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Numerical and analytical analysis of groundwater influence on the pile ground heat exchanger with cast-in spiral coils

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Abstract

With widespread application of ground-coupled heat pump (GCHP) system, heat transfer process of pile ground heat exchanger (PGHE) has attracted much attention. Previous researches, studying the impact of groundwater flow, mainly focus on the PGHE with cast-in U-tubes. However, compared with the PGHE with U-tubes, PGHE with cast-in spiral coils has better heat transfer performance and is more suitable for a modern city with high building density. Therefore, in this paper, a 3-D simulation model and a simplified analytical model are established to investigate the influence of groundwater flow on the thermal performance of PGHE with cast-in spiral coils. A comparison between these two models is carried out. Both numerical and analytical results show that the groundwater flow has an enhancing effect on the heat transfer performance of the PGHE with spiral coils and can accelerate the heat transfer process into stability. When the seepage velocity is 1e-5 m/s, the average enhancing rate is 22.98%.

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1. Introduction

Since the current worldwide air pollution mainly caused by the burning fossil fuels has aroused great concern, more attention has been paid to renewable energy system. The GSHP technology with its high efficiency (due to the increased heat exchange area) and environmental friendliness has showed a rapid growth tendency, especially in China. With the development of the GSHP technology, a new geothermal heat exchange (GHE) system, called Pile Geothermal Heat Exchanger (PGHE) system, begins to apply in engineering practice. Piles not only provide supportiveness, but also act as heat exchangers. In a typical

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PGHE system, one closed-loop pipe with its configuration of U-tube or spiral coils is buried in each concrete pile.

Several analytical-models, such as cylindrical model [1] and ring-coil heat source model [2], have already been established to describe the heat transfer performance of PGHE system. But, in these models, the soil is assumed to be a solid body and only conduction process is taken into consideration in the modelling process. These assumptions may not be reasonable in some cases. When the systems established above or run through the ground water table, heat exchange rate of PGHE will be affected by the ground water flow. Heat transfer process may be enhanced by the convection process between the energy pile and the ground water flow.

In this paper, based on the ring-coil heat source model, a 3-D simulation model with a corresponding physical mathematical model is established to study the effect of groundwater seepage on heat transfer performance of PGHE system. The influences of various hydraulic gradients and soil structure are investigated by parametric studies.

2. Analytical model

The heat transfer process among energy pile, underground water and soil is unsteady and complicated. Therefore, there are several assumptions existing in the analytical modelling process:

- This new model consider the spiral heat exchanger as a series of ring-coils with a constant spacing of b ;
- The underground medium is taken as homogeneous saturated porous medium, and its thermal properties do not change with the time and other parameters;
- The heating rate per unit length of heat source is constant at q_l ;
- The initial temperature in the whole medium except heat source is t_0 and the excess temperature is $\theta = t - t_0$.

Based on the former assumption, the conduction and convection in the pile-soil system can be described by the following equation [3]:

$$\rho c \frac{\partial t}{\partial \tau} + \rho_w c_w u \frac{\partial t}{\partial x} = k \left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} \right) \quad (1)$$

Where ρ , c and ρ_w , c_w are volume specific heat capacity of porous medium and water respectively, k is the coefficient of heat conductivity and u is the velocity of groundwater flow. Based on the Green function and using the moving instantaneous point heat source method [4], the temperature response equation can be obtained. The seepage direction is assumed as the direction of increasing x . By introducing the dimensionless variables: $\theta = \frac{\gamma \theta r_0}{q_l}$, $Fo = \frac{a\tau}{r_0^2}$, $B = \frac{b}{r_0}$, $X = \frac{x}{r_0}$, $Y = \frac{y}{r_0}$, $H_1 = \frac{h_1}{r_0}$, $H_2 = \frac{h_2}{r_0}$, $L = \frac{U r_0}{a}$. Then, the equation can be obtained as follow:

$$\theta_f = \frac{B}{16\pi^{5/2}} \sum_{n=0}^{m-1} \int_0^{2\pi} d\varphi' \int_0^{Fo} \exp \left[-\frac{[X - \cos\varphi' - L(Fo - Fo')]^2 + (Y - \sin\varphi')^2}{4(Fo - Fo')} \right] \cdot \left\{ \exp \left[-\frac{(Z - H_1 - nB - 0.5B)^2}{4(Fo - Fo')} \right] - \exp \left[-\frac{(Z + H_1 + nB + 0.5B)^2}{4(Fo - Fo')} \right] \right\} \frac{dFo'}{(Fo - Fo')^{3/2}} \quad (2)$$

Where m is the number of the ring coils, it is equal to $\text{int} [(H_2 - H_1)/B]$, in which H_1 is the dimensionless distance of the pile top to the ground surface, H_2 is the dimensionless distance of the pile bottom to the ground surface and B is the dimensionless spacing between two ring coils.

3. Simulation model

The heat transfer process of pile geothermal heat exchangers can be divided into three parts: 1) heat convection process between the circulating fluid and the pipe wall; 2) heat conduction in the concrete pile; 3) heat transfer in the soil under the groundwater seepage condition. One 3-D finite element simulation model is established to study the seepage effect on PGHE system. This simulation model can be divided into four parts: 1) circulating water; 2) polyethylene pipe; 3) concrete pile and 4) soil. The geometrical size of the energy pile varies with the building's style and dimension. It can range from several meters to tens of meters. Due to the limitation of resource, it is assumed that the depth of the pile foundation is only 6.7m. The spiral pipe buried in the concrete pile has a screw spacing of 400 mm with an inner diameter of 28 mm and an outer diameter of 32 mm. Besides, the soil domain is modelled as a rectangular solid with the dimensions of 20m×20m×14.7m. The mesh dividing process is conducted in ANSYS ICEM, and CFX code is selected to solve 3-D heat transfer problem. Considering a large steep temperature gradient may occur near the pipe well, a fine mesh is generated in this area. Total mesh of the liquid domain is 6,352,080.

4. Results

4.1 Comparison between analytical solution and numerical solution

To validate the simulation model and the analytical model, a comparison is conducted between numerical results and the analytical solution. This comparison is carried out over a period of 800h ($Fo=12.14$) of continuous operation at cooling mode. Different groundwater velocity conditions, which are assumed to be $2e-6m/s$ and $5e-6 m/s$, are taken into considered. One point ($x=2.1,y=0$) is selected as the reference point to monitor the temperature response of these two models.

Fig. 1 shows the calculation results from simulation model and analytical model. At the low seepage velocity ($2e-6$, $L=1.18$), a small difference occurs at the beginning period. This could be caused by the simplification in the analytical model, in which the pile is assumed to be vacuous and seepage can directly pass through the pile domain. This means that the temperature response is overly accelerated by the groundwater in the analytical model. But, on the whole, it has a good agreement between simulation model and analytical model at the low seepage velocity. The relative difference is larger at the high seepage velocity ($5e-6$, $L=2.96$).

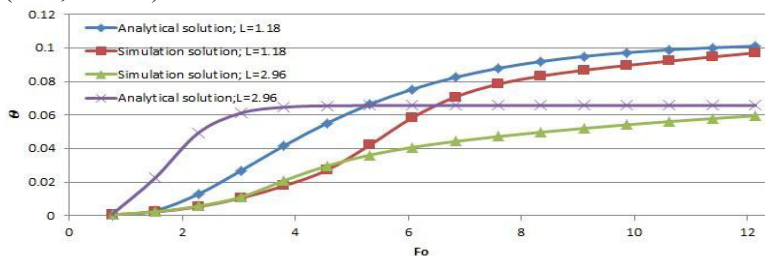


Fig. 1 Comparison of temperature response between numerical and analytical results

4.2 Heat exchange rate and fluid temperature

Instantaneous heat exchange rate of spiral coil heat exchanger is determined by instantaneous temperature difference between fluid inlet and outlet, mass flow rate and specific heat of the fluid, with the Eq. 3 shown as follows:

$$q_l = \frac{Q}{l} = \frac{c_p m (T_{inlet} - T_{out})}{l} \quad (3)$$

where C_p is the specific heat of the water and l is length of the energy pile.

Fig.2 shows the simulation results of instantaneous heat exchange rate of the spiral coil system at none and seepage condition with mean seepage velocity of $1e-5$ m/s. It can be seen from the charts that the seepage can effectively enhance the heat exchange rate. In this test operation period, the maximum and the average enhancing rate is 32.37% and 22.89% respectively.

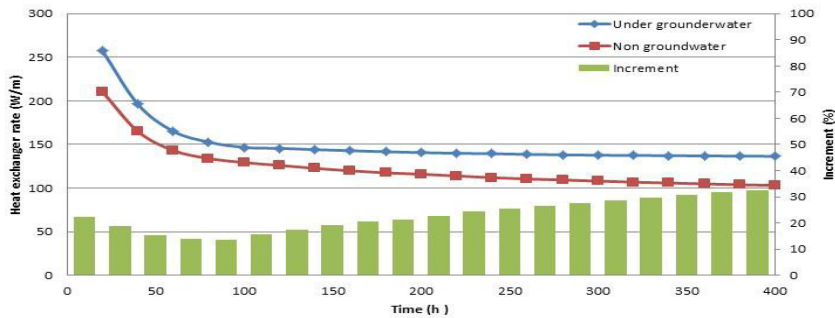


Fig. 2 Temperature distribution under different operation condition

(a) Non seepage at 400h; (b) Non seepage at 800h; (c) Seepage at 400h; (d) Seepage at 800h

The simulation results show that with the increase of hydraulic gradient, the heat exchange rate will grow, but the increase rate of this enhancing effect is reduced. The data also suggests the groundwater can accelerate the heat transfer process into stability. Under the hydraulic gradient of 0.003, the groundwater keeps the heat exchange rate stabilized around 154.8W/m at the operation time of 130h. When the hydraulic gradient reaches 0.006, the stabilization time will be shortened to 45h with the heat exchange rate of 163.95W/m.

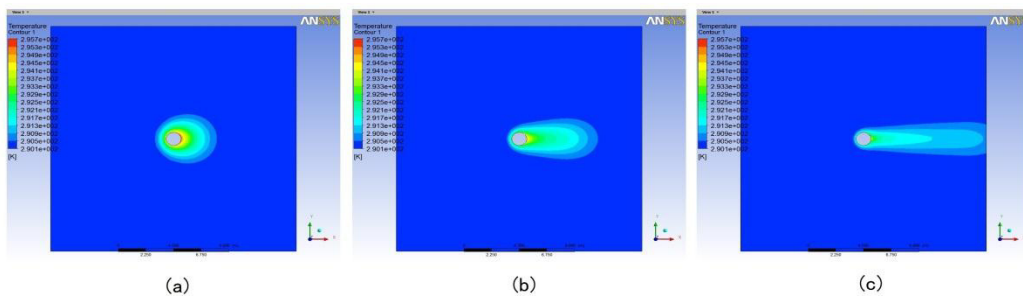


Fig. 3 Temperature distribution under different hydraulic gradient at the operation time of 200h

(a) $J=0.001$; (b) $J=0.003$; (c) $J=0.006$

5. Conclusions

The analytical model has a good agreement with numerical model at low speed seepage condition, but a large relative difference occurs at high speed situation. Both numerical and analytical results show that the groundwater flow has an enhancing effect on the heat transfer performance of the PGHE with spiral coils and can accelerate the heat transfer process into stability. When the seepage velocity is $1e-5$ m/s, the average enhancing rate is 22.98%. The simulation data suggest that with the increase of hydraulic gradient, the heat exchange rate will grow, but the increase rate of this enhancing effect is reduced.

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