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Thermal performance of two types of energy foundation pile: Helical pipe and triple U-tube

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HIGHLIGHTS

- A new model to analyse energy piles with *n*-U-tubes and helical pipe is presented.
- Measurements for energy piles with 3-U-tubes and helical pipe were performed.
- The numerical models consider the axial heat conduction in the ground and pile.
- The helical pipe provides a better thermal performance than 3-U-tubes.
- The pitch between the turns of the helix affects the peak load.

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ABSTRACT

When foundation piles are required to deal with a building's stability problems, the installation of a ground source heat pump is a very attractive, cost-effective solution. The pipes of the ground heat exchangers can be buried in the piles and coupled with the heat pump. The heat exchanger pipes can be arranged as a helical coil or U-tubes. This paper conducts a comparative analysis of the helical and triple U-tube configurations inside a foundation pile.

A detailed numerical simulation tool was used to conduct the analysis. The problem of heat transfer was solved by means of an equivalent electrical circuit of suitable thermal resistances and capacitances. This paper also looks at a model that uses *n*-U-tubes inside a bore and takes into account axial heat conduction in the ground and the borehole, as well as the borehole's thermal capacitance.

Before use, the detailed numerical simulation tool was compared with field measurements carried out on two energy piles equipped with two different circuits: one helical and one triple U-tube. After tuning, the two circuits were investigated under the same conditions in the short term, and the peak load conditions were analysed. Finally, the influence of the pitch between the turns of the helix was also analysed.

1. Introduction

Ground Source Heat Pump (GSHP) systems have recently become promising technology for heating space and cooling buildings due to their high energy efficiency and consequently to their environmental advantages [1,2].

Closed-loop systems are unquestionably the most widespread options. In these systems, a heat pump is coupled with the ground by means of heat exchangers that can be oriented vertically or horizontally. The vertical systems are the most frequently installed, especially in commercial buildings, since they use the least amount of land. Moreover, deep borehole heat exchangers are much more energy efficient than shallow installations.

In GSHP systems, the ground acts as a heat source in heating mode and a heat sink in cooling mode. A suitable heat-carrier fluid circulating inside ground heat exchangers extracts energy from warmer ground in heating mode, but it transfers the heat of the heat-pump condenser to the ground to cool a building. Incorporating the heat exchangers into the building foundations is an interesting solution [3], as it reduces the initial cost of drilling boreholes and the ground surface to install a borefield, as drilling is often a barrier to implementing a GSHP system.

The use of foundation piles as heat exchangers beneath the ground is a notable alternative to conventional ground heat

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Nomenclature

A_{T}	annual amplitude of the monthly average air temperature cycle (K)
a	thermal diffusivity (m^2/s), surface absorptance (−)
C	volume heat capacity (J/K)
i	ground discretization index in radial direction
j	ground discretization index in vertical direction
L_{bore}	borehole length (m)
m	maximum discretization index in vertical direction
n	maximum discretization index in radial direction
P	pitch between turns of helix (m)
q	heat flow per unit length (W/m)
q^*	heat flow per unit length without borehole thermal capacitance and axial heat conduction (W/m)
r	radius (m)
r_{max}	radius from axis borehole beyond which the undisturbed ground is considered (m)
R	thermal resistance (K/W)
R_{ext}	convection thermal resistance at earth surface (m^2 K/W)
R_{conv}	convection thermal resistance per unit length (m K)/W
R_{p0}	thermal resistance between pipe inside surface and borehole wall in single U-tube per unit length (m K/W)
R_{pp}	thermal resistance between pipes in single U-tube per unit length (m K/W)
T	temperature (K)
T_{ext}	external air temperature (K)
T_{g}	undisturbed ground temperature (K)
T_{m}	annual average air temperature (K)
$T_{-\Delta\tau}$	temperature at previous time step (K)
T_0	borehole wall temperature (K)
z	depth (m)

Greek symbols

ε	surface emittance (−)
λ	thermal conductivity (W/(m K))
τ	time (s)
$\Delta\tau$	discretization time step (s)
Δz	length of control volume in vertical direction (m)

Subscripts

b	borehole, borehole zone
d	deep zone
eq	equivalent
g	ground
p	pipe
r	radial direction
s	surface zone
w	heat-carrier fluid
z	depth direction

exchangers. When used in this way, they are also known as "energy piles". Moreover, the concrete of the pile is a suitable medium for exchanging heat with the surrounding ground due to its good thermal conductivity and thermal storage capacity.

The problem of heat transfer between an energy pile and the surrounding ground, as well as inside the same pile, can be analysed analytically or numerically. Analytical solutions are more flexible than numerical ones since they are more effective in terms of both time and human resources. Numerical approaches, however, allow a more realistic calculation and a more accurate space description of the ground's thermal and physical properties. A range of studies has been performed on energy piles.

A cylindrical source is an initial approach to investigating energy piles. Man et al. [4] modified the cylindrical heat source model in order to take into account both the radial dimension and the thermal capacitance of the borehole or pile grouting. Analytical solutions were performed for both the infinite and finite length of the cylindrical heat source. However, the solutions took into account only one homogeneous medium outside and inside the heat source; a constant temperature was also applied to the ground surface when the finite length was analysed. At a later stage, an analytical solution for the helical heat source was developed [5]; the effective geometry of the helical pipe was also taken into account. Li and Lai [6] proposed an analytical approach to solving heat conduction problems in infinite and semi-infinite anisotropic media with a helical line source, which was created by integrating a point source along the helix. Zhang et al. [7] used a line heat source, cylindrical heat source and ring-coil heat source [8] to investigate heat transfer around buried coils of energy piles. They combined models that included conduction and advection in order to take into account the effect of the groundwater flow. They concluded that the effect of groundwater is considerable when the velocity of the water flow reached a certain order of magnitude. Bozis et al. [9] used an infinite line source model to compare alternative designs of cast-in-place energy piles. They analysed the number of U-tubes, pipe dimensions and types, and flow conditions.

Pahud and Fromentin [10] provided an accurate numerical modelling of an entire thermal process involving energy piles and the surrounding media, improving the TRNSYS simulation environment with a module of this component (called PileSim). This simulation tool employed the Duct Ground Heat Storage Model (DST), which was solved numerically, in order to analyse energy piles with vertical U-tubes. Lee and Lam [11] developed a simplified three-dimensional finite difference model for a single cylindrical energy pile with U-tubes. They validated their model with analytical results based on the finite line source model. They analysed the effects of the thermal properties of the grouting material and ground, the pipe connection configurations and the pipe separations on the thermal performance of an energy pile with eight pipes.

A range of energy-pile literature is also based on field experiments. Hamada et al. [12] reported the field performance of a heat pump with an energy pile system in a building for both office and residential use. Gao et al. [13] investigated several types of energy piles with a series of performance tests; they also carried out numerical simulations in correlation to their experimental results [14]. Wood et al. [15] evaluated via field experiments the performance of two loop configurations (U-tube and coaxial), used in conventional boreholes or in energy piles. Park et al. [16] presented an experimental and numerical study on the thermal performance of a prototype of a precast high-strength concrete energy pile. Furthermore, they analysed two different heat exchangers inside the pile: the W and triple U-tube.

The helical configuration is attractive, essentially because it is based on short ground heat exchangers [17]. The present paper cites numerical case-studies based on field-test results performed in the province of Venice to develop pile–ground interaction mechanisms applicable to GSHP; the aim was to evaluate thermal response and performance of energy piles equipped with triple U-tube and helical pipes. The energy piles and ground were numerically modelled in accordance with the CaRM approach [18–21]. Numerical simulations were also used to back-calculate the