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Research Paper

A machine learning approach to energy pile design

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ABSTRACT

Incorporating ground heat exchangers (GHEs) into building foundations allows them to also provide thermal energy for space heating and cooling. However, this introduces certain constraints to ground-source heat pump (GSHP) design, such as on the geometry, and thus a different design approach is required. One such approach, introduced in this article, uses machine learning techniques to very quickly and accurately determine the maximum amount of thermal energy that can reasonably be provided. A comprehensive validation of this methodology for energy piles is presented, using different geometries and thermal load distributions, drawing conclusions about how the approach can best be utilised.

1. Shallow geothermal systems and energy piles

Ground-source heat pump (GSHP) systems can be used to efficiently provide geothermal energy for heating and cooling purposes. These shallow geothermal energy systems extract and reject heat from and to the ground within a few tens of metres below the surface. The heat pump upgrades this thermal energy and is connected to an acclimatisation distribution circuit within the building, which transfers the heat to and from the building, as well as to a series of ground heat exchangers (GHEs), which transfer the heat from and to the ground [1]. A GHE, which traditionally can take many forms such as vertical boreholes or horizontal trenches, contains loops (usually high-density polyethylene (HDPE) pipes) with a circulating fluid (usually water) that acts as the heat conductor in the process. These systems are known to typically be able to run at a coefficient of performance (COP) of about 4, meaning producing 4 kW of heating/cooling energy for every 1 kW of electricity consumed [2–4]. Moreover, GSHP systems are the most used amongst the different applications of direct geothermal energy [5] and have attracted much attention over the past decade for the purpose of better understanding how they can be most suitably and efficiently utilised and designed [6–10].

A promising application of GSHP systems that can minimise their capital cost is the use of energy piles, where the GHE loops are incorporated within pile foundations as shown in Fig. 1 [11–18]. Since the most significant associated cost of these installations is drilling, by adding the loops into the piles (already needed for structural purposes) that cost is considerably minimised as drilling is already accounted for; a detailed breakdown and analysis of these costs can be found in the literature [19]. However, due to the high variability of potential pile configurations and geometries and the fact that this technology is relatively new to the industry, there is a notable absence of available reliable and *fast* design tools for energy piles and limited information on not only how the design can be undertaken but also how efficient the technology can be [20].

A key difference between energy piles and typical vertical borehole GHEs is that for the former, the pile number, configuration and length are not primarily designed to fulfil the (thermal) energy needs of the building, but rather for its geo-mechanical stability. This leaves little room for optimisation of the geothermal ground loop design, as the main design parameters, such as the (energy) pile length and separation, are pre-determined. Therefore, the provision of 100% of the heating and cooling energy required (thermal load) cannot be guaranteed and instead a hybrid system must often be used, to complement the produced geothermal energy using auxiliary means [21,22].

An important challenge is to accurately determine the maximum thermal energy that the geothermal system can provide using the already structurally designed energy piles, which can be either very difficult and time consuming or not as reliable as required using the limited existing design approaches (detailed numerical simulations or analytical commercial software respectively) [20]. While there exist ‘geothermal’ parameters that are not necessarily fixed in energy pile design projects, such as the pipe loop diameter, flow rate and geometrical configuration of the pipes, identifying the amount of thermal energy the energy piles can provide in the first place is extremely important. A further optimisation of the above-mentioned parameters can further increase heat exchange rates with the ground and thus

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Nomenclature

CDM	"Cooling Dominant Monthly" type of thermal load distribution, –
CON	"Constant" type of thermal load distribution, –
COP	coefficient of performance, –
$C_{p\ material}$	specific heat capacity of material, J/(kgK)
MAE	mean absolute difference between predicted and expected/ "actual" T_{fluid}, °C
R^2	coefficient of determination, –
RMSE	root mean square difference between predicted and expected// "actual" T_{fluid}, °C
t	time, sec
$T_{farfield}$	average annual ground temperature, °C
T_{fluid}	average fluid temperature within pipe loop, °C
TL	thermal load, W
TRD	"Typical Residential Daily" type of thermal load distribution, –
TS	thermal storage, W
$x_{1...n}$	input data to a prediction model or relationship, unit depends on data
$y_{1...m}$	output data to a prediction model or relationship, unit depends on data
ΔT_{max}	difference in maximum average fluid temperatures between predicted and expected/"actual" T_{fluid}, °C
ΔT_{min}	difference in minimum average fluid temperatures difference between predicted and expected/"actual" T_{fluid}, °C
$\lambda_{material}$	thermal conductivity of material, W/(mK)
$\rho_{material}$	density of material, kg/m^3

potentially increase the amount of provided energy. However, this paper focuses on novel ways of *quickly* and *accurately* estimating how much energy can be provided first and foremost (for fixed/typical geothermal parameters), while future research is expected to expand this methodology into also accounting for pipe geometry (diameter, configuration, etc.) and fluid flow rate. The research herein expands on a study presented in [23] and incorporates machine learning techniques to overcome the challenge of estimating the amount of thermal energy that can be provided fast and accurately. The new approach is the first step in expediting and facilitating the optimisation of the design of a hybrid GSHP system. A statistical prediction model, which can be used alongside complex finite element (FE) computational models to calculate the optimal amount of energy that can be extracted from a geothermal system implemented in an underground structure (e.g., energy piles), is presented and validated against the alternative and considerably more computationally expensive FE models.

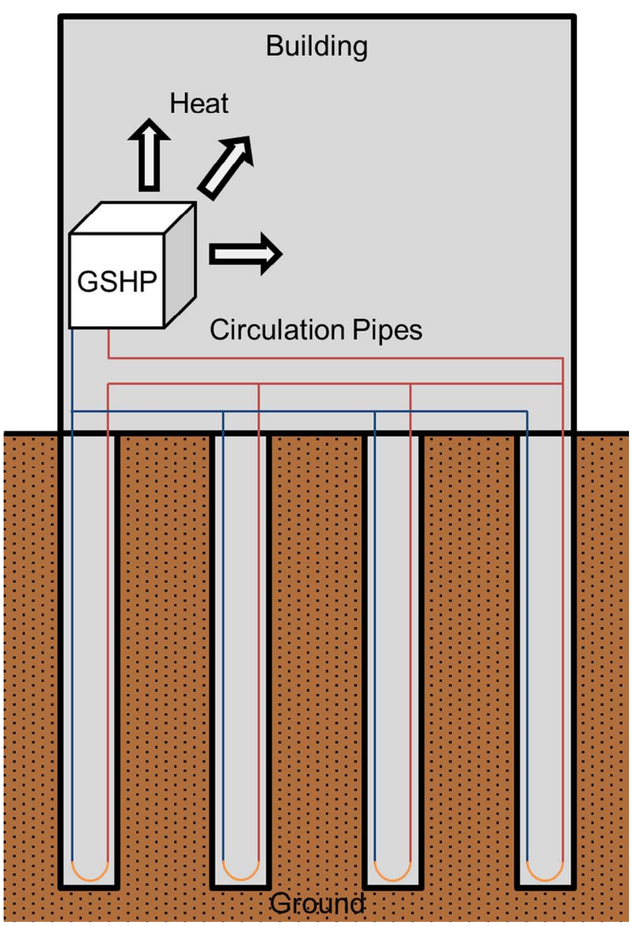

Fig. 1. Energy piles schematics in heating mode (Not to scale).

2. Proposed methodology

In this section, a summary of the limited current approaches to energy pile GSHP systems is briefly presented, followed by a detailed description of the proposed approach, including an overview of machine learning principles as well as the technical details of the proposed prediction model.

2.1. Current approaches

A common energy pile design approach, specifically for complex geometries, is to use a numerical simulation/model, to analyse a GSHP design, although semi-analytical approaches are also being developed [24]. Finite element numerical simulations are typically more flexible than analytical approaches, since they adopt significantly fewer assumptions and have fewer constraints regarding the parameters of the problem, such as its geometry, but they can be computationally expensive. Typical numerical simulation input requirements include the geometry, the material properties and operational conditions (including the fluid flow rate), the thermal load distribution and the use of appropriate (coupled) physics (i.e. governing equations and boundary conditions to model coupled heat transfer and fluid flow). The simulation computes many values relevant to design, such as the temperature of the fluid at the outlet pipe (exiting the ground loop) over time, by adopting a varying input temperature of the fluid at the inlet pipe (entering the ground loop) over time. This inlet fluid temperature arises from the thermal load distribution that needs to be satisfied, in order to provide the required thermal energy to the building (the temperature difference between the inlet and outlet should be maintained in such a way that it fulfils the thermal demand), as explained in detail in [8,25–28]. During the calculation process, the geometric and material design values remain of course constant with time (to fulfil the structural requirements). It is also very important to note that inlet fluid temperature (coming from the heat pump) can usually be controlled and programmed by a mechanical engineer. From the results of the simulation, of most interest is the fluid temperature distribution within the GHE loops. The temperature of the fluid needs to be within a specified operating range, based on the heat pump used, as well as to avoid extremes that could cause undesirable effects, such as freezing of the ground and heave (overcooling or overheating the ground).

However, as mentioned in Section 1, when designing a system with energy piles the geometry and properties of the materials available are