Article

Study of Thermal Inertia in the Subsoil Adjacent to a Civil Engineering Laboratory for a Ground-Coupled Heat Exchanger

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Abstract: This document presents a study of thermal inertia in the subsoil adjacent to the Civil Engineering laboratory of the Technological Institute of Sonora (ITSON) in the south of Sonora, Mexico, in service of the development of a solution proposal of a ground-coupled air heat exchanger for the cooling months. The research was divided into three phases: first, the monitoring of temperature in 10 layers of the ground; second, the analysis of thermal ground properties; and last, the design and simulation of a ground-coupled air heat exchanger. The objectives were to determine the variation in the thermal inertia of the soil with depth and over time and to determine the optimum depth for a ground-coupled heat exchanger system. The second objective was to develop a design proposal for a ground-coupled heat exchanger for the university laboratory. We found that the optimum depth is 3.0 m in a soil with high-compressibility clay with 21% humidity and 0.152 W/mK of thermal conductivity. However, the proposed design identified the best depth for the cooling system as 3 m considering a ground-coupled heat exchanger for a volume of 222.2 m3, corresponding to the volume of the classrooms of the building. With this design, the approach was to reduce the temperature by at least 10 °C on the hottest day (41 °C) of the year studied. We concluded that with this kind of system, the climate of the building studied could reduce the thermal load of active AC systems and reduce the energy load by 59%.

Keywords: air–earth heat interchanger; thermal comfort; thermal conductivity

1. Introduction

According to the International Energy Agency (IEA) [1], due to a combination of warmer environmental temperatures and greater economic activity, energy consumed to cool buildings has doubled since the year 2000 to reach 2075 TWh in the year 2018, representing 10% of global energy consumption. It is estimated that in 2000, there were 816 million air-conditioning units in the world, increasing to 1761 million in 2018. In México, the number of air-conditioning units went from 8 million in 2000 to 18 million in 2018, and it is expected that in 2050, there will be 126 million. This increasing number of air-conditioning units will result in higher electricity consumption, the generation of pollutants, and will have adverse effects on climate change. However, there are methods that make it possible to reduce the magnitude of the problem of thermal comfort in buildings in a more sustainable and economical way. Strategies for cooling constructions can be divided into two large groups: passive cooling and active cooling. There are also complex techniques that combine both strategies and tend to be more efficient.
Passive cooling is responsible for reducing cooling loads or minimizing construction heat gains without resorting to mechanical equipment. One such method is the use of ground–air heat exchanger tube systems, also known as Provençal or Canadian tubes, which take advantage of the soil’s thermal inertia. Due to its thermal inertia, the temperature at a point in the soil at a certain depth does not change appreciably over time. The above allows the ground to be used as a very stable source or store of heat, an important advantage compared to systems that use solar energy. Among the alternative systems for heating and cooling, those that take advantage of this property of the ground (ground source heat pumps or earth–air heat interchangers) have had an appreciable growth in the last decades [2,3]. In these systems, a heat exchange is conducted between the building and the ground using a device which consists of pipes buried in the ground horizontally or vertically; a fluid (usually air or water) circulates through these tubes, which allows heating of the building in winter and cooling in summer. Case studies of the use of geothermal energy in air-conditioning and ventilation systems in Germany, Portugal, and Turkey have reported savings in energy consumption of 45%, 30%, and 36% compared to the use of traditional HVAC systems, in addition to reductions in carbon dioxide (CO$_2$) emissions of 28%, 30%, and 36%, respectively [4]. Even though Mexico ranks fourth in installed capacity for electricity generation with geothermal energy [5], the use of geothermal energy in medium, low, and extremely low enthalpy applications is exceptionally low, only 155.82 MW [6]; however, some studies have been conducted. The Mexican Center for Innovation in Geothermal Energy (Centro Mexicano de Innovación en Energía Geotérmica, CeMIEGeo) developed demonstration projects of ground source heat pumps for the air-conditioning of residential and commercial spaces in the towns of Los Humeros, Puebla, and Mexicali, Baja California; they estimated savings in the use of electricity for refrigeration of USD 17,160 and USD 64,350 in the first year, respectively. In the case of Los Humeros, Puebla, the comparison between a conventional electric heater and a ground source heat pump showed savings of USD 27,886 per year, in favor of the ground source heat pump [7]. In another investigation, a ground source heat pump system, implemented in a classroom located in the city of Chihuahua, Chihuahua, reached on average a cooldown effect of 14 °C [8].

Feasibility studies show that drilling and/or excavation to install the exchanger tube system represents the main environmental [9] and economic cost, reaching 25% to 58% [10] of the total investment.

Ciudad Obregon is in the extreme south of the state of Sonora, Mexico. The average altitude is 40.00 m above sea level. In this locality, there is a very severe climate [11] (see Figure 1), in which the monthly average temperatures during the summer are far from the thermal comfort temperature (from 17 to 27 °C), reaching, generally, 32 °C on average and 25 °C and 38 °C as minimum and maximum temperatures, respectively. On the other hand, during the winter, temperatures reach 17 °C on average. Also, temperatures reach a minimum of 10 °C and a maximum of 25 °C. This creates a problem of thermal comfort that the inhabitants usually solve in a conventional way (air-conditioners, evaporative coolers, fans, and heaters), using methods that result in high electricity consumption and indirectly contribute to the generation of pollutants.

The Civil Engineering Laboratory (LV-800) of the Department of Civil Engineering of the Technological Institute of Sonora (ITSON) has presented problems with thermal comfort since its inauguration which it has tried to solve with different means (evaporative air and air-conditioning systems). Although these solutions have worked to a greater or lesser degree, they do not entirely solve the problem. They contribute to the production of pollutants and are expensive due to the high electricity and maintenance costs. Furthermore, their lifespans are limited. One way to solve or alleviate the problem would be to implement a low-electricity, clean, and non-hazardous system known as a ground–air heat exchanger. Since a significant proportion of the possible cost of a ground source heat pump system corresponds to drilling, it is important to carry out a study that allows finding a suitable depth at which to place the heat exchange tubes, so that the thermal properties of the subsoil allow an adequate electricity savings to be obtained with the lowest possible
excavation cost. We consider that there is an optimal depth in the subsoil of the LV-800 that allows implementing a system of ground–air heat exchangers to reduce the requirements of conventional air conditioning.

The overall objective of this study is to determine the quasi-seasonal variation in the thermal inertia of the subsoil at ITSON’s Nainari campus to identify an optimal depth for implementing a ground–air heat exchanger system. This system aims to cool the interior of the LV-800 building during hot weather. The specific objectives include defining the stratigraphic column of the subsoil, measuring temperature variations with depth during the warmest and coldest months, determining the depth at which the underground temperature maintains comfort level during summer, and designing a solution to reduce classroom temperatures in the selected building by at least 10 °C on the hottest day of the year. The study is temporarily divided into three phases, covering specific time periods in 2018 and 2019. The geographic scope is confined to the Nainari campus of the Sonora Technological Institute in Obregon City, Sonora, Mexico (Figure 2), with the survey conducted behind the LV-800 building. The geographical coordinates of the sounding point are 27°29′37.4″ N; 109°58′16.3″ W.

Figure 1. Daily average temperatures (in red) maximum temperature (blue), minimum temperature (in brown), and average cumulative precipitation by month (cyan) in Ciudad Obregón, Sonora (1951–2010) [11].

Figure 2. Location of the Civil Engineering Laboratory (LV-800), Nainari campus, ITSON.
2. Materials and Methods
Thermal Behavior Analysis

Initially, the aim was to obtain information on the variation in soil temperatures with the lowest possible economic investment, so a 4 m deep well was drilled with a hand auger (Phase 1). Some time later, with the results of the first phase study, it was necessary to extend the depth of the study to 10 m and its scope by determining more thermal properties of the soil. The analysis of the thermal behavior of the subsoil was conducted in three parts divided into two phases, which are shown in the following figure (Figure 3) and explained below.

**Figure 3.** Analysis of the thermal behavior of the subsoil.

Temporal delimitation
Phase 1: From 25 August to 6 October 2018;
Phase 2, first stage: From 11 August to 13 October 2019;
Phase 2, second stage: From 26 October to 26 November of the year 2019.

2.1. Phase 1

To determine the thermal inertia of the subsoil in Phase 1, a place located 3 m north of the LV-800 building of the Technological Institute of Sonora (ITSON), Nainari campus, was geographically delimited (see Figure 2). With the help of a manual auger to perform the drilling, LogTag brand Trix-8 and Haxo-8 temperature recorders were placed, which have an accuracy of ±0.5 °C for a range of measurement temperatures from −20 °C to +40 °C, at the following depths: 0.15 m, 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m, 3.5 m, and 4.0 m. The sensors were attached to a PVC tube, and this was introduced into the shaft, which was filled entirely (see Figure 4a–c). Through these sensors, the maximum and minimum temperatures were obtained from 25 August to 6 October 2018; later, the average temperatures were calculated. The subsoil temperatures are compared with the air temperature registered by the ITSON Climatological Station, located a few meters from the site. Information from the weather stations of the Red de Estaciones Meteorológicas Automáticas de Sonora (REMAS) was also used to complement the data from the ITSON Climatological Station. Also, the average statistical trend of the temperature was calculated by using a spreadsheet.
Lowest, highest, and average temperatures for each month in 2019 (record registered by REMAS and the ITSON weather station).

Table 1. Lowest, highest, and average temperatures for each month in 2019 (record registered by REMAS and the ITSON weather station).

<table>
<thead>
<tr>
<th>Month</th>
<th>Lowest Temperature [°C]</th>
<th>Highest Temperature [°C]</th>
<th>Average Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>25.87</td>
<td>41.47</td>
<td>33.43</td>
</tr>
<tr>
<td>September</td>
<td>20.31</td>
<td>37.59</td>
<td>27.72</td>
</tr>
<tr>
<td>October</td>
<td>17.16</td>
<td>40.04</td>
<td>27.53</td>
</tr>
<tr>
<td>November</td>
<td>12.78</td>
<td>35.23</td>
<td>23.59</td>
</tr>
<tr>
<td>December</td>
<td>8.73</td>
<td>26.49</td>
<td>19.12</td>
</tr>
</tbody>
</table>

2.2. Phase 2

For the characterization of the soil during phase 2, while drilling from 0.0 m to 10.0 m in depth with a drilling truck, the Standard Penetration Test [12] was performed, and unaltered soil samples were taken at every 1.0 m depth (see Figure 5). These samples were subjected to classification tests such as granulometry, liquid limit, plastic limit, and natural moisture content (see Table 1). With this information, the samples obtained were classified using the Unified Soil Classification System of the American Society of Testing Materials, ASTM.
temperatures are compared with the air temperature registered by the ITSON Climatological Station, located a few meters from the site. To measure the thermal diffusivity (\(\alpha\)), thermal conductivity (\(A\)), and heat capacity (\(C_p\)) of the soil, altered samples recovered were compacted to have a density close to that of the undisturbed soil (see Figure 7a,b). The thermal conductivity was measured by means of the THB 100 equipment from the Linseis company [13]. This equipment uses the Transient Hot Bridge (THB) method to measure the heat transport properties of materials and combines the Hot Wire, DIN EN 993-14 [14], and Transient Hot Strip methods, DIN EN 993-15 [15]. A THB6N type sensor is placed inside the sample, which includes a metallic conductor in the form of a band set in tandem. The band emits a constant flow of heat during measurement. This causes a rise in temperature. Knowing the increase in temperature as a function of time, it is possible to calculate the thermal properties of the material sample [16]. Before testing, the sensor was calibrated with Polymethylmethacrylate (PMMA) samples provided by the manufacturer.

![Experiment schematic in the second phase.](image)

**Figure 6.** Experiment schematic in the second phase.

![Thermal conductivity tests with the THB 100.](image)

**Figure 7.** Thermal conductivity tests with the THB 100.

2.3. Heat Exchanger Design and Simulation

In addition to the thermal behavior of the ground, it is important to mention the design consideration of the heat exchanger. The design proposes a centrifugal fan that impulses air into the buried exchanger, where air flow transfers heat to the ground and conducts it to the infrastructure. PVC pipes were chosen due to their ideal working characteristics, as PVC can withstand temperatures of up to 80 °C and is widely available worldwide. Section 3.2 shows the input parameters for the sizing and simulations needed in the simulation.

Based on the restrictions given below regarding the building dimensions, the area available for construction and the load partial heat to be removed, a heat exchanger system was modeled (Figure 8), driven by a fan which is correctly adapted to the mentioned requirements.
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The Civil Engineering Laboratories building (Figure 9) has a volume of 3107.5 m$^3$, of which 222.2 m$^3$ correspond to the classrooms that will be conditioned by the proposed system. Two areas are available in the north of the building for the excavation and location of heat exchangers with areas of 562 m$^2$ and 1150 m$^2$, respectively.

Figure 9. Civil Engineering Lab Building (ITSON).
2.4. Climate Conditions

The data of weather conditions such as air temperature in the area were provided by the university, based on the data registered for its weather station and for the Network of Meteorological Stations Automatic Machines of Sonora (REMAS in Spanish).

The data in Figure 10 correspond to the air temperatures from 13 August 2019 to December 31 of the same year. It was observed that August and September have the highest temperatures and, from October, begin to decline until reaching the lowest point in December.

![Air Temperature from August to December 2019](image)

**Figure 10.** Air temperature from August to December 2019 (recording carried out by REMAS and the ITSON weather station).

It was identified that there were two design parameters: by type of fluid and location by layers. The options could be evaluated and compared once the final design of each one was achieved.

Considering the type of fluid, the final design can be driven by a heat pump that works with water, or by a centrifugal fan that takes ambient air from the surroundings and carries it towards the exchanger. For this case, we selected air pumps because they regularly require less space for installation, and they might have lower initial installation costs, particularly for horizontal configurations, as they typically involve trenches or shallow digging. The liquid-type systems could have higher efficiency, but they have a higher installation cost, and that is the main reason this kind of system is not widely available in this region.

On the other hand, the location by layers corresponds to the ground level (10 layers separated from each other) in which the exchanger would be placed. To select the best possible option, analysis matrices were used to make decisions that considered vital parameters for the development of the present project, such as economic feasibility, maintenance costs, heat removal capacity, mounting complexity, and safety.
2.5. Sizing

The design of the heat exchanger was carried out through a balance of energy and the recommendations of the methodology of the International Ground Source Heat Pump Association (IGSHPA).

A centrifugal fan was selected based on the volume at condition and the number of necessary air changes to fix a flow.

For a better visualization and schematization of how the heat exchanger would look, a schematic model was made to obtain an idea of how it would look with the design properties, such as material, tube diameter, etc., already mentioned above, as shown in Figure 8.

For the sizing of the buried exchanger, first it is necessary to choose a centrifugal fan considering the air flow needed to produce a number of volume renovations to the acclimatized zone.

\[ V_{\text{total}} = ae * V \left[ m^3 \right] \quad (1) \]

where \( ae \) is the amount of air exchanges, \( V_{\text{total}} \) is the airflow needed to acclimatize, and \( V \) the volume; after this calculus, the diameter of the pipe is defined taking into account that it is necessary to consider a turbulent flow or fulfill an upper 10,000 Reynolds number with Equation (2).

\[ Re = \frac{4 \hat{V}}{\pi D_i \nu} > 10,000 \quad (2) \]

where \( \hat{V} \) the flow inside the exchanger is, \( D_i \) is the internal diameter of the pipe, and \( \nu \) is the kinematic viscosity of the fluid. On the other hand, the length of the pipe is determined by the law of the conservation of energy.

\[ q_{\text{conv}} = E_{\text{int}} = \dot{m} c_p \Delta T = \rho \hat{V} c_p \Delta T \quad (3) \]

In this case, \( \rho \) is fluid density, \( c_p \) the specific heat, and \( \Delta T \) the difference between in and out temperature of the exchanger. Another way of seeing the convective heat is presented in Equation (4) [17].

\[ q_{\text{conv}} = \frac{\Delta T_{\text{ml}}}{\frac{1}{h \pi D_i L} + \frac{\ln \left( \frac{D_o}{D_i} \right)}{2 \pi k_t L}} \quad (4) \]

where \( \Delta T_{\text{ml}} \) is the log mean temperature, \( h \) is the coefficient of heat transfer by convection, \( L \) is the length of the pipe, \( D_o \) is the external diameter, and \( k_t \) is the thermal conductivity of the pipe.

After balancing Equations (3) and (4), it results in:

\[ \rho \hat{V} c_p \Delta T = \frac{\Delta T_{\text{ml}}}{\frac{1}{h \pi D_i L} + \frac{\ln \left( \frac{D_o}{D_i} \right)}{2 \pi k_t L}} \quad (5) \]

The mean logarithmic temperature was used since it considers the rate of transfer change due to soil temperature.

\[ \Delta T_{\text{ml}} = \frac{T_{\text{in}} - T_{\text{out}}}{\ln \left( \frac{T_{\text{in}} - T_s}{T_{\text{out}} - T_s} \right)} \quad (6) \]

where \( T_{\text{in}} \) is the inlet temperature to the exchanger, \( T_{\text{out}} \) is the exchanger outlet temperature, and \( T_s \) is the soil temperature, all expressed in °C.
To obtain the coefficient of heat transfer by convection, it is necessary to determine the exact Reynolds number and Nusselt number for turbulent flow (a condition that had to be met when selecting the internal diameter).

\[ Re = \frac{4V}{\pi D_i \nu} \]  

(7)

\[ Nu = 0.023 Re^{1/3} Pr^{1/3} \]  

(8)

\[ h = \frac{Nu k_a}{D_i} \]  

(9)

2.6. Simulations

With the physical limitations stated previously, the reference values that can be assumed to represent the behavior of the buried heat exchanger will be analyzed with “Flow Simulation of SolidWorks” to improve the design and place it in the best layer to obtain the best temperature gradient and the lowest excavation cost.

The simulation process will be made in two steps, simulation and stratigraphic column validation and simulation of the heat exchanger in each soil layer. The model of the stratigraphic column consists of 10 soil layers, each one with their own estimated properties and one meter deep, the remaining ones in the computational domain above the surface layer contain air with environmental conditions such as ambient temperature, solar radiation, atmospheric pressure, and wind speed. The 3D model is presented in Figure 11.

![Figure 11. Three-dimensional model of the stratigraphic column.](image)

The results of the simulation will be compared with the thermal response of the ground, recorded by the thermocouples, to establish mistakes like (BIAS) statical bias and RMSE.

After the stratigraphic column simulation is validated, the next step will be simulating the heat exchanger of Figure 12 in each one of the soil layers and searching the temperature gradient achieved in each.
3. Results

3.1. Experiments

Figure 13 was prepared with all the data acquired from 25 August to 6 October 2018, at the hottest hour of the day (2:30 p.m.). The average as well as the maximum and minimum daytime temperatures at the indicated time were determined for each depth and plotted. The figure shows the variation with depth in the maximum (red curve), minimum (green curve), and average temperatures (light blue curve). This graph is a support element used to determine at what depth the soil temperature is adequate to assist in the air-conditioning of the building. Deeper into the ground, the separation between the maximum and minimum temperature curves is reduced. In the first meter of depth, maximum temperatures decrease rapidly, related to the predominant soil type (silty sand) and radiation. From 1 to 3 m, temperatures are still above the average air temperature (30 °C), although the soil is clay. It is from 3 m down that the soil temperature is below the air temperature, and adequate thermal conditions are found to use heat exchangers to improve the thermal comfort of the architectural space [18–21] (soil type: low-compressibility clay, with 12.4% humidity).

The average as well as the maximum and minimum daily temperature values measured in the soil at 3:40 p.m. every day from 11 August to 13 October were determined for each depth and plotted. The variation with depth in the maximum, minimum, and average temperatures is shown. In Figure 14, around 3 m deep, there is a spot where the temperatures in the well are closer to those of thermal comfort. Between 4 and 7 m, there is an increase in temperatures, probably because the soil is sandy in this range. From 7 m onwards, the soil is again mainly clay, and a significant reduction in temperatures and a more considerable difference between the maximum and minimum temperatures is observed. If we only consider the thermal inertia of the soil, the latter is the most suitable depth to install heat exchange wells for the application considered [18–21]. If we also consider installation economy factors, a depth of 3 m is more suitable.

Up to this point, we have been elucidating the ground’s daytime behavior as a heat sink. However, we now turn our attention to its behavior at night. Figure 15 illustrates that the soil behaves as a heat source within the initial meters of depth. For example, let us consider the graph for the months of October to November at 3:40 a.m., with a reference ambient temperature of 19 °C. Notably, at a depth of 7 m, the soil temperature stabilizes at 28 °C.
3. Results
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Figure 13 was prepared with all the data acquired from August 25th to October 6th, 2018, at the hottest hour of the day (2:30 p.m.). The average as well as the maximum and minimum daytime temperatures at the indicated time were determined for each depth and plotted. The figure shows the variation with depth in the maximum (red curve), minimum (green curve), and average temperatures (light blue curve). This graph is a support element used to determine at what depth the soil temperature is adequate to assist in the air-conditioning of the building. Deeper into the ground, the separation between the maximum and minimum temperature curves is reduced. In the first meter of depth, maximum temperatures decrease rapidly, related to the predominant soil type (silty sand) and radiation. From 1 to 3 m, temperatures are still above the average air temperature (30 °C), although the soil is clay. It is from 3 m down that the soil temperature is below the air temperature, and adequate thermal conditions are found to use heat exchangers to improve the thermal comfort of the architectural space [18–21] (soil type: low-compressibility clay, with 12.4% humidity).

Figure 14. Maximum, average, and minimum temperatures inside the well during the hottest hour of the day for 11 August to 13 October 2019 (Phase 2a).

It is interesting to observe the substantial temperature decrease observed at a depth of 6 m. This is particularly striking, as this zone contains deposits of sand and sandy silt. The local average air temperature during this period (19 °C) closely aligns with thermal comfort standards. Moreover, heating is typically unnecessary for buildings in Obregon City. As a result, when designing and implementing a heat exchanger system, only the summer conditions will be taken into consideration.
Figure 15. Maximum, average, and minimum temperatures inside the well during the hottest hour of the day for 14 October to 29 November 2019 (Phase 2b).

Figures 16 and 17 show the typical evolution over time of the ambient temperature (air) and the soil temperature from 0 m to 10 m, during August and November, respectively. The behavior is analogous to that reported by other researchers [22, 23]. There is a sinusoidal thermal wave, whose amplitude decreases as it goes deeper into the subsoil. However, from a depth of 1 m, the temperature variation is small (1 to 2 °C) compared to the air temperature variation (10 to 15 °C). This fact is important when choosing the depth that the wells of the ground–air heat exchanger system will reach, since it can increase the efficiency of the system.

3.2. Properties of the Soil

Effect of soil type on thermal properties:

As can be seen in Table 2, the higher thermal conductivity was presented in soils with sand or silt. In contrast, clay soils or with a higher proportion of this material had lower conductivities. This is consistent with that reported by other researchers [24–28]. Sands and silts have a higher heat capacity than clays. Thermal diffusivity was higher in the clays than in the other soils assessed. Due to the above and because in a geothermal heat exchanger a material is required that rapidly absorbs the heat of the cooling fluid, clay is preferable in this context.
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Sands and silts have a higher heat capacity than clays. Thermal diffusivity was higher in...

Figure 16. Time series behavior of temperature at different depths and air temperatures in August 2019.

Figure 17. Time series behavior of temperature at different depths and air temperatures in November 2019.
Table 2. Main properties of the soils found from boring.

| Depth (m) | Soil Type     | Water Content (%) | Moisture Density (kg/m³) | Thermal Diffusivity, a (mm²/s) | Thermal Conductivity, λ (W/mK) | Effusivity, b (Ws²/²/m²K) | Heat Capacity, Cp (kJ/kgK) | Reference Values
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0–1.0</td>
<td>Silty sand (SM)</td>
<td>9</td>
<td>1980</td>
<td>133</td>
<td>0.43</td>
<td>419</td>
<td>1.211</td>
<td></td>
<td>( \lambda = 2.3 \pm 0.4 ) [24]</td>
</tr>
<tr>
<td>1.0–2.0</td>
<td>Silt (ML)</td>
<td>7</td>
<td>2039</td>
<td>4</td>
<td>0.17</td>
<td>84</td>
<td>0.088</td>
<td></td>
<td>( \lambda = 1.1 \pm 0.9 ) [29]</td>
</tr>
<tr>
<td>2.0–3.0</td>
<td>Clay (CL)</td>
<td>12</td>
<td>1733</td>
<td>179</td>
<td>0.19</td>
<td>15</td>
<td>0.002</td>
<td>( \lambda = 2.1 \pm 0.6 ) [24]</td>
<td></td>
</tr>
<tr>
<td>3.0–4.0</td>
<td>Clay (CH)</td>
<td>21</td>
<td>1855</td>
<td>228</td>
<td>0.15</td>
<td>11</td>
<td>0.001</td>
<td>( \lambda = 1.3 \pm 0.3 ) [30]</td>
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</tr>
<tr>
<td>4.0–5.0</td>
<td>Sand (SP)</td>
<td>22</td>
<td>1843</td>
<td>292</td>
<td>0.20</td>
<td>14</td>
<td>0.002</td>
<td>( \lambda = 0.3 \pm 0.2, \lambda = 0.7 \pm 0.04, \text{Cp} = 2085 \pm 925 ) [32]</td>
<td></td>
</tr>
<tr>
<td>5.0–6.0</td>
<td>Sandy silt (ML)</td>
<td>19</td>
<td>1870</td>
<td>40</td>
<td>0.08</td>
<td>19</td>
<td>0.013</td>
<td>( \lambda = 2.3 \pm 0.4 ) [24]</td>
<td></td>
</tr>
<tr>
<td>7.0–8.0</td>
<td>Clayed silt (ML)</td>
<td>27</td>
<td>1800</td>
<td>95</td>
<td>0.20</td>
<td>28</td>
<td>0.014</td>
<td>( \lambda = 2.1 \pm 0.6 ) [24]</td>
<td></td>
</tr>
<tr>
<td>8.0–9.0</td>
<td>Clay (CL)</td>
<td>29</td>
<td>1756</td>
<td>103</td>
<td>0.21</td>
<td>30</td>
<td>0.015</td>
<td>( \lambda = 0.4 \pm 0.6 ) [29]</td>
<td></td>
</tr>
<tr>
<td>9.0–10.0</td>
<td>Silty clay (CL)</td>
<td>27</td>
<td>1517</td>
<td>1</td>
<td>0.41</td>
<td>426</td>
<td>0.673</td>
<td>( \lambda = 0.3 \pm 0.2, \lambda = 0.7 \pm 1.3 ) [31]</td>
<td></td>
</tr>
</tbody>
</table>

Effect of water content on thermal properties:

For similar types of soil, it was observed that the higher the percentage of water by weight, the higher the thermal conductivity and thermal diffusivity. Which is consistent with what has been reported in other articles [24,25,28–30,35]. There appears to be a direct correlation between the water content and the heat capacity of the soil. In a geothermal heat exchanger cooling system, a depth in which the water content helps to maintain adequate thermal conductivity and that does not present variations should be preferred.

There are two depths favorable to taking advantage of the temperature exchange in the summer (at 3 m and at approximately 7 m). According to the characteristics of the soil, it can be observed that the optimum depth for the installation of the soil–air exchanger (Provençal or Canadian tubes) is 3 m deep, in a high-compressibility clay soil with 21% humidity and 0.152 W/mK of thermal conductivity, unlike in Canada [22].

The reasons for choosing the 3 m depth are as follows:

1. At this depth, there is a clayey stratum, which presented one of the lowest thermal conductivities of those found (0.191 W/mK from 2 to 3 m and 0.152 W/mK from 3 to 4 m).
2. There will be fewer variations in the moisture content of the soil, a key factor in the thermal properties of soils.
3. The temperatures (28 to 32 °C) are close to those of thermal comfort (26 °C), allowing the energy consumption of conventional devices for air-conditioning to be reduced.
4. There is less variation in soil temperature throughout the year (1 to 2 °C).

Regarding the 7 m depth, it seems unviable operationally and economically for three reasons: a. the cost of excavation is higher, b. system maintenance is complicated and expensive, and c. the pipes would be subjected to higher pressures and more resistant ones would be required.

3.3. Sizing and Simulation

The results for the sizing of the geothermal heat exchanger are presented in Tables 3–9 and were obtained by following the formulas given in Section 2.5. In summary, the buried heat exchanger will be constructed from PVC pipes and joints (Table 4). It will consist of an air inlet fed by a centrifugal fan (Table 3) located on the surface. On the other side, the outlet will connect to the infrastructure to be air-conditioned. It will be considered to be
placed in a layer 3 m under the ground and will have a total length of 410 m occupying an area of 440 square meters. The pipes will have a diameter of 20 cm. The centrifugal fans that will drive the system will each be capable of moving 510 cubic meters of air per hour. This system can cover 40 to 50% of the existing thermal load. Moreover, we selected the maximum temperature of 41 °C as the input parameter expecting to obtain to 30 °C as the output temperature (Table 5). To reduce the amount of data, we show the results of the Mean Logarithmic Temperature for four of the nine layers studied (Table 6); the 0–1 m layer was not studied because of the influence of irradiation on this layer. With these results, we calculated for each layer the minimal pipe length (Tables 7 and 8).

Table 3. Fan selection data.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>222.2</td>
<td>m³</td>
</tr>
<tr>
<td>Air Exchange per Hour</td>
<td>5</td>
<td>1/h</td>
</tr>
<tr>
<td>Total Volumetric Flow</td>
<td>1111</td>
<td>m³/h</td>
</tr>
<tr>
<td>Angular Speed</td>
<td>1700</td>
<td>RPM</td>
</tr>
<tr>
<td>Power</td>
<td>1/2</td>
<td>HP</td>
</tr>
<tr>
<td>Flow</td>
<td>510</td>
<td>m³/h</td>
</tr>
</tbody>
</table>

Table 4. Pipe diameter selection data.

| Flow (V)                     | 0.1417     | m³/s       |
| Air Kinematic Viscosity (ν)  | 16–69 × 10⁻⁶| m²/s       |
| Reynolds Number (Re)         | 10,000     | /          |
| Equation                     |             |            |
| Internal Diameter (Di)       | 0.192      | m          |
| External Diameter (Do)       | 0.200      | m          |
| Thermal Conductivity (ki)    | 0.16       | W/mk       |

Table 5. Pipe length selection data.

| Inlet Temperature (Tin)      | 41.47      | °C         |
| Outlet Temperature (Tout)    | 30         | °C         |
| Air Density (ρ)              | 1.1348     | kg/m³      |
| Air Specific Heat (cp)       | 1.007      | kJ/kgK     |
| Air Kinematic Viscosity (ν)  | 16–69 × 10⁻⁶| m²/s       |
| Air Thermal Conductivity (ka)| 0.0269     | W/mk       |
| Air Prandtl Number (Pr)      | 0.706      | /          |
| Flow (V)                     | 0.1417     | m³/s       |
| Length Equation              | L = \frac{\nu \sqrt{\frac{T_{in}-T_{out}}{\Delta T_{ml}}}}{\ln(\frac{\pi}{\nu})} + \left(\frac{1}{h \pi D_i} + \frac{\ln(\frac{\pi}{\nu})}{2 \pi k_i}\right) |
| Mean Logarithmic Temperature Equation | \Delta T_{ml} = \frac{41.47 - 30}{\ln(\frac{\pi}{\nu})} |

Table 6. Mean logarithmic temperature per layer.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Max. Temperature (°C)</th>
<th>Mean Logarithmic Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–2 m</td>
<td>35.1</td>
<td>0.257</td>
</tr>
<tr>
<td>3–4 m</td>
<td>31.12</td>
<td>1.5</td>
</tr>
<tr>
<td>6–7 m</td>
<td>29.59</td>
<td>3.41</td>
</tr>
<tr>
<td>9–10 m</td>
<td>27.15</td>
<td>7.11</td>
</tr>
</tbody>
</table>
Table 7. Pipe length selection equations.

<table>
<thead>
<tr>
<th></th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds Number</td>
<td>( Re = \frac{4 \times 0.1417}{\pi \times 0.192 \times 16.69 \times 10^{-6}} \times 56,301.82 )</td>
</tr>
<tr>
<td>Nusselt Number</td>
<td>( Nu = 0.023 \times 56,301.82^3 \times 0.706^{1/3} \times 129.34 )</td>
</tr>
<tr>
<td>Thermal Convection</td>
<td>( h = \frac{129.34 + 0.0269}{0.192} \times 18.12 \frac{W}{m^2K} )</td>
</tr>
<tr>
<td>Pipe Length</td>
<td>( L = 1.1348 \times 0.1417 \times 1007 \times (\frac{1}{18.12 + \pi \times 0.192 \times \ln(\frac{0.2}{0.192})}) \times \pi \times 0.16 )</td>
</tr>
</tbody>
</table>

Table 8. Pipe length by layer.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Mean Logarithmic Temperature (°C)</th>
<th>Heat Exchanger Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–2 m</td>
<td>0.257</td>
<td>955.28</td>
</tr>
<tr>
<td>3–4 m</td>
<td>1.5</td>
<td>163.67</td>
</tr>
<tr>
<td>6–7 m</td>
<td>3.41</td>
<td>72.01</td>
</tr>
<tr>
<td>9–10 m</td>
<td>7.11</td>
<td>34.53</td>
</tr>
</tbody>
</table>

Table 9. Parameters of simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow of the centrifugal fan</td>
<td>510 m³/h</td>
</tr>
<tr>
<td>Exchanger material</td>
<td>PVC</td>
</tr>
<tr>
<td>Exchanger length</td>
<td>200 m</td>
</tr>
<tr>
<td>Length by step</td>
<td>10 m</td>
</tr>
<tr>
<td>Number of steps</td>
<td>20</td>
</tr>
<tr>
<td>External diameter</td>
<td>200 mm</td>
</tr>
<tr>
<td>Internal diameter</td>
<td>192 mm</td>
</tr>
</tbody>
</table>

The result of the stratigraphic column simulation is shown in Figure 18. It can be observed that the behavior of sinusoidal temperature in the superficial layer changes with the day/night change, while the rest remains as a straight line with a small slope. This behavior is because solar radiation only affects the surface.

Figure 18. Simulation output of temperature of ground vs. time between each layer from 13 to 20 August 2019.

Figures 19 and 20 show us that the error between simulation and the thermal response remains at ±1 °C along all the soil layers, excluding the surface layer, where the model
did not obtain a correct approximation of the radiation model. Another reason for this discrepancy is that the placement of the bore could be cast by a shadow and the real irradiation over the ground was less than the simulation.

The next step consisted of performing a simulation of an exchanger in each of the layers of the previous simulation in order to validate the results obtained. The parameters of the simulations are shown in Table 9.

Figure 21 depicts the tests conducted across all layers, except for the surface due to the previously observed error. Specifically, the layer between 9 and 10 m is omitted due to uncertainties regarding the properties and temperatures below this depth. In this scenario, it becomes evident that the fluid and solid temperatures at 7.5 m are nearly identical, suggesting that the heat exchanger is unlikely to be significantly influenced by fluctuations in the external environmental temperature.

Figure 22 illustrates the outcomes of a simulation performed using SolidWorks to analyze a heat exchanger system with varying depths (1.5, 2.5, 3.5, 4.5, 6.5, 7.5, 8.5 m). These depth values were specifically chosen to minimize the influence of the outermost layers of materials. The graph presents the temperature differential between the heat exchanger’s inlet and outlet, essentially representing the heat dissipation of the fluid. The greater heat loss observed is indicative of the fluid’s capacity to exchange heat with the surrounding environment, considering both the properties of the exchanger and the ground.

The initial layer at a depth of 1.5 m exhibits a slower rate of heat dissipation, likely due to its proximity to the surface. In contrast, the layer situated at 5.5 m boasts superior
thermal conductivity, enabling the fluid to readily exchange heat. However, layers at 7.5 and 8.5 m, despite having suitable properties, exhibit the highest overall heat loss. Depths ranging from 2.5 to 6.5 m exhibit similar thermal behavior.

Figure 21. Stratigraphic simulation with buried exchanger at 7.5 m deep.

Figure 22. Simulation output of temperature loss of the fluid inside the heat exchanger on 18 August 2019.

An estimation was conducted for the peak cooling load within the space, assuming optimal insulation. Considering various factors such as heat generated by individuals, computers, and lighting, the projected load is approximately 5661 watts (equivalent to around 19,315 BTU/h). In contrast, the peak cooling capacity of the proposed system stands at 3330 watts (equivalent to approximately 11,362 BTU/h). As the system was designed to reduce the ambient temperature by 10 degrees within the space, it could be utilized as an economizer or to cool half of the required volume when the proposed system alone cannot achieve the desired comfort temperature.
4. Discussion

The findings derived from this investigation offer a first approach to understanding the soil thermal characteristics and their implications for the optimization and effectiveness of geothermal heat exchangers. This understanding holds great significance for advancing sustainable and efficient air-conditioning systems for desert climates, especially in Latin America, where these kinds of systems are overlooked.

The optimal depth was found to be 7 m from an energy perspective, but we consider that at a 3 m depth, the cost of excavation and maintenance is better. There is a study [36] conducted in Coahuila, Mexico, with which we were able to make comparisons, obtaining the following result: the optimal depth found is the same, so the yield is identical. In this research, the authors consider this depth good for winter (heating), and we found that the optimum depth is useful for summer and fall.

The system, since its conception, was not proposed to cover the total peak cooling capacity; it was designed to reduce the number of days of using traditional HVAC systems for this space. The system’s cooling capacity is 59% of the peak cooling needs using only a 370 W fan and the ground-coupled heat exchanger.

Also, while we have observed quasi-seasonal fluctuations in soil temperatures, the long-term efficiency implications of this variability are yet to be ascertained. Longitudinal surveys can provide invaluable insights into the system’s enduring stability and necessitate any requisite adaptations. A pertinent question revolves around the integration of geothermal heat exchangers with other renewable energy technologies, such as solar panels due to the high irradiance in the region [37].

5. Conclusions

The study showed that, from a depth of 3 m, seasonal variations in soil temperature are significantly reduced. While on the surface, the difference between maximum and minimum temperature was about 20 °C, from a 3 m depth, the difference in seasonal variation is 2 °C.

In the end, it was not considered necessary to use the system to heat the building because the temperatures in the subsoil were above the air temperature and close to thermal comfort. In addition, heating buildings during the winter is not common in the area. This allows the design requirements of the system to be reduced and for the system to be more economical.

Due to a poor approximation in the radiation model, there is a considerable gap between the simulation values and the data recorded in the surface layer. However, this is not the case for the layers below the above-mentioned, since the BIAS remains between 0 °C and +1 °C, thus demonstrating that geothermal energy is not influenced by external factors, but only by the intrinsic properties of the ground.

In addition, clay strata with thermal properties suitable for a cooling system with soil–air heat exchange pipes at 3 and 7 m depth were found. The greater economy in terms of resistance of the materials that form the pipes, excavation, maintenance, and repair requirements made it preferable to install such a system at 3 m depth.

Given the declining reserves of fossil fuels, rising electricity costs, and growing concerns over air pollution and global warming, well-designed earth cooling tubes can serve as a sustainable alternative to conventional compressor-based air-conditioning systems in tropical regions. These tubes can significantly reduce or eliminate the need for such systems, while also providing the added advantage of controlled, filtered, and temperate fresh air intake. This feature is particularly valuable in tightly sealed and well-insulated buildings that prioritize energy efficiency.


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Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author, [I.S.-T.].

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Conflicts of Interest: The authors declare no conflict of interest.

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