From Fundamentals to Applications in Geotechnics
D. Manzanal and A.O. Sfriso (Eds.)
IOS Press, 2015

doi:10.3233/978-1-61499-603-3-704

Geothermal Energy in Loess: A Detailed Numerical Case Study for Cordoba

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Abstract. Ground-source heat pump (GSHP) systems efficiently heat and cool buildings using sustainable geothermal energy accessed via ground heat exchangers (GHEs). Loess covers vast parts of the world, thus the use of piles or 'micropiles' is extensive in these areas, including Cordoba, Argentina. These foundations could be used as 'energy piles' in GSHP systems, with a minimal additional cost. This paper presents a case study of a representative real building in Cordoba where foundations are also used as GHEs. The thermal properties of local soils were experimentally measured and used in detailed state-of-the-art finite element models. Results from the realistic simulations show that the partial substitution of electrical heating and cooling systems with geothermal systems could significantly reduce energy consumption and the size of associated infrastructure, despite the relatively low thermal conductivity of loess. Moreover, accounting for natural surface thermal recharge, which is routinely ignored in GHE design, increases the ability of the energy piles to supply energy to the heat pumps. This case study shows the potential of GSHP technology in a local environment well suited for it and gives incentives to geotechnical engineers to start considering the technology in their designs and practices, even in loess.

Keywords. Energy pile, geothermal, sustainability, thermal conductivity, loess

1. Introduction: Ground Source Heat Pump Systems and Loess Deposits

Ground-source heat pump (GSHP) systems efficiently heat and cool buildings using sustainable geothermal energy accessed via ground heat exchangers (GHEs). In closed loop systems, GHEs comprise high density polyethylene (HDPE) pipes embedded in specifically drilled boreholes or trenches or even built into foundations, all within a few tens of meters from the surface (Figure 1). GSHP systems operate at a coefficient of performance of about four throughout the year, basically delivering four kilowatts of heating or cooling for every kilowatt input into the heat pumps [1-4].

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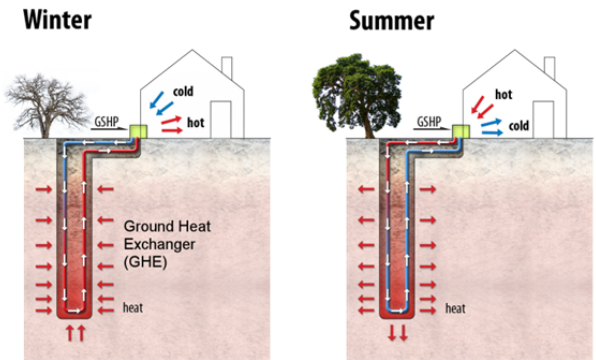

Figure 1. Schematic of a GSHP system in heating (winter) and cooling (summer) modes.

Loess is an unstable soil that develops collapse due to water content and/or load increases. Loessial soils are aeolian sediments composed mainly by fine sand, silt and clay particles that accumulate when deposited by wind (primary loess) and sometimes particles are re-transported by water or snow (secondary loess). In both cases, particles are frequently cemented by either precipitated calcium carbonate or silicates [5-7]. Loess covers vast parts of the world, about 10% of the landmass, and is encountered across New Zealand, from Western Europe to China (including Russia), across North America and in regions across South America (e.g., 35% of Argentina) [7-9].

In particular, loess deposits cover large areas of Cordoba, Argentina and are tens of metres in thickness. Given these predominant ground conditions, the use of piles for multi-story buildings or 'micropiles' for lighter residential buildings is extensive. These foundations could be used as 'energy piles' (i.e., GHEs) in GSHP systems. However, GSHP technology has not been yet implemented in South America despite its proven significant economical and environmental benefits. Moreover, there are virtually no studies conducted on the feasibility and design of geothermal systems in loessial soils. Therefore, there is a missed opportunity in current practice to use deep foundations with a dual purpose, structural and as GHEs, with a minimal additional cost. The GSHP alternative becomes even more attractive in the areas where natural gas infrastructure is not available and only expensive LPG gas or wood is used for heating. GSHP systems can significantly reduce the use of these fuels in these areas and at the same time can provide an alternative clean energy for conditioning of buildings.

To exemplify the benefits of GSHP systems in loess deposits and highlight potential issues, this paper presents a numerical case study of a representative real building in Cordoba, where foundations are also used as GHEs.

2. Site Description

The case study, a residential building, is located 2 km west of Cordoba city (Argentina) and consists of a typical residential 2-story building with a footprint of approximately 85 m^2 in a 475 m^2 lot (17.6 x 27 m) (Figure 2 left). The geological formation corresponds to a wind plain aggradation mid Pleistocene early Holocene. This domain is characterised in the field of Cordoba city and its periphery, on both sides of the valley of the Suquía river, by a gently undulating plane of sedimentary cover-loessoide silt with a regional tilt to the east of the order of 0.5%.

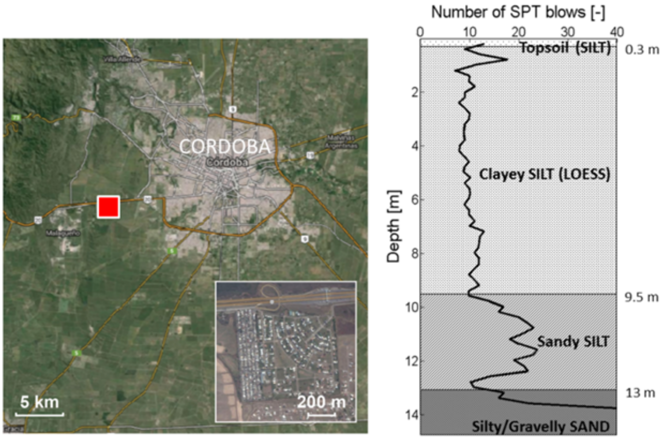

Figure 2. Site location (left), representative soil profile and SPT profile within the site (right).

The formation consists of 4 distinguishable layers (Figure 2 right): non-plastic silt with some organic matter (z=0 to z=0.6 m below ground surface); collapsible non-plastic silt with some clay and sand (z=0.3 m to z=9.5 m) (loess); low plasticity silt with sand (z=9.5 to 13 m); and a sand with silt and gravel layer (z> 13.0 m).

The water table was not found within 14 m below the ground surface at the time of the geotechnical site investigation that was conducted during the dry season (winter). In the loess layer, the natural water content was found to be about 17% and the dry density about 1.4 g/cm^3. The foundations of this case study involves a total of 13 piles, 9.5 m deep, with 9 piles of 0.4 m diameter and 4 (central) piles of 0.6 m diameter.

3. Soil Thermal Characterisation

There is limited published literature about the thermal properties of loess, let alone of the soils in Cordoba. The thermal needle probe method was used for the determination of thermal conductivity of 'typical' loessial silts from Cordoba following ASTM recommendations [10]. Figure 3 summarises the measured thermal conductivities for a range of dry densities and water contents, resulting between 0.36 and 0.88 W/(m.K).

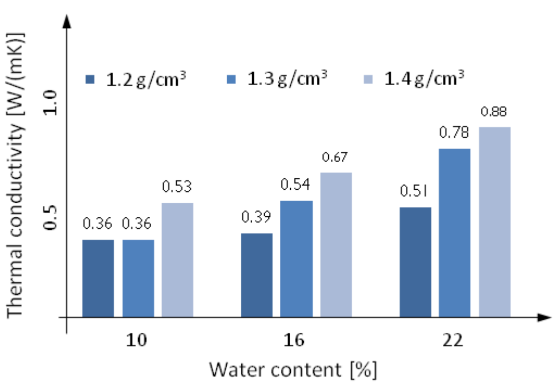

Figure 3. Loess thermal conductivity for a range of dry densities and water contents.

4. Numerical Modelling

The aforementioned data are used in detailed finite element simulations of the GHE field corresponding to the building using a state-of-the-art model recently developed. The model can account for the local geology, surface thermal recharge and the local weather for a more realistic representation of GHEs. An overview of the model and the geometry and initial and boundary conditions of the case study follows.

4.1. Governing equations

A 3D numerical model based on first principles has been developed and implemented using finite element methods [11, 12]. The governing equations for fluid flow and heat transfer are coupled numerically within the finite element package COMSOL Multiphysics to evaluate thermal performance of GHEs. The geomechanical behaviour is excluded from the scope of this paper, given the negligible effects reported elsewhere.

Heat transfer around and in the GHEs is modelled primarily by conduction and convection. Heat conduction occurs in the soil, pile concrete and HDPE pipe wall, and partially in the carrier fluid (water) circulating in the pipe; while heat convection dominates in the carrier fluid, since there is no groundwater flow in the soil.

The fluid flow in the pipes and the heat transfer in the fluid are simulated using 1D elements that solve the continuity and momentum equations (fluid flow) and energy equations (conductive-convective heat transfer). These results are coupled to the 3D heat transfer in the GHEs and the surrounding soil to save computational time. In these domains, an energy balance governing equation for conductive heat transfer is used:

$$\rho_m C_{p,m} \frac{\partial T}{\partial t} = \nabla(\lambda_m \nabla \mathrm{T}) \tag{1}$$

where ρ_m is the density of the given material (i.e., pipe, concrete or soil) in kg/m^3, $C_{p,m}$ is the heat capacity of the materials in J/(kg.K), T is temperature in K and λ_m is the thermal conductivity of the materials in W/(m.K).

This model has been recently validated against a few available analytical solutions, and full scale experimental data, and further details can be found in those references [11, 12]. The model is capable of accurately predicting heat transfer between the ground and the GHEs in both laminar and turbulent regimes, homogeneous and heterogeneous soil profiles, and flexible to explore a number of different pipe placement configurations in steady state and transient conditions.

4.2. Case study: geometry, initial and boundary conditions

Figure 4 shows the finite element model and the key initial and boundary conditions, together with the GHEs (piles) configuration. The 13 GHEs are spaced between ~2 to 4.4 m. Only the 4 piles in the middle row are 0.6 m in diameter, allowing the insertion of 3 HDPE U-loops, whose spacing between inlet and outlet pipes is 0.16 m (a detail is shown in the figure as well). The remaining 9 piles can accommodate only 2 of these U-loops, given their reduce diameter of 0.4 m.

The parameters used in all numerical models are shown in Table 1. The initial and farfield ground temperature $T_{farfield}$ was set as a constant 18˚C (~ local constant ground temperature at depths between ~5 and ~100 m). In reality, $T_{farfield}$ is not constant and varies with depth z and time t of the year; these variations derive from the surface air temperature fluctuations throughout the year.

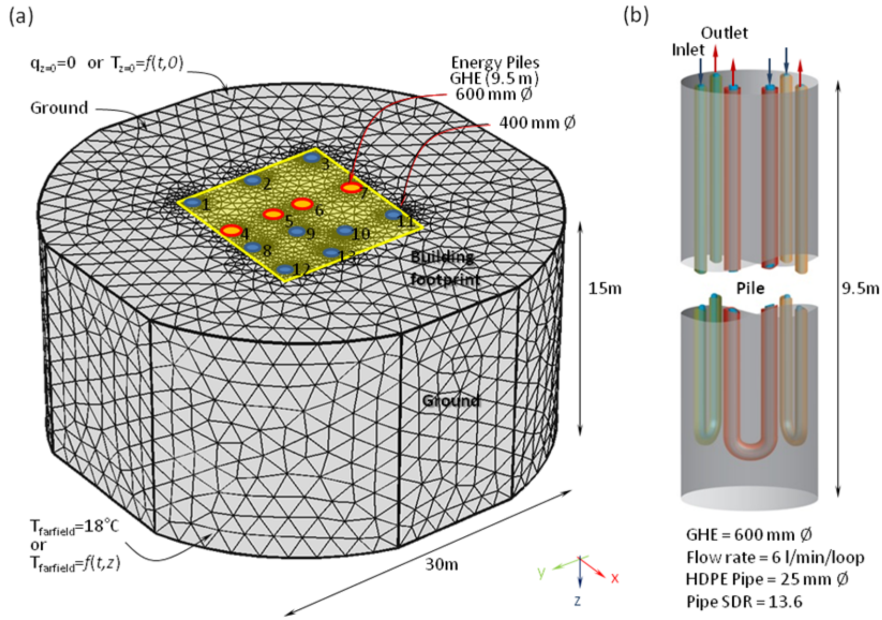

Figure 4. Finite element model used in the simulations, with soil limits far enough to minimise artificial boundary effects. The building footprint and a detail of a 0.6 m energy pile are also shown.

Table 1. Summary of the key input parameters used in the numerical models.

Material	λ_m W/(m.K)	$C_{p,m}$ J/(kgK)	ρ_m kg/m^3	$T_{farfield}$ ˚C	Diameter m	Spacing m
Loess (soil)	0.700	1,200	1,600	18 or *f(t,z)**	-	-
Concrete (piles)	2.100	850	2,350	-	0.4 & 0.6	2 to 4.4
HDPE (pipe)	0.400			-	0.025	0.16
Water (fluid)	0.582	4,180	1,000	-	-	-

* $f(t,z)=18+1.07\cdot 0.25\cdot 14\cdot \exp\left(-0.0031552z\sqrt{1/0.364538}\right)\cdot\cos\left[(2\pi/365)(t-238-0.18335z)\sqrt{1/0.364538}\right]$

Thus, some heat is exchanged between the air and the ground (surface thermal recharge/discharge) and it is accounted for in additional simulations (i.e. $T_{farfield} = f(t,z)$).

For simplicity, the annual peak building thermal load was estimated based on rules of thumb for typical gated community residencies (heating = 0.035 kW/m^3 or 30 kcal/h/m^3; cooling = 0.058 kW/m^3 or 50 kcal/h/m^3) rather than detailed energy balance calculations. Our case study comprises a total of 160 m^2 covered area, of which 20 m^2 is for a double garage that does not need conditioning. Thus, for 2.6 m height ceilings, the peak heating and cooling demands result in 12.7 and 21.1 kW respectively.

5. Results and Discussions

There are a number of design strategies that could be implemented when deciding on a residential GSHP system, including aiming to provide 100% of the heating and cooling required or to combine geothermal with auxiliary systems (i.e., designing a hybrid system). Perhaps the first question to be answered is what the geothermal installed capacity of this residential building would be if all 13 of its piles were used as GHEs.

Figure 5-a shows the total building heating and cooling demand distribution throughout a year, based on the peak demands (12.7 kW and 21.1 kW respectively, Section 4.2) and the air temperature recorded in 2014.

Our numerical modelling revealed that the 13 piles are unable to satisfy 100% of the house thermal demands. One alternative is to drill additional GHEs outside the footprint of the house in the available land of the lot. Another alternative is to consider hybrid systems: the GSHP system covers part of the demand and the auxiliary systems (e.g., smaller gas heater(s), smaller air conditioner unit(s), etc.) are either used to top up the supply of heating or cooling (Case 1) or just turned on when this base demand exceeds the geothermal capacity (Case 2). Thus, these two load distributions cases are investigated in this paper. Case 1 implies that the auxiliary system is running most of the time concurrently with the GSHP, while Case 2, only a number of days each year.

The average fluid temperature variations (i.e., $(T_{inlet}+T_{outlet})/2$) obtained from 20-year numerical simulations are presented in Figure 5-b. It is observed that satisfying Case 1’s thermal load distribution results in a reasonable temperature range (3.5 to 44.3˚C), compatible with most heat pumps. On the other hand, Case 2 results in a fluid temperature drop to a minimum of -1.6˚C in cold seasons (which is acceptable with an antifreeze solution) and rise to a maximum of 56.7˚C in warm seasons.

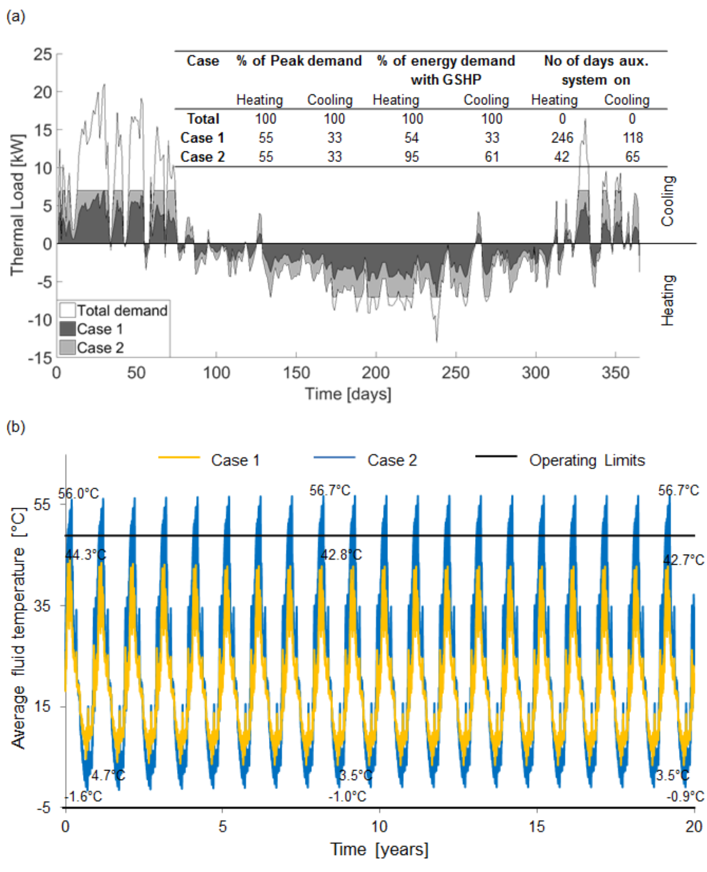

Figure 5. Thermal load distributions throughout a year and GHE response along 20 years.

This maximum is higher than typical GSHP recommended EWT (entering water temperature to the heat pump). It follows that this GHE field is not capable of delivering the thermal load defined for Case 2. Thus, we focus on Case 1 from now on.

Figure 6 shows the temperature field at mid-depth of the energy piles (about 5 m below ground surface) throughout the last year of operation (year 20). The figure shows that freezing is avoided in the GHE field for Case 1, with no point within the soil or the energy piles reaching less than 3.8˚C, even during the coolest seasons when the GHEs extract most of the thermal heat from the ground. Therefore, potential structural problems due to concrete freezing and/or soil heaving are circumvented.

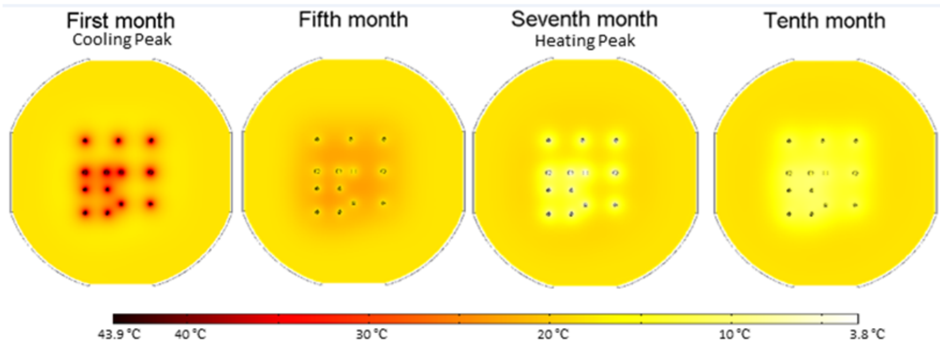

Figure 6. Temperature field in the 13 piles and surrounding soil at 5 m below surface, during year 20.

The results shown so far did not account for the effects of surface air temperature variations on the efficiency of the system (i.e., $T_{farfield}$ = 18˚C). To account for these effects, a time and depth varying temperature is now prescribed to the ground including the farfield boundary using Baggs et al.'s ground temperature formulation [13]. Numerical results (see Figure 7) show that when the air temperature variations and therefore, the surface thermal recharge/discharge are accounted for, the maximum temperature reached by the fluid is about 3.3˚C lower than that of the (simplified) constant farfield temperature models. In other words, the application of a more realistic boundary condition on the numerical models assists the GHE field to fulfil the required thermal demand.

In this specific case study, if the initial and farfield ground temperature are assumed as constant, a minor increase in the peak cooling provided by the GSHP system (e.g., 20%) will increase the maximum fluid temperature such that it exceeds the acceptable EWT range of most of commercially available heat pumps (i.e., from about 45˚C to 50˚C) and will reduce the efficiency and functionality of the system. However, if the more realistic surface thermal exchange is included in the simulations, then the cooling capacity of the GHE field may increase.

From these results, it follows that even though the low thermal conductivity of loess (0.7 W/(m.K)) and relatively shallow GHEs (~10 m) affect thermal efficiency of the GSHP systems, the incorporation of a GSHP system into the inexorably needed 13 structural piles (described in Section 2) leads to about 30% savings in the conventional energy usage (e.g., electricity or fossil fuels) and in the energy bills, with the GSHP satisfying 54% of the heating needs and 33% of the cooling needs. Although this GHE field cannot provide 100% of the required heating and cooling demand, it can be used to provide part of the building thermal demand with little additional capital cost.

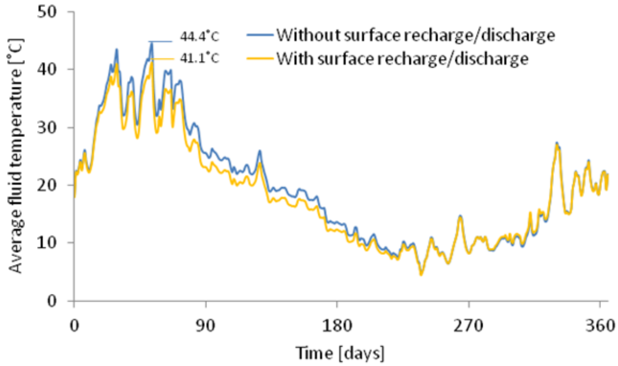

Figure 7. Average GHE fluid temperature with and without surface thermal recharge/discharge.

6. Conclusions

Pile and micro-piles, of extensive use in the loessial areas, can be easily converted into GHEs while being built. Results from the realistic detailed modelling show that the partial substitution of electrical heating and cooling systems with geothermal systems could significantly reduce energy consumption and the size of associated infrastructure (electricity grid). The temperate climate dominating in Cordoba presents ideal conditions for GSHP systems allowing thermal recharge of the ground between seasons and thus maximizing the heating and cooling capacity that energy piles can achieve. This case study shows the potential of GSHP technology in environments dominated by loess, so that geotechnical engineers can consider it in their designs and practices.

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