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Parametric study for the long term energetic performance of geothermal energy piles

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Abstract.

Geothermal energy constitutes an important renewable resource that will become increasingly prominent in future constructions. A common method of extraction and usage consists of installing, inside the foundation piles of buildings, U-shaped heat exchangers called "energy piles".

In this paper such installations are addressed by means of a full parametric study, performed for a hall-type commercial building in a cold climate. By computing the transient heat transfer between energy piles and ground for a period of 20 years, guidelines for a preliminary sizing of the geothermal system as a whole are provided. These are valid for this specific building and climate, for a clay-type soil and without assuming thermal storage.

A highly nonlinear behaviour of the expected yield in relation to pile separation and evaporator extraction power is observed. Furthermore, 15m-long piles are found to be more efficient than those with double length, a smaller extraction power seems to be more favourable and differences in the pile diameter have little impact for heat transfer.

A geothermal system sizing guide, which is useful for a preliminary quantitative test prior to any installation, is introduced. Even though our specific results are valid only for a commercial hall-type building in Finland, our procedure is qualitatively general and can be utilized for any given building type and climate zone.

1. Introduction

Energy efficient buildings have become one of the primary concerns of the actual construction industry and research. Since future structures will be required to satisfy increasingly stringent constraints in terms of energy efficiency [1], the usage of renewable sources is now established as a prominent field of investigation.

In this respect, geothermal energy [2, 3] is one of the most sought-after solutions, due to the feasibility of geothermal systems and the possibility of underground (namely, invisible) installations. A particularly intriguing solution is given by ground-source heat pumps, which utilize ground heat exchangers (GHE) [4] to extract the heat stored inside the ground under a building. Some widespread practice consists indeed of installing heat exchange piping into the pile foundations of buildings, thus creating a GHE system known as geothermal energy piles [5, 6]. This is similar to a method that employs boreholes for geothermal energy extraction [7, 8], with the economical advantage that drilling a new borehole can be avoided, since the heat exchange piping can be installed into an already existing foundation pile.

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Heat transfer processes between the energy piles and surrounding soil have been the object of various investigations for decades [9]; these include conduction through the ground within large volumes and convection inside the pipes, which can be often longer than 30m. The according calculations are therefore rather involved, due to the system size and to the inhomogeneous thermal properties of materials and soil layers, which can exhibit large variations according to location and depth [10, 11].

Due to these technical difficulties, numerical simulations have proven to be very effective in the energetic assessment of concrete geostructures for energy extraction and storage in the ground [12]. For instance, the authors of [10] formulate a mixed 1D-3D approach, to simulate both the 3D heat transfer occurring in pile and surrounding ground as well as the 1D heat and fluid flow inside the probe. Additionally, Cecinato and Loveridge develop in [13] an FEM model to investigate the impact of different design choices for shorter operational times (for about one week), and find the number of pipes to be the most influential design parameter, when compared to increasing the pile dimensions or acting on the fluid flow.

The study of heat transfer under the building is unfortunately only one part of the story: for a realistic full energy performance assessment of the geothermal system, one needs also to consider how the heat transfer in the foundation combines with the heat exchangers and pumping system above [10, 11, 14], a challenging task that is going to be investigated in the following sections.

The paper is organized as follows: the building model is discussed in Section 2.1 and our modelling of the heat pump load profile is described in Section 2.2. Section 3 features our results, together with a geothermal plant sizing guide in Section 3.1. A discussion of our findings is given in Section 4, and conclusions are finally drawn in Section 5.

2. Method

In the present study the coupling between GHE installation design and pumping system was investigated through parametric studies, by simulating the one year performance of different energy piles configurations with an IDA-ICE 4.61 model [15] that was validated in [16]. The thermal energy that can be extracted either monthly or yearly for a commercial hall-type building (Figure 1) located in the cold climate of Finland was computed. The thermal performance of the full system was calculated by considering both the heat pump profile and the thermal mass of the soil medium in which the piles were buried.

Our results are listed in both graphic and table form, addressing two different pile lengths and reporting the evaporator sizing power and expected yield per ground surface area in function of the pile separation. The energy demand covered by the heat pump was also calculated, and a geothermal system sizing guide that can be applied to the construction design at preliminary stages is provided.

2.1. Building model and case study parameters

Our model was entirely developed in IDA-ICE, Figures 1 and 2. Our case study corresponded to the building geometry and envelope parameters reported in Table 1. For the indoor air, the fresh air flow was 1.1 l/(sm^2) and the setpoint 18 °C. The heating demand of the building at the design temperature of -26°C amounted to about 465 kW, and Helsinki-Vantaa weather data for the year 2012 were used. The simulated clay had the following thermal properties: thermal conductivity 1.1 W/mK, porosity 56%, saturation 100%, bulk density 1250 kg/m³, wet density 1812 kg/m³, volumetric heat capacity 3343 kJ/(m³K) and heat capacity 1845 J/(kgK). Heat gains and occupancy instead held as follows: each occupant generated 2 W/m², the lighting 8 W/m², the equipment 1 W/m². The occupancy periodwas 8:00-21:00 for 6 days out of 7, and the occupancy rate was 1.0. Finally, the AHU heat recovery was 80%.

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Figure 1. IDA ICE model for the commercial hall.

Figure 2. IDA-ICE simulation model based on the source file.

The operation performance of energy piles and boreholes is typically assessed on a simulation period of 20 years [5]. In order to make all the considered cases comparable, in the parametric study the ground source heat pump was sized to 50% of the overall heating demand for each and every simulation. One should also account for the extraction capability of the piles system. The building model size will thus vary according to heat pump power, energy piles total length and specific heat extraction rate (given in W/m). This generated a large number of different building models to be implemented.

In IDA-ICE, a detailed computation for a single case of this type may take up to 3 days, therefore in order to save time and eliminate the risk of erroneous model settings, a simplified approach was developed. The piles were not directly connected to the detailed plant with heat pump and building, which were replaced by an hourly time-step based on the heat pump evaporator load data.

Running an energy simulation for the initial model defined in Table 1 then generated an hourly time-step load data for the heat pump evaporator for one year, which could be used for each single case. The upper limit of the building design heat load corresponded to T=-26 °C. In other words, each case could be generated by using only one input parameter – the design heat load. The profile used for generating the heat pump evaporator load data assumed a constant annual T=15.8 °C for the ground.

 Table 1. Building model parameters for the reference simulation.

Building size	66 x 137.4	m
Roof (310mm) U	0.12	$W/(m^2K)$
Floor (EPS100) U	0.09	$W/(m^2K)$
Walls (Sandwich 230mm) U	0.16	$W/(m^2K)$
Windows (SHGC 0.51) U	1.0	$W/(m^2K)$
Air tightness q_{50}	2	$\mathrm{m}^3/(\mathrm{m}^2\mathrm{h})$

2.2. Heat pump load profile and operation

In general, there exist two possible options for the heat pump operation, one at constant (on/off) load and the other with partial (inverter) load. In the first case, the heat pump is turned ON and will operate at full load in the presence of heat demand in the building. In contrast, the inverter heat pump allows for a partial load operation, typically within the range 30%-100%.



Figure 3. Annual load profile for the heat pump evaporator.

In our assessment, the hourly average (dynamic) data previously generated from the building load profile in Section 2.1 were used as input. Accordingly, the heat pump was allowed to operate at partial load, meaning that our results are applicable only to plants provided with inverter heat pumps.

The heat pump evaporator load data were generated from the building load data (which were based on the annual average COP of the heat pump). It was assumed that the mean annual ground temperature and resulting average brine temperature would remain in the 5°C to 10°C range during the heat pump operation, thus an annual average heat pump COP of 4.5 was applied. The COP was determined by means of a heat pump performance map data with a condenser side outlet temperature of 45°C. In Figure 3, the evaporator load profile is presented in green colour and the heat pump condenser load in yellow, while the remaining amount in red should be met with top-up heating.

The simulation started by feeding liquid mass flow data into the input link of the energy piles model, then a feedback controller measured the brine outlet T and fed a new inlet T value. The latter temperature was computed according to a pre-set ΔT value (in this particular study, $\Delta T = 3$ K). As the brine inlet temperature hit the limited pre-set value (-1°C here), it stayed constant until the brine outlet exceeded 1°C. Such control logic guaranteed non-freezing ground temperatures, and simulated the heat pump turning off due to a low T of the evaporator inlet fluid.

Finally, the additional so-called "free thermal storage" effect that is provided by the floor heat loss to the ground was also implemented, by feeding the floor surface temperature to the energy piles model in IDA-ICE as a ground surface T (with thermal properties of the floor structure defined in Section 2.1). The free thermal storage effect can substantially increase the piles' performance, as illustrated in Table 2 and discussed in Section 4.

The geothermal plant sizing guide relies on the simulation results. The heat pump evaporator sizing is given by $Q_{\text{evap}} = Q_{\text{cond}}(\text{COP} - 1)/\text{COP}$, with COP=4.5 as discussed above, which

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80 75 70 65 60 55 50 45 40 35 30 25 20 15 80 75 70 65 60 sizing power, W/m 60 W/n Evaporator 20 15 10 10 0 3.25 3.5 3.75 4.25 4.5 5.25 5.5 5.75 Distance between pile

Figure 4. Energy need vs simulated yield for 200 W/m, 6m spacing and 30m length, first year of simulation.

Figure 5. Results for evaporator power (solid) and condenser yield (dashed) of 30m-long energy piles.

determines the energy piles length $L = Q_{\text{evap}}/(W/m)$. The maximum power found during a 20-year simulation in this study is represented as "evaporator sizing power W/m" in Figure 5.

3. Results

The piles modelled in our simulations were either 15m or 30m long and buried in clay, with thermal properties given in Section 2.1. The design heat load was 360 kW and the annual heating energy demand was 168 MWh, consistently with the benchmark simulation discussed in Section 2.1. A spacing of 6m, 4.5m and 3m corresponded to 36, 48 and 121 piles respectively.

To illustrate, Figure 4 shows the results of a simulated case where the heat pump evaporator was sized at ca 215 kW. The pink line describes the *expected* evaporator yield (energy need), with the *simulated* performance of the heat pump in blue (case 200 W/m for 6m spacing and 30m length, only the first year was computed). The simulation results are summarized in Figure 5, where the evaporator power per unit length (in [W/m]) and expected area yield (in $[kWh/m^2a]$) are plotted in function of the pile spacing.

The effect of different pile lengths (either 15m or 30m) is compared in Figures 6 and 7, which report the expected yield resulting from the initial heat pump evaporator sizing power (20, 40 or 60 W/m), again in function of the pile spacing. Our results for every configuration are finally summarized synthetically in Table 3 (the contribution of thermal storage was not addressed, it will be included in a future work).

3.1. Geothermal plant sizing guide and example

In this section we are going to estimate the approximate energy piles length (or number) and their performance depending on the building design heat load Q and annual energy need E. The procedure can be extended to include different soil types, and also thermal storage when this is required. The steps to be performed are the following:

(i) Determination of building design heat load and annual heating energy need. Consider a commercial hall-type building with the following initial parameters: design heat load (design temperature -26°C) Q = 360 kW, annual energy need $E \sim 183$ MWh.

(ii) Sizing the heat pump evaporator.

First of all, one should estimate the heat pump condenser sizing Q_{cond} . In this particular study, according to the building load profile (Figure 3), a condenser power sized to ca 50% of the building design heat load is able to cover up to 98.9% of the annual demand, with only 1.1% covered by top-up heating. This means that a heat pump with ca 50% less output

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Figure 6. Results of yield per ground surface area of 15m-long energy piles.



Figure 7. Results of yield per ground surface area of 30m-long energy piles.

power can be installed. The heat pump condenser is then sized accordingly as 180 kW and the evaporator as $Q_{\text{evap}} = 140$ kW (see Section 2.2), with an annual average for the COP.

(iii) Estimation of the total pile field length and condenser yield.

Let us assume that each pile is 30m long. The simulated energy piles performance under the conditions at points (i) and (ii) above is plotted in Figure 5, thus we can collect simulated performance data for three different initial evaporator sizing values: 20 W/m, 40 W/m and 60 W/m. The total energy piles length L is computed as in Section 2.2, thus it is only a function of the system sizing and geometry.

The specific yield per unit length E/L [kWh/m] is instead given directly by the simulations, finally returning the total expected condenser yield as $E = E/L \times L$ [kWh]. The results for an evaporator sizing of 20 W/m, 40 W/m and 60 W/m and 3m, 4.5m and 6m pile spacing are given in Table 2.

In other words, for e.g. 60 W/m the maximal energy yield without thermal storage is 103 MWh for 6m pile spacing, if the building annual energy need is 168 MWh. We can accordingly conclude that since the demand (168 MWh) is larger than what is produced by the energy piles (103 MWh), one should either install more piles, or consider the contribution of thermal storage.

To calculate how many piles are needed, we should simply compute the total length by dividing the annual need by the condenser yield. This gives $168000 [kWh] : 44 [kWh/m] \sim 3818 m$, corresponding to n = $3818m/30m = 127.3 \sim 127$ energy piles with spacing 6m. The heat pump condenser power should be 180kW and the evaporator power 140W. With this amount of piles (which should be certainly rounded to e.g. 128 for a feasible pile field application), thermal storage is not needed.

Table 2. Simulated condenser and total yield for 60 W/m evaporator sizing, L=30m.

Pile spacing	Condenser yield	Total yield
$\begin{array}{c} 6\mathrm{m} \\ 4.5\mathrm{m} \\ 3\mathrm{m} \end{array}$	44 kWh/m 39 kWh/m 27 kWh/m	103 MWh 91 MWh 63 MWh

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3.2. Impact of pile outer diameter on performance

For all the configurations reported in Table 3, an energy pile with double U-pipe and 170mm outer diameter was considered. To assess the impact of the pile's outer diameter, 20 simulations with smaller piles (outer diameter 125mm) were conducted. These resulted in 125mm piles being less performing by 2% compared to 170mm piles, which is not very significant. We accordingly conclude that the pile diameter is not important for the heat transfer efficiency, in agreement with earlier studies [13, 17].

Table 3. Summary of the study results in table format, extraction power 20 W/m, 40 W/m and 60 W/m (the empty column is due to an oversized system).

		$step \ 3m$		step 4.5m		step 6m	
		15m	30 m	15m	30 m	15m	30 m
20 W/m	evaporator sizing power, W/m	20	18	20	19	- - -	20
	yield, kWh/m	21	20	22	22		21
	ground area yield, kWh/m2a	34	62	14	27		20
	demand covered by the heat pump	97%	90%	97%	96%		97%
40 W/m	evaporator sizing power, W/m	33	22	37	31	38	34
	yield, kWh/m	37	25	41	35	41	37
	ground area yield, $kWh/m2a$	57	77	26	43	19	35
	demand covered by the heat pump	83%	56%	92%	76%	94%	84%
60 W/m	evaporator sizing power, W/m	38	24	47	35	50	40
	yield, kWh/m	42	27	52	39	55	44
	ground area yield, kWh/m2a	65	83	32	48	26	41
	demand covered by the heat pump	63%	40%	77%	57%	83%	66%

4. Discussion

The set of our results can be analysed by investigating Figures 4 to 7 and Table 3. We recall that these are valid for a period of 20 years and for a pile field buried in clay, without assuming thermal storage.

First of all, the energy performance is not proportional to the initial evaporator extraction power. From Figure 4 we see that for most of simulation hours the energy need for a largely sized heat pump evaporator (200 W/m) is much higher than the geothermal system yield. This is evident also when comparing the 60 W/m to the 20 W/m curves in Fig.5, i.e. a three times larger evaporator heat extraction rate does not return three times the power and yield.

Secondly, the piles' separation seems not to be a crucial factor for energy performance if the initial evaporator heat extraction rates are low. Fig.5 shows a hardly linear performance/spacing ratio for piles with same length, since for 20 W/m both evaporator sizing power and expected yield even stay constant although the spacing is doubled.

On the other hand, Figures 6 and 7 show instead very clearly that a high yield per ground surface area [kWh/m2a] is strongly correlated with a smaller spacing. A low 20 W/m evaporator power can indeed return more than three times the yield with 3m spacing compared to a 6m

spacing. Note here the nonlinearity of yield versus heat extraction rate and pile length (30m-long piles return a roughly double yield only for 20 W/m).

Table 3 reports a sample of these results, summarizing them in a more immediate form. The added information is the demand covered by the heat pump, calculated as the % difference between required and produced heat, which is clearly larger for the lowest 20 W/m initial evaporator power. We conclude that 15m long piles performed better than 30m long piles, due to proximity to the building floor boundary, where floor heat losses provide a free thermal storage effect. Besides, a larger spacing is generally preferable. The more distant the piles, the less they interacted with each other, thus the more heat could be extracted without assuming thermal storage. According to the simulated results, the evaporator yield varied from 20 to 55 kWh/ma, depending on the expected initial evaporator sizing power.

5. Conclusions

The study at hand considered a parametric study of performance for a geothermal energy pile field providing heating to a commercial type building. Our computer simulations addressed the heat transfer processes occurring inside the soil surrounding the energy piles, and quantified their effect on the performance of the entire heat extraction system connected to the building.

Running simulations pertaining a period of 20 years, including stress tests with very low external temperatures, various system parameters were tracked. For instance, the effect of different piles length, their spacing and performance with respect to the extraction system efficiency were assessed.

A high nonlinearity of the expected yield in relation to spacing and evaporator extraction power was observed, leading to favour a 15m length and a smaller extraction yield. The parametric simulations were conducted for different extraction powers and energy pile field configurations, thus it was possible to present the results in the form of specific power [W/m] and yield [kWh/m] which allow a preliminary sizing for any building. To illustrate how the developed method works, a geothermal system sizing guide, including a preliminary assessment of both plant and energy pile field, was also presented.

One should keep in mind though that any quantitative results included in our investigation are only valid for a commercial hall-type building in a cold climate. The impact of thermal storage in the ground surrounding the energy pile field was also not addressed here, which constitutes another limitation. Moreover, comparing the role of different soil types could be very interesting. Finally, experimental validation and performing a theoretical cross check of our results on physical grounds would be very valuable. All these considerations provide motivation for future work.

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