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# A new practical numerical model for the energy pile with spiral coils

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ABSTRACT

Pile foundations or energy piles serve as ground heat exchangers (GHEs) of ground source heat pump system (GSHP) in some cases. Modeling this kind of GHE is important in the system design. This paper built a new practical numerical model for the energy pile with spiral coils. This model includes a 1-D transient convection–diffusion sub-model for the fluid domain and a 1-D transient diffusion sub-model for the solid domain. The fluid model and the solid model can be solved by a sequential computing algorithm. The two sub-models were compared with analytical models respectively, and filed test data was used to verify the whole model. Results showed that this model is accurate.

## 1. Introduction

Ground source heat pump systems are attractive in space heating or cooling because of their potential high energy efficiency. Ground heat exchangers are key elements of ground source heat pump systems. Horizontal-pipe ground heat exchangers [1] or vertical U-tube ground heat exchangers (GHEs) [2,3] are the main types in engineering, while energy piles or pile geothermal heat exchangers are another interesting alternative [4–6]. Horizontal GHEs are occupancy, and vertical borehole GHEs are expensive in most areas. Energy piles serve as both the foundations of a building and heat exchangers of its air-conditioning system, with no extra cost for drilling boreholes. The pipe arrangement of pile geothermal heat exchangers includes U-tube, W-tube types [5,7–14] and spiral coils [4,6,15–18]. The interest of this paper is the pile geothermal heat exchanger with spiral coils.

Modeling the pile geothermal heat exchanger with spiral coils is important in the system design. There are many good works in this field. Cui [6] employed a ring-coil heat source model to predict the thermal response of the pile geothermal heat exchanger. Man [15] gave a line heat source and a solid cylinder source model and conducted comparison. In the paper of Li [16], the point source, line source, and spiral coil source models were given. The above models are all analytical ones. Park [4] studied the pile geothermal heat exchanger with spiral coils by experiments and numerical simulation, and concluded that the models of Cui [6] and Man [15] are accurate. However, these analytical models have some faults: (1) they were built with the hypothesis of a constant heat load. When using them in a time-varying load case, the time superposition technique should be employed and it may be very time-consuming. (2) They seem complicated and computation is not easy to implement in practice [15]. (3) These models do not consider the difference of thermal properties of the pile and the soil. (4) They only consider the heat conduction in the solid domain, while they do not compute the temperature variation in pipes. Suryatriyastuti [18] carried out a 3-D numerical heat transfer analysis on the energy pile. This work only considered the constant heat load case and the seasonal change of a building's load was not taken into account. The 3-D numerical model is a very good researching tool, but it may not be practical in engineering because of its slow computing speed and much requirement for computer resources. So developing a new computation model for the energy pile and providing a practical tool for designing ground source heat pump systems is of value.

For practicality, the following considerations must be satisfied: (1) The model can predict the temperature response in the solid region including the pile and the soil and the temperature distribution in the pipe. (2) The heat load or the inlet temperature is arbitrary, constant or time-varying. (3) The thermal properties in the pile and the soil regions are not necessarily the same. (4) Computing shall be fast. For the above considerations, this paper

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**Nomenclature**

| | |
|---|---|
| *AE*, *AP*, *AW*, *B* | coefficients of the numerical fluid equations |
| *a*, *b* | coefficients of the numerical solid equations |
| *Cp* | specific heat, J/(kg K) |
| *D* | diameter of the pile, m |
| *F* | cross-section area of the pipe, $m^2$ |
| *Fo* | Fourier number |
| *h* | convective heat transfer coefficient, $W/(m^2\ K)$ |
| *L* | depth of the pile, m |
| *l* | length of one set of coils, or axial coordinate |
| *n* | group number of spiral coils |
| *p* | spiral pitch |
| *Q* | heat load imposed on the pile, W |
| *R* | thermal resistance, (m K)/W |
| *r* | radius, m |
| $r'$ | dimensionless radius |
| *T* | temperature °C, |
| *t* | time, s |
| *u* | water velocity through the pipe, m/s |
| *V* | volume of control element, $m^3$ |

*Greek letters*

| | |
|---|---|
| $\Delta l$ | spatial increment in the l-direction, m |
| $\Delta r$ | spatial increment in the r-direction, m |
| $\Delta t$ | step time, s |
| $\lambda$ | thermal conductivity, W/(K m) |
| $\Theta$ | dimensionless temperature |
| $\rho$ | density, $kg/m^3$ |
| $\rho c$ | volumetric specific heat capacity, $J/(m^3\ K)$ |

*Subscripts*

| | |
|---|---|
| *e* | east interface of the control volume |
| *f* | foundation pile |
| *i* | the *i*th node in the r-direction, $i = 1, 2, \ldots, M$ |
| *j* | the *j*th node in the l-direction, $j = 1, 2, \ldots, K$ |
| *pe* | PE pipe |
| *s* | the soil |
| *w* | water, or west interface of the control volume |

*Superscript*

| | |
|---|---|
| $\tau$ | the $\tau$ th step |

will develop a simplified 1-D numerical model for the pile geothermal heat exchangers with spiral coils. This model includes two sub-models: a 1-D diffusion model for temperature computation in the solid region, and a 1-D convection–diffusion model for temperature computation in the pipes. In our previous papers, similar methods were used successfully to model the vertical U-tube ground heat exchanger [19] and the air-earth heat exchanger [20].

Section 2 briefly describes the configuration of the pile geothermal heat exchangers with spiral coils. Section 3 develops the new model. Section 4 verifies the new model by comparisons with analytical models and a field test. Section 5 discusses the application briefly.

## 2. Configuration of the pile foundation GHE with spiral coils

The configuration of a spiral coil pile foundation GHE is shown in Figs. 1 and 2. The diameter and depth is D and L respectively. PE pipe is employed. The pipes are wrapped around the reinforced bar. They are put into the foundation pit at the same time and then cement is casted into the pit. In the vertical direction, there may be several sets of coils connected parallel, as shown in Fig. 2. The pitch of spiral coils is about 100 mm.

## 3. 1-D numerical model of pile GHE with spiral coils

### 3.1. Hypothesis

The heat load or the inlet temperature of GHE is time-varying.

Suppose that thermal properties of the pile and soil are isotropic, and they do not change with temperature. Thermal properties may be different in the pile and soil. The vertical temperature distribution of the solid domain is uniform and only considered is the temperature variation in the radial direction. A 1-D transient heat conduction model *T*(*r*, *t*) can be employed in the cylindrical coordination system.

Heat transfer happens between the fluid in pipes and the pile surface. The fluid temperature changes in the length direction of pipes. A 1-D transient convection–diffusion model *T*(*l*, *t*) can be employed.

### 3.2. Explicit discrete equations for the solid domain

Meshes of the solid region are given in Fig. 3 (only half GHE is plotted.). In the r-direction, there are M control volumes or nodes. In the pile, the nodes are denoted by $i = 1, \ldots, N$. In the soil/rock region, the nodes are denoted by $i = N + 1, \ldots, M$. Nodes are uniformly located in each solid region. Three special nodes shall be noted. The first node $i = 1$ is located in the center, with only one interface. The node $i = N$ represents a mixed control volume: half is soil and the other half is cement. Node *M* is located on the boundary of the *M*th control volume which is in the far field.

Using thermal capacity–resistance method [21], heat conduction in the solid region can be described by Fig. 4. Every control volume has its heat capacity and two adjacent nodes are connected with a thermal resistance. The heat flux is imposed on the *N*th node. The boundary of the *M*th control volume is an adiabatic one.

Applying energy conservation rule to every control volume, explicit discrete equation can be derived. The temperature of the first node ($i = 1$) can be computed by

$$T_1^{\tau} = a_{1,e}T_2^{\tau-1} + b_1T_1^{\tau-1} \tag{1}$$

$$a_{1,e} = \frac{\Delta t}{\rho_f c_f V_1 R_{1,e}} \tag{2}$$

$$b_1 = 1 - a_{1,e} \tag{3}$$

$$R_{1,e} = \frac{\Delta r_f}{2\pi(\Delta r_f/2)L\lambda_f} \tag{4}$$

$$V_1 = \pi(\Delta r_f)^2 L/4 \tag{5}$$

$$\Delta r_f = \frac{r_f}{N-1} \tag{6}$$

where *a* and *b* are equation coefficients; $\Delta t$ is the step time, s; $V_1$ is the volume, $m^3$; $\Delta r_f$ is the space increment, m; $r_f = D/2$ is the radius of the pile, m; *L* is the depth of GHE, m; $\lambda_f$ is the heat conductivity of the pile, W/(m K); $\rho_f c_f$ is the volumetric capacity, $J/(m^3\ K)$; $R_{1,e}$ is the thermal resistance between Nodes 1 and 2, (m K)/W.