soil thermal resistance
	Effective monthly thermal resistance (R_{gm})	mK/W	0.15	Effective monthly soil thermal resistance
	Effective daily thermal resistance (R_{gd})	mK/W	0.04	Effective daily soil thermal resistance

Table 6. Geometric design parameters (Adapted from Visintin, 2023).

Parameter	Unit	Value
Number of Slinky coils (N)	-	35
Coil pitch	(m)	0.5
Trench maximum length	(m)	17.5
Trench width	(m)	0.6
Minimum pipe length per trench	(m)	108.37
Number of trenches	-	3

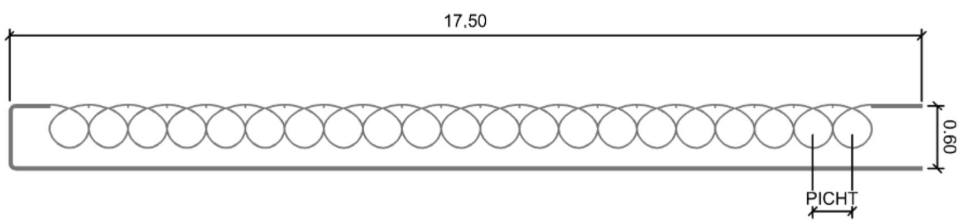

Figure 5. Geometric layout and parameters of the horizontal Slinky-type ground heat exchanger

In Equation 3, the total pipe length (L) required for the horizontal ground heat exchanger arranged in a Slinky configuration can also be expressed in terms of its geometric parameters. In this context, N denotes the number of Slinky loops (or circular turns), L_l is the pipe length per loop (m), P represents the pitch, defined as the distance between the centers of adjacent loops (m), and d is the radius of each circular loop (m). The total length L can thus be derived from the number of loops multiplied by the length of pipe in each loop, accounting for the geometry and spacing of the configuration. This approach enables accurate estimation of the required pipe length when the installation adopts a compact coiled layout, optimizing thermal performance while minimizing the area required for installation.

Based on the defined parameters, the minimum required lengths were established: 306.7 m for summer and 125.8 m for winter. The trench configuration was limited by site constraints, prompting the use of Slinky-type exchangers to maximize thermal exchange in a confined space.

4.1 Sensitivity analysis

A sensitivity analysis was performed to quantify the influence of key parameters on the required length of horizontal ground heat exchangers, with results presented in Figure 6 to Figure 8. The discussion emphasizes the physical interpretation of the observed trends, their consistency with previous studies, and their implications for system design under different climatic and geological conditions.

The results presented in Figure 6 clearly indicate that soil thermal conductivity is the dominant parameter controlling exchanger length. An increase in conductivity from 0.8 to 1.8 W/m·K leads to an approximate 50% reduction in the required length for both heating and cooling modes.

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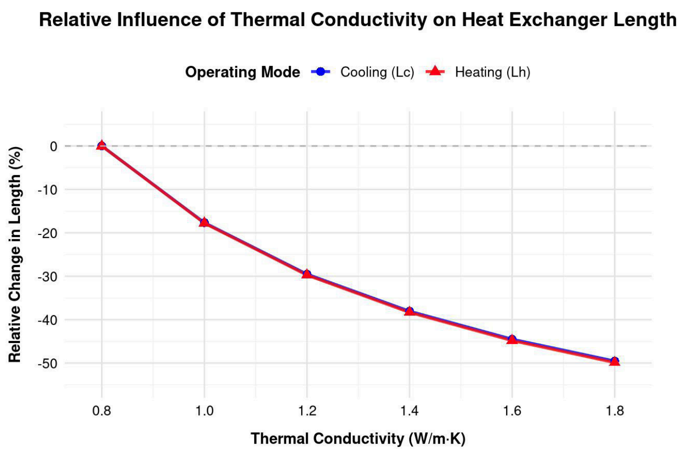

Figure 6. Relative influence of thermal conductivity on heat exchanger length.

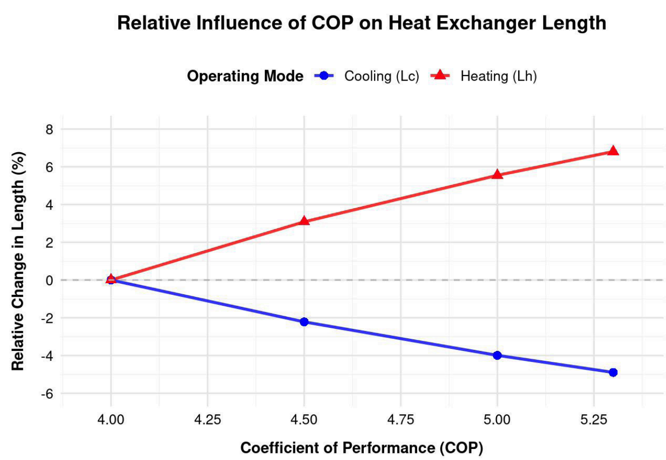

Figure 7. Relative influence of COP on heat exchanger length.

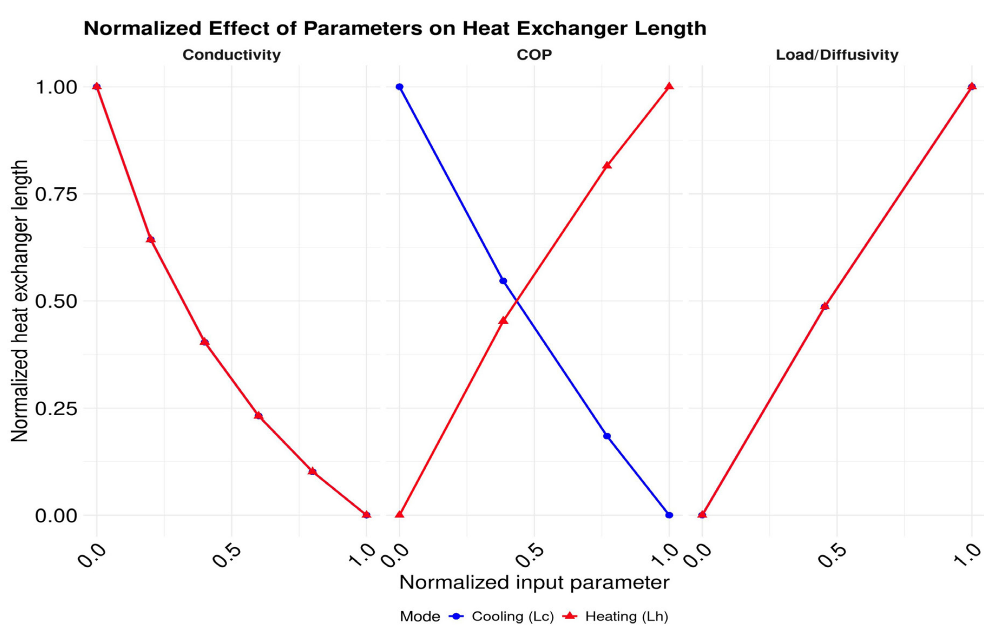

Figure 8. Normalized effect of parameters on heat exchanger length.

This strong sensitivity is consistent with Fourier's law of heat conduction and reflects the direct proportionality between conductive heat transfer capacity and the thermal properties of the surrounding soil. Similar magnitudes of influence have been reported in analytical and numerical studies of horizontal ground heat exchangers, confirming that uncertainties in thermal conductivity are one of the primary sources of design variability (Li et al., 2019; Urresta et al., 2021). Brazilian studies further emphasize that heterogeneous soil profiles and weathering conditions can lead to substantial spatial variability of conductivity values, reinforcing the need for site-specific thermal characterization (Hamza & Vieira, 2011; Gomes & Hamza, 2013; Tonus, 2023). From a practical standpoint, these findings support the use of thermally enhanced backfills or bentonite-based grouts as effective mitigation measures to reduce exchanger length and installation costs, as also observed in experimental investigations reported in the literature (Li et al., 2019).

The influence of the coefficient of performance (*COP*), shown in Figure 7, is comparatively moderate but reveals a clear asymmetry between operating modes. Increasing *COP* reduces exchanger length by approximately 5% under cooling conditions, while increasing the required length by nearly 7% under heating conditions. This behavior reflects the thermodynamic imbalance between heat rejection and heat extraction processes, which has been widely discussed in the context of seasonal ground-source heat pump performance (Noorollahi et al., 2018; Yang et al., 2010). In regions where heating and cooling demands are not balanced throughout the year, this asymmetry can contribute to long-term ground temperature drift and performance degradation if not properly addressed. Studies focusing on warm and temperate climates, including those representatives of Brazilian conditions, indicate that such effects are particularly relevant for horizontally installed systems operating at shallow depths (Gomes & Hamza, 2013; Tonus, 2023).

The normalized sensitivity analysis presented in Figure 8 confirms the predominance of thermal conductivity, followed by soil thermal diffusivity and *COP*. The results indicate that a 60% increase in diffusivity allows for shorter exchangers and corresponds to an approximate 47% increase in allowable thermal load. This highlights the importance of not only conductive properties but also the soil's thermal storage capacity, which governs transient heat transfer behavior. Previous transient modeling studies have demonstrated that soils with higher diffusivity exhibit faster thermal recovery between operating cycles, reducing thermal interference and improving long-term system performance (Urresta et al., 2021; Yang et al., 2010). Brazilian experimental and modeling studies similarly report that diffusivity plays a key role in shallow geothermal performance, particularly in unsaturated or seasonally varying moisture conditions (Delgado et al., 2016; Visintin, 2023).

Despite the clarity of the observed trends, the results must be interpreted considering the limitations of the adopted analytical approach. Soil moisture variability, which can significantly alter both thermal conductivity and diffusivity, was not explicitly modeled, although its importance has been widely documented (Delgado et al., 2016; Urresta et al., 2021). Thermal interference between adjacent trenches, axial heat losses along long horizontal runs, and the assumption of steady-state conditions may further contribute to discrepancies between predicted and actual system performance (Noorollahi et al., 2018). Additionally, geometric simplifications and the assumption of constant material properties neglect heterogeneities commonly observed in natural soils, particularly in tropical and subtropical environments (Hamza & Vieira, 2011; Visintin, 2023).

From a design perspective, the results support the adoption of conservative safety factors in the range of 1.2 to 1.3, especially for cooling-dominated applications where long-term thermal accumulation may occur. This recommendation is consistent with international design practices and with Brazilian assessments of shallow geothermal systems under variable climatic conditions (Li et al., 2019; Gomes & Hamza, 2013; Tonus, 2023). Comprehensive, site-specific investigations focusing on soil thermal properties, stratigraphic variability, and long-term thermal response are therefore essential prior to final design. The use of distributed temperature monitoring along the exchanger is also recommended to validate design assumptions and support adaptive operational strategies, as suggested by Noorollahi et al. (2018). Overall, the discussion confirms that soil thermal characterization is the primary determinant of horizontal ground heat exchanger performance, followed by transient soil response and system efficiency parameters.

5. Conclusion

The sizing of geothermal systems represents a fundamental step in the development of efficient and technically feasible projects. In the Brazilian context, where shallow geothermal applications are still at an early stage of dissemination, the discussion of appropriate design methodologies and their applicability to different soil types is particularly relevant. This study contributes to this discussion by evaluating the performance and limitations of an analytical approach applied to horizontal ground heat exchangers installed in residual clayey soil under subtropical climatic conditions.

The analytical methodology proposed by Kim et al. (2018a) was adopted, as it refines the classical formulation of Kavanaugh & Rafferty (1997) by incorporating temporal variations in ground temperature, allowing for a more realistic representation of annual thermal demands. The method proved effective for preliminary sizing, enabling the integration of building loads, soil thermal properties, and operational parameters into a consistent design framework. Nevertheless, important limitations remain, as the model does not explicitly account for external environmental factors such as solar radiation, shading effects, soil moisture variability, and precipitation.

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These factors have been identified by Shi et al. (2022) and Visintin (2023) as critical for accurately capturing near-surface thermal behavior and long-term system performance, particularly for shallow horizontal installations.

The results indicate that, for the residual clayey soil analyzed, substantially longer pipe lengths are required under summer operating conditions (306 m) compared to winter conditions (126 m). This asymmetry reflects both the seasonal imbalance between cooling and heating loads and the relatively low thermal conductivity commonly associated with clayey soils, especially under partially unsaturated conditions. The sensitivity analysis further confirms that soil thermal conductivity is the dominant parameter governing exchanger length, followed by thermal diffusivity and system efficiency.

From a practical standpoint, the adoption of a horizontal Slinky-type configuration proved technically suitable for the imposed site constraints. The standing Slinky arrangement allowed for a high heat exchange density per unit area, making it a viable solution for installations with limited available space. However, the results also highlight the need for conservative design margins and careful consideration of soil thermal variability, particularly in cooling-dominated applications where long-term thermal accumulation may occur.

Overall, this case study demonstrates that horizontal geothermal systems can be technically feasible in residual clayey soils typical of southern Brazil, provided that site-specific thermal characterization is performed, and the limitations of analytical design methods are clearly acknowledged. The findings reinforce the importance of integrating geotechnical, climatic, and operational factors in the design of shallow geothermal systems and contribute to the advancement of geothermal energy applications in the Brazilian context.

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Declaration of interest

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

Authors' contributions

Amanda Fetzer Visintin: conceptualization, data curation, funding acquisition, investigation, methodology, project administration, resources, supervision, validation, visualization, writing - original draft preparation, writing - reviewing and editing. Bianca Penteado de Almeida Tonus: visualization, writing - reviewing and editing. Karen Santos Schmidt: visualization, writing - reviewing and editing. Natalia Gelinski Ratacheki: visualization, writing - reviewing and editing. Vítor Pereira Faro: conceptualization, funding acquisition, methodology, project administration, resources, supervision, validation, writing - reviewing and editing.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of use of generative artificial intelligence

This work was prepared with the assistance of generative artificial intelligence (GenAI) ChatGPT (OpenAI) with the aim of revising the manuscript and improving text clarity. The entire process of using this tool was supervised, reviewed and when necessary edited by the authors. The authors assume full responsibility for the content of the publication that involved the aid of GenAI.

List of symbols and abbreviations

d	Radius of each circular loop
f_{o1}	Monthly Fourier number
f_{o2}	Daily Fourier number
f_{of}	Annual Fourier number
p	Period duration of temperature oscillation
q_a	Annual heat exchange between the ground and the system
q_{cond}	Heat rejection rate from heat pump condenser do ground
q_{evap}	Heat extraction rate from ground to heat pump evapotator
q_{lc}	Linear ground heat rejection rate (cooling)
q_{lh}	Linear ground heat extraction rate (heating)
t	Time
tc	Phase shift time
y	Depth below the ground surface
Ba	Barium
COP	coefficient of performance
COP_c	Coolingcoefficient of performance
COP_h	Heating coefficient of performance
F_o	Fourier number
F_{sc}	Short-circuit loss factor

G	g-function
G_1	Monthly ground thermal response function
G_2	Daily ground thermal response function
G_f	Annual ground thermal response function
GHE	Horizontal ground heat exchangers
GSHP	Ground source heat pump
H_2O	Water fluid
HDPE	High-density polyethylene
L	Pipe length
L_c	Pipe length for summer cooling load
L_h	Pipe length for winter heating load
LL	Liquid Limit
L_l	Pipe length per loop
N	Number of Slinky loops
N_u	Nusselt number
P	Pitch
PI	Plasticity Index
PL	Plastic Limit
PLF	Part-load factor
PLF_{mc}	monthly cooling part-load factor
PLF_{mh}	monthly heating part-load factor
R_e	Reynolds number
R_{film}	Thermal resistance of fluid-to-pipe
R_{ga}	Effective ground thermal resistances associated with long-term (annual)
R_{gd}	Effective ground thermal resistances associated with short-term (daily)
R_{gm}	Effective ground thermal resistances associated with medium-term (monthly)
R_p	Thermal resistance of pipe
R_s	Thermal resistance of soil
R_{tube}	Thermal resistance of pipe wall
SiO_2	Silica
Sr	Strontium
T_{amp}	Annual amplitude of air temperature
T_g	Ground temperature
T_h	Ground temperature reaches its seasonal maximum values
Ti	Titanium
T_{in}	Inlet fluid temperatures circulating through the system
TiO_2	Titanium dioxide
T_l	Ground temperature reaches its seasonal minimum values
T_{med}	Annual air temperature
T_{out}	Outlet fluid temperatures circulating through the system
Zr	Zirconium
π	Mathematical constant
α	Thermal diffusivity of the soil

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