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Study on heat transfer of pile foundation ground heat exchanger with three-dimensional groundwater seepage

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ABSTRACT

An increasing number of high-rise buildings are being designed, enabling the use of pile foundation to also act as ground heat exchangers (GHEs) of ground source heat pumps (GSHPs). These so-called energy piles include heat exchange pipes already cast into the pile foundation to produce a new type of GHE. Groundwater seepage, by means of advection, plays an important role in improving the heat transfer performance of energy pile. Existing research has studied heat transfer mechanism of energy pile when groundwater is considered to flow in one direction only, and in two directions also. No studies, however, have been introduced explaining the effects of three-dimensional (3-D) groundwater seepage (i.e. in three directions) on the heat transfer between pile and underground medium.

This paper presents a new mathematical model about the heat transfer of energy pile with 3-D groundwater seepage, whereby the analytical temperature responses solutions induced by both infinite and finite models are obtained. Comparisons between pure conduction and combined heat transfer were made, and the temperature distributions in a 3-D seepage environment are explained. In addition, the characteristics involved in the new model were explored and then the factors exerting influence on heat transfer are described. The 3-D groundwater seepage is more advanced and realistic, and the research described in this paper is usefully relevant to promoting the development of energy piles of GSHP.

1. Introduction

With the sustained development of ground source heat pump (GSHP) technology, more and more attention has been paid to the innovation of ground heat exchanger (GHE). The borehole GHEs have been the main type of GHE and the corresponding heat transfer models have made progress [1,2]. In recent year, the building pile foundation support structure, includes built in heat exchange pipes, to act as a new type of GHE known as "pile foundation GHE" or "energy pile"[3,4]. The pile diameter is obviously larger than that of traditional borehole, and spiral coils rather than U-tubes are usually adopted [5–7]. Therefore, the heat transfer quantity per metre of energy pile is greater compared with borehole GHE. The GHEs of GSHP system are composed of both borehole and pile foundation GHEs while piles of building are taken into account. Energy piles, on their own, are usually insufficient to cope with the buildings' air conditioning load because the number of piles is limited, and the surplus load is assumed by borehole GHEs. Pile foundation GHEs are favorable for the development of GSHP system, because the land area needed for borehole GHEs is reduced and the initial cost of drilling boreholes is also dropped. Accordingly, the pile foundation GHEs have become increasingly noteworthy and gradually adopted in the engineering projects. The schematic diagram of an energy pile with spiral coils is shown in Fig. 1.

The depth of the pile is always greater than ten metres and groundwater seepage is a significant factor affecting the heat transfer between pile and the surrounding medium, and the heat transfer mode is converted from pure conduction to combined heat transfer containing conduction and groundwater advection [8,9]. Groundwater seepage improves the heat transfer performance of pile foundation GHEs as any heat accumulation around the pile is alleviated. The impact becomes more and more obvious as the groundwater velocity steadily increases. Investigations on pure conduction of pile foundation GHE has gained fruitful results, and related theoretical research is relatively mature [10–12]. Studies on heat transfer for energy pile with groundwater flow has made progress until nowadays, and researchers are gradually explaining the role of groundwater seepage in the process of heat transfer, and a series of mathematical models and the correspond-

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Nomenclature

h_1, h_2	depth (m)
h	depth of finite spiral-source (m)
x, y, z	rectangular coordinate (m)
X, Y, Z	dimensionless rectangular coordinate
H	dimensionless depth
r_0	coil radius (m)
r	radial coordinate (m)
q_l	heating rate per length source (W m^{-1})
u	total velocity (m s^{-1})
u_1	velocity along x-direction (m s^{-1})
u_2	velocity along y-direction (m s^{-1})
u_3	velocity along z-direction (m s^{-1})
U	total dimensionless velocity
U_1	dimensionless velocity along X-direction
U_2	dimensionless velocity along Y-direction
U_3	dimensionless velocity along Z-direction
a	thermal diffusivity (m^2 s^{-1})
R	dimensionless radius
c	specific heat (J kg^{-1} K^{-1})
Fo	Fourier number
t_0	initial temperature (K)
t	temperature (K)
k	thermal conductivity (W m^{-1} K^{-1})

Greek symbols

ρ	density (kg m^{-3})
τ	time (s)
ψ, φ, β, θ,φ	angle
Θ	dimensionless excess temperature
T	excess temperature (K)

Superscript

$'$	integration parameter

Subscripts

i	infinite model
f	finite model

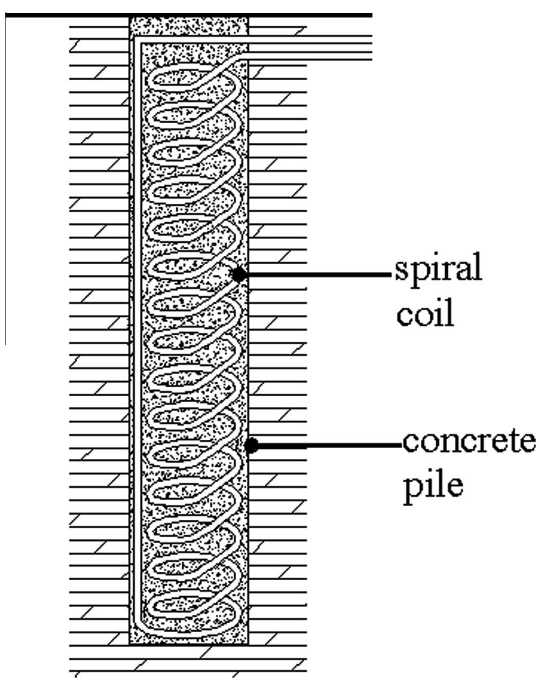

Fig. 1. The pile foundation GHE with spiral heat exchange coils.

ing analytical solutions have been proposed. In addition, numerical simulations have been studied of the influence of groundwater seepage. However, although the pile foundation GHE is three-dimensional (3-D), the work done has assumed either one-dimensional (1-D) seepage flow (e.g. in the x-axis direction) or two-dimensional (2-D) seepage flow [13]. In fact, groundwater seepage is caused by the local hydraulic gradient and it is a vector including orientation and value. It is reasonable to state that groundwater conducts seepage by means of 3-D velocity, which means groundwater seepage has components in three directions. 3-D groundwater seepage is the acknowledged style, 1-D and 2-D seepage occur while two directions' and one direction's components are respectively zeros. Fig. 2 explains that 3-D groundwater

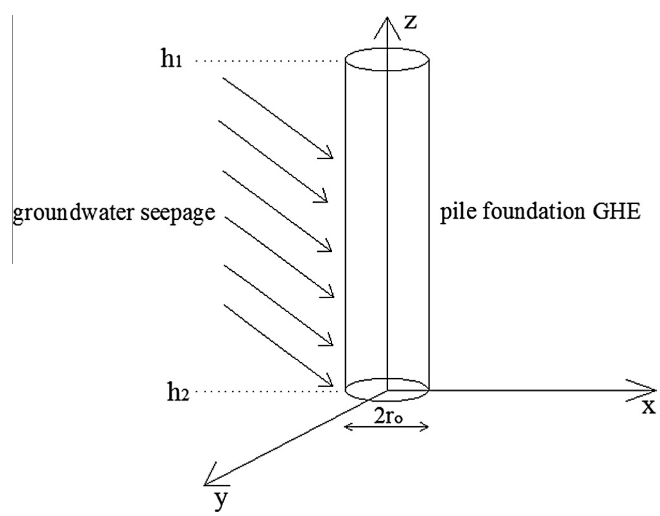

Fig. 2. Groundwater flows past pile foundation GHE in 3-D velocity's way.

flows across a pile foundation GHE, and the groundwater velocity has component velocities along x, y and z directions; this case is in accordance with the actual situation of groundwater seepage because the hydraulic gradient is usually 3-D distribution.

Little research on the heat transfer of pile foundation GHEs has related to such 3-D groundwater flows. It is necessary to provide a new mathematical model for revealing the heat transfer of 3-D pile foundation GHE passed by groundwater with 3-D velocity, and then to explore the characteristics involved in the new models. This paper describes research conducted to this end.

2. Models of pile foundation GHE with 3-D groundwater seepage

The start and the end positions of an energy pile along z direction are respectively denoted h_1 and h_2, and the velocity value of groundwater is u. q_l is the heat transfer quantity per metre length of energy pile and τ is the time. (x, y, z) and (x', y', z') are any point's coordinates except heat source and heat source point's coordinates, respectively. k is the heat conductivity and a is the thermal diffusivity. ρ and c are