Extended Abstract

Energy Efficiency Evaluation in Thermo-Active Structures

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Abstract

A numerical study was performed for evaluating the geothermal potential of foundation piles used as heat exchangers with the ground, for seasonal heat storage. It is based in a case-study of a building in Aveiro Campus University, equipped with a shallow geothermal heat pump system (GSHP) designed to support most part of the energy demands for the building's acclimatization. The modeling of a single pile (60 cm diameter and 10 m length) was performed using FLAC, an explicit Lagrangian finite difference software. The influence of the soil thermal properties and location of the water table level were investigated regarding the efficiency of the system. The influence of the building's slab on the thermal performance of the pile was investigated as well. The soil conductivity was obtained by means of empirical relations and through laboratory characterization tests. Different thermal loading conditions on the energy pile and foundation soil were examined. They correspond, respectively, to thermal loads from the building service operation and from estimates based on local climate. In turn, climate data records concerning temperature from different sources in the city of Aveiro were considered. Data from the simulation \of those scenarios is discussed considering how these aspects must be taken into account for assessing the ground thermal fluxes and how they influence the energy efficiency of the system.

In general, when the water table is considered closest to the surface, the GSHP performs better than if considered at lowest point. Overall, considering a slab as a temperature boundary between soil and building hinders the efficiency of the thermo-active pile, reversing the direction of the heat flux in the soil, if a long term analysis is considered (5 years).

Keywords: Geothermal; Shallow geothermal; Thermal energy; Efficiency; Energy structures; Thermo-active pile; numerical.

1. Introduction

Ground source heat pumps (GSHP) are a mature technology that allow the transport of thermal energy from a heat source to a heat sink by means of an electrical compressor. This technology may reach point-of-use efficiency of 500% and over and uses a renewable source of energy, reducing greenhouse emissions by more than 66% and uses less than 75% of electricity when comparing with conventional HVAC systems.

In this thesis, an actual GSHP system is analysed regarding its thermal interactions with the surrounding soil and with the building associated with it. The first goal to be met consists on investigating and outlining the different aspects that affect the performance of an actual ground source heat pump (GSHP) system working since 2013, in an academic building located in Aveiro, Northwest of Portugal.

The ultimate objective of this master thesis is to make a preliminary assessment of the thermal behaviour of the mentioned shallow geothermal heat pump system. This analysis will be done under an efficiency perspective, by evaluating how well can the soil transfer heat in different conditions and what is the thermal response of that soil under the thermal load imposed by the SGHP. For this purpose, a numerical simulation using software *FLAC 2D* will be performed.

2. Shallow Geothermal Energy

2.1. The different uses for geothermal energy

Geothermal energy can be sorted into three different categories based on the temperature level of the source. High enthalpy resources, used mainly for electricity generation; medium enthalpy resources, used mostly for direct heating; Low enthalpy resources, used for indirect heating.

Low enthalpy resources may also be called shallow geothermal resources, since they use the thermal energy existing in the shallow layers of soil. The concept behind shallow geothermal energy utilization states that one may harness or dump thermal energy from and to the soil, respectively. In the Winter, thermal energy would be gathered from shallow soil and transported to a building in order to heat the colder air. The opposite occurs in the Summer season, where soil works as a deposit for the thermal energy retrieved from a building's usable space. Such processes are associated with Indirect heating and cooling, which requires the support of certain machines called heat pumps. Heat pumps use the same principle as a refrigerator, moving heat from one place to another, with the help of a little electrical energy input.

2.2. Heat transfer in soils

In nature, there are three modes of heat transfer [2]: Convection, conduction and radiation. Conduction heat results from the random spread of heated particles that occurs when a higher energy region contacts with a lower energy region, or in other words, heat diffusion. Convective heat transfer combines diffusion with the transport of heated particles by the motion of a fluid, which is what defines advection. Radiation is related to the heat transfer across vacuum or a transparent medium by propagation of electromagnetic waves.

Thermal properties are what determines the behaviour of materials when subject to any given thermal action. The most important thermal properties are thermal conductivity (λ) and heat capacity (C). Soils are heterogeneous materials, which comprise three different phases: solid, liquid (mainly water) and gas (mainly air, assumed dried). Therefore the concept of effective thermal properties λ_{eff} and C_{eff} may be used to characterize the soil's combined thermal conductivity among the individual properties of the multiphase constituents. These properties may be determined by: empirical methods; laboratory tests and field tests.

2.3. Shallow geothermal heat transfer systems

As of today, there are two main approaches to effectively use low enthalpy thermal energy. One of them gathers heat from a heat wasting source and stores it underground in an underground thermal energy store (UTES) for further use. The second method utilizes the already mentioned ground source heat pumps (GSHP) to transfer heat from a source to a usable space. Although both systems are similar in many concepts, for the purpose of the case study presented in chapter 3, heat transfer systems refer to the applications using GSHP. [3]

A ground source heat pump system can be decomposed in three global components: primary circuit, heat pumps and secondary circuit. The primary circuit establishes thermal trades with the soil, using of lengths of heat exchanger pipes installed in the soil. The secondary circuit transports the usable heat energy to the end user. Both these circuits are connected by the heat pump, which transports heat from one circuit to another, with the help of a small electrical input.

The primary circuit is always installed by means of a geotechnical application, including grouted boreholes, horizontal trenches, ground water wells, energy foundations. Energy Foundations are the denomination given to structural foundations equipped with heat exchanger pipes integrated into its steel mesh. The pipework involved in the mentioned solutions are usually made from polyethylene due to its flexibility and durability. Diameters range from 25mm to 60mm. This master thesis focuses on a case study of a building that includes, in its design, more than 80 energy piles.

3. Case Study: The CICFANO University Building

3.1. Building overview

The building evaluated in this investigation is designated by CICFANO (Complexo Interdisciplinar de Ciências Físicas Aplicadas à Nanotecnologia e Oceanografia), and was built in 2012. The GSHP was integrated in the project from the beginning, but it has only been functional since mid-2013. The building is founded on 110 piles, 85 of which being equipped with heat exchanger pipes. The piles are 10 meters long and diameters vary between 400mm or 600mm.

The acclimatization of the building results of a combination of techniques, including a GSHP and a Biothermal Heat Pump System (BHPS) as heat sources. The geothermal system is controlled in real-time by a software, and the heat pump equipment works with a COP of 4.1.

In order to study the thermal behaviour of the soil underneath the CICFANO building, when subject to the thermal loads of the SGHPS, three elements must be assessed: Climate; Energy demands of the building; Soil characterization.

3.2. Climate analysis and energy demand

For the climate analysis, temperature data was retrieved from two sources (Campus of Aveiro University and *worldweatheronline*). The best analytical fit for the different temperature data was the sinusoidal function ($R^2 > 0.98$). After comparing the curves obtained for both sources and for different time frames, the chosen function was:

$$T = 15.46 + 4.52 * sin(t * 2\pi/31536000 + 2.36)$$

This function will be used in the numerical simulation to represent the climate action at the surface of the soil. This specific curve, represents temperatures felt during the 2013/2014 season (year of the inauguration of the GSHP from the CICFANO).

This assessment of energy demand focuses on two aspects: what are the building requirements and what trades are expected from the thermo-active piles. In accordance with the data provided by the University of Aveiro, the building's requirements for heating are 96.1 MWh/year for heating and 62.3 MWh/year for cooling. Due to the limited depth of the energy piles, the system is only expected to satisfy 75% and 65% of of heating and cooling demands, respectively. As a simplification, it is assumed that building only requires heating if temperatures drop below the average temperature (section 3.2) and, similarly, it only requires cooling if temperatures rise higher than that value. It is assumed, also as a simplification, that the thermal load on a single pile is applied uninterruptedly over 365 days of cooling/heating. The resulting step function of the heat load applied on a single pile during one year is shown in figure 1:

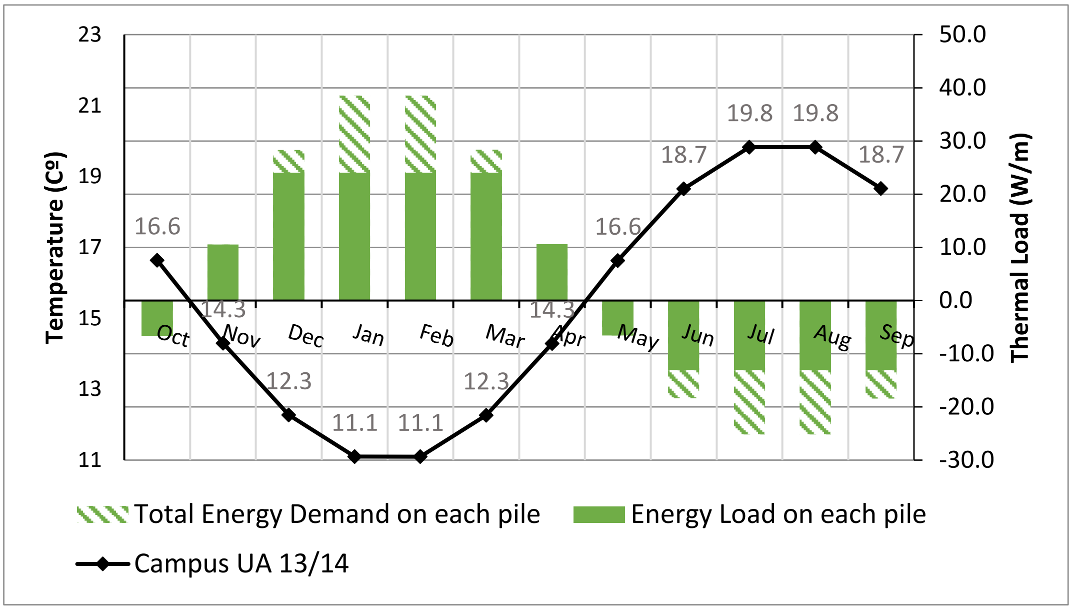

Figure 1. Energy Demands of the CICFANO building

3.3. Soil analysis

The soil from the CICFANO's foundations can be divided in an upper sand layer, about 5 meters thick and a stiff lower silty clay layer with at least 15 meters of thickness. Disturbed samples from both layers were analyzed in the laboratory regarding their grain size distribution. Classification and results for that analysis can be seen in table 1.

Table 1. Verifications performed using FLAC software

SP : Poorly Graduated Sand				MI-CL : Silty Clay with sand			
Cc	Cu	%Gravel	%Sand	LL	PL	PI	%fines
0.82	3.75	27	71	22.9	17.8	5.1	75

The thermal conductivity of the upper sand layer was measured by Cruz (2017) in his work. For the dry sand, Cruz determined a dry effective thermal conductivity of 0.44W/mK $(e_0 = 0.334\,; Sr = 0)$. Using that value as reference, investigations were performed on the lower clayey soil, in order to establish a relation. Table 2 shows the results obtained from the analysis of an undisturbed sample from the lower layer, regarding its void ratio, porosity and degree of saturation. Table 3 shows the results obtained from the mineralogical evaluation performed using the reference intensity ratio (RIR) method on the X-Ray diffraction test.

According to the mineralogical evaluation, both layers will have similar λ_s. Since sample from the lower layer displays a porosity of 0.326, effective thermal conductivity may be calculated empirically estimated to be $\lambda_{eff} = 1.96\,W/mK$ considering saturated state and a geometric average among the constituents. As a summary, the geotechnical model used in the numerical simulation is presented in figure 2.

Table 2. Verifications performed using FLAC software

w (%)	G_S	$\gamma_{dry}(g.cm^{-3})$	$\gamma_{sat}(g.cm^{-3})$	Sr (%)	e_0		χ (%)
18.2	2.70	1.82	2.15	100	0.483		0.326

Table 3. Verifications performed using FLAC software

	Crystalline Composites (%)						
	Quartz	Muscovite	Albite	Microcline	Orthoclase	Chlorite	Kaolinite
Upper Layer	93	1	1	4	1	-	-
Lower Layer	92	1	1	3	1	1	1

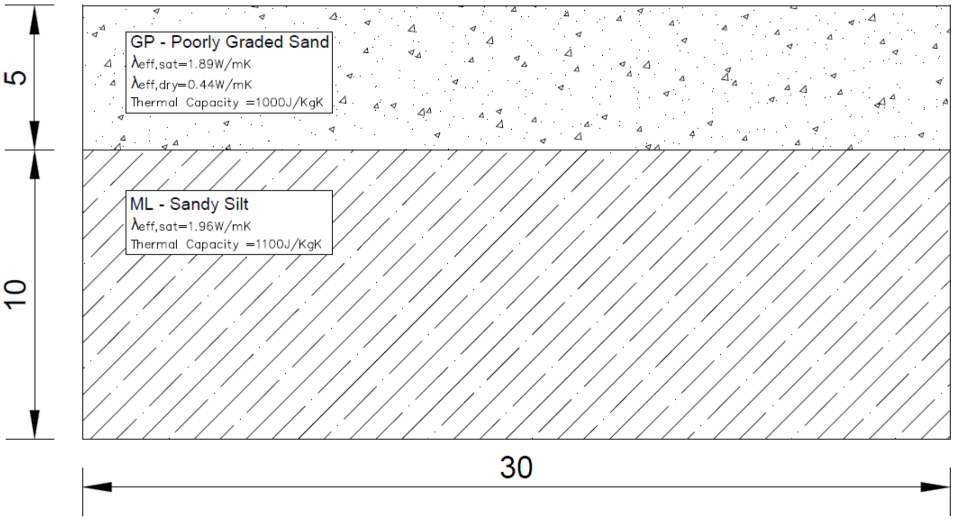

Figure 2. Energy Demands of the CICFANO building (dimensions in meters)

4. Numerical Modelling

4.1. Preliminary numerical verifications

Prior to the development of the case study model using this numeric tool, a few summary verification problems are solved in order to demonstrate the reliability of upcoming results. The goal is to compare the results obtained using FLAC with well described analytical solutions, and using inputs of the same nature and intensity as the ones analysed in section4.2 A summary of the verifications is presented in table 4.

After these simulations were performed using FLAC 2D, it was found that the grid used in section 4.2. should have at least 40 meters of width, instead of the 20 meters considered at first.

Numerical outputs are very close to analytical values, with differences lower than 0.05ºC. Both transient and steady state conduction have been verified for two different kinds of heat source: a temperature boundary and a heat flux boundary.

Table 4. Verifications performed using FLAC software

Model	Configuration	Verification	Analytical Solution	Grid Tested [m x m]
Infinite Line Source	Axysimetric state	Steady state conduction	Nowacki (1962)	20x20 and 40x40
		Transient state conduction	Nowacki (1962)	40x40
Infinite Half Space		Steady state conduction	Fourier Law of Conduction	40x40
		Transient state conduction	Wealthy (1974)	40x40

4.2. Numerical Modelling of a thermo-active pile

In this chapter, an evaluation of the thermal behaviour of the CICFANO GSHP system was performed, considering an efficiency perspective. The numerical analysis was performed using FLAC 2D. Three cases were considered based on two realistic positions of the water table, and also on the influence of the building's bottom slab as a boundary condition.

Table 5. Verifications performed using FLAC software

	Water table	Slab boundary	Thermal conductivity	Climate Action	Thermal Pile Load
Case 1	At surface	Non existing	Sand: (1.89 W/mK) Silt: (1.96 W/mK)	Equation (1)	Step function (figure 1)
Case 2	At 5 meters depth	Non existing	Sand: (0.44 W/mK) Silt: (1.96 W/mK)		
Case 3	At 5 meters depth	Constant indoor temperature			

Case 1 considers the sand layer fully saturated, which corresponds to winter case, case 2 considering the sand layer completely dry, which corresponds to summer case, and case 3 is based on the summer case model (case 1), In case 3 a second simulation will be performed taking in consideration the existence of a slab on the surface of the model, surrounding the head of the pile. This slab is a realistic boundary condition modelled as an applied temperature (constant indoor temperature). The model used for the three cases is resented in figure 3.

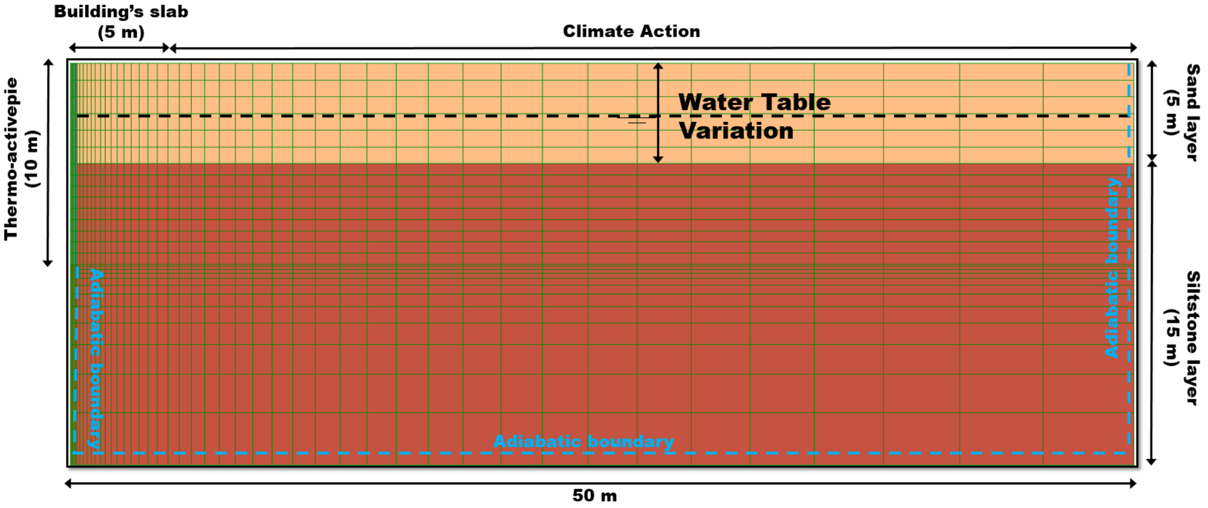

Figure 3. Model used in the numerical simulation with the relevant boundaries, inputs and dimensions

The simulation performed computes temperature variations in the soil mass. However, different kinds of temperature data can be extracted from models such as the following:

- Vertical temperature profiles: Values of the temperature registered on every grid point located at a certain distance x from the axis.
- Extreme temperature profiles: For the total duration of the simulation, these profiles specifically register the highest and lowest values of temperature computed on each grid point located at a certain distance x from the axis.
- Temperature histories: For a certain grid point with coordinates (x, y), a history registers the values of temperature computed on each time step.
- Temperature average (T_{avg}): Variable formulated to determine the average temperature felt among a certain number of grid points of the model.

Temperatures obtained for case 2 (dry sand) are more extreme than the ones obtained for case 1 (saturated sand). However, average temperatures throughout elapsed time are not affected by that fact. The influence on the thermo-active pile on the soil temperatures is becomes clear by examining the differences in the extreme temperature profiles, between the reference profile (no pile installed) and the remaining profiles.

The introduction of the slab as a boundary condition (case 3) produces globally higher temperatures than cases 1 and 2. Furthermore, minimum temperatures in the soil are radically increased from cases 1 and 2. In case 3, temperatures are never lower than their initial value in some areas (always increasing).

From the data acquired in the previous simulations, it is possible to elaborate a calculation of the heat flux passing through the soil, perpendicularly to the pile axis (direction x). Since this analysis is purely conductive, the heat flux on each point was calculated by using Fourier's law of conduction. After calculating the heat flow for each point of a profile was calculated, they were integrated in the cylindrical area respective to each profile, becoming a measurement of the energy per second (Watt) transferred by the soil at a certain distance from the source.

Overall, case 1 (saturated) transfers heat better than case 2 (dry). In fact, the flux wave through the soil travels faster and more efficiently in the saturated sand. In case 3, heat flux reverses its natural direction right after the first year, when compared with cases 1 and 2. Such analysis can be seen in figure 4.

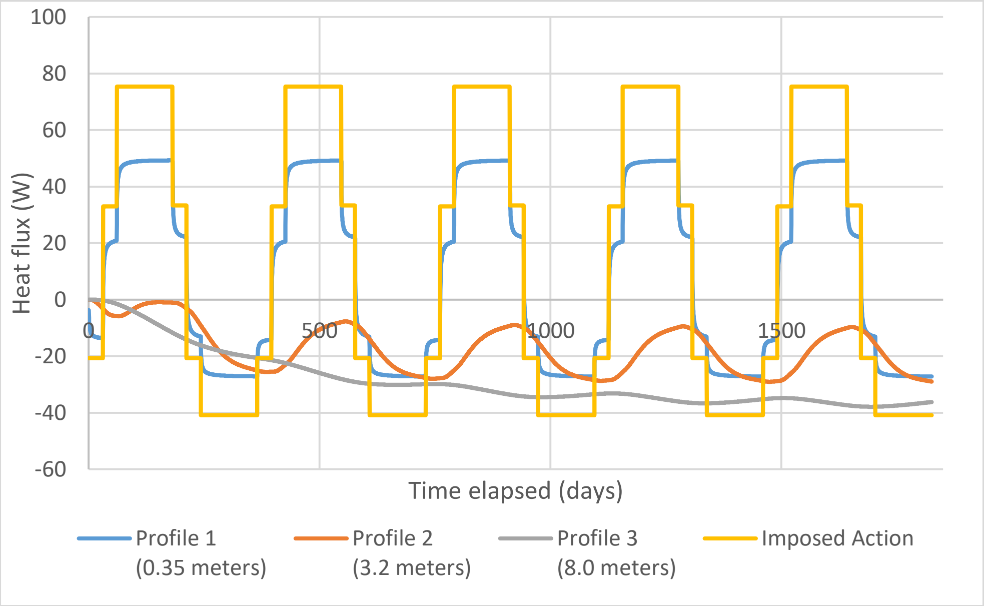

Figure 4. Thermal power held by the soil mass in 3 different areas for case 3, over 5 years

5. Conclusions

Despite the different soil types used in the geotechnical model, their mineralogy is similar. Therefore, it is concluded that in the CICFANO case study, the different thermal parameters used will depend mostly on the hydrological conditions assumed for the soil.

Even though the saturated scenario produces slightly higher temperatures in the soil over time, such overall warming doesn't translate in a loss of thermal efficiency. In fact, it is the other way around. The dry soil seems to be incapable of transferring heat as efficiently as the saturated. A reduction in the amount of heat transferred by dry soil has a real impact on the building's acclimatization process.

Among the three cases studied, temperatures either stabilize after the first year (case 2), or they rise at an average rate of 0.05ºC per year, over a time lapse of 5 years (case 1). Including the presence of the slab into the simulation causes the system to become overheated. In fact, after 3 years, the pile is attempting to absorb heat from the soil, and instead, heat is moving away from the pile.

Overall, using a conduction only analysis and assuming no water advection within the soil mass, the GSHP system seems to be sustainable over a 5-year span for cases 1 and 2. However, assuming that the building's slab is at a constant indoor temperature, the system will not be able to respond efficiently, at least in the long therm. However, the GSHP was analysed as a separate part of the CICFANO building. In reality, the complementary biological source heat pump as proven effective in supplying thermal energy when the GSHP cannot. The building's acclimatization using renewable energy sources is always secured.

Acknowldegment

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