International Journal of Heat and Mass Transfer 84 (2015) 119–129

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Study on spiral source models revealing groundwater transfusion effects on pile foundation ground heat exchangers

Wenke Zhang [a,*], Hongxing Yang [a], Ping Cui [b], Lin Lu [a], Nairen Diao [b], Zhaohong Fang [b]

[a] Renewable Energy Research Group, The Hong Kong Polytechnic University, Hong Kong, China
[b] Key Laboratory of Renewable Energy Utilization Technologies in Buildings, Ministry of Education, Shandong Jianzhu University, Jinan, China

ARTICLE INFO

Article history:
Received 30 April 2014
Received in revised form 28 November 2014
Accepted 11 December 2014

Keywords:
Spiral source models
Groundwater transfusion
Pile foundation
Ground heat exchangers
Heat exchange tubes

ABSTRACT

This paper presents a new spiral source heat transfer model for simulating the heat transfer performance of pile foundation ground heat exchangers (GHEs) with existence of groundwater transfusion. The model takes heat conduction and convection of groundwater into account and is more accurate than those previously proposed such as solid cylindrical model and ring-coil model to describe the heat transfer behavior. Besides, some shortages and deficiencies are improved and overcome, especially in terms of the configuration of spiral heat transfer tubes. The analytical solutions of the model are obtained to exhibit the temperature response at any point in the underground medium around the pile foundation GHEs. The parameters that exert impacts on the heat transfer process has been investigated and discussed in the paper. The pure conduction case and combined heat transfer case are compared, and the heat exchange efficiency between the pile foundation GHEs and surrounding medium can be improved as a result of the influence of groundwater transfusion. The meliorative effect is becoming increasingly evident with time or velocity of groundwater. The research contributes to more understanding of the potential for pile foundation GHEs and the degrees which the heat transfer efficiency affected by groundwater flow.

1. Introduction

With the development of the ground source heat pump (GSHP) technology, more and more attentions are paid on it. This technology made great contributions to the greenhouse heating [1], the current status and underground energy in Europe were analyzed [2], and the relationship between GSHP and the building envelop of Europe was explored [3], even the dynamic performance of GSHP fitted with frequency inverters for part-load control were discussed [4]. There is an increasing awareness of the variety of ground heat exchangers (GHEs) in the industry, Georgios and Soteris kalogirou conducted a review including systems, models and applications on conventional GHEs [5]. Nowadays, the investigations and discussions are not only limited to conventional vertical and horizontal GHEs, but also to pile foundation GHEs. U-type heat exchange tubes are usually placed into boreholes to form vertical GHEs, which can save land area, but the drilling cost of boreholes is significant. Horizontal heat exchange tubes are distributed under the ground if there is sufficient area but the heat transfer between the tubes and the surrounding medium is easily affected by the ambient air temperature above the ground because the tubes are placed in shallow trenches [6,7]. P.M. Congedo etc. analyzed the performance of this kind of GHE while different configurations of heat exchangers were employed [8].

At present, vertical borehole GHEs application is the mainstream in China due to limited land in urban areas, but this will inevitably lead to high initial cost on drilling boreholes. Researchers and engineers have realized that by incorporating GHEs into the pile foundation which often form the bearing structure of high-rise buildings, a certain proportion of the heating or cooling load can be undertaken in this way and the remaining load is taken by conventional GHEs thereby reducing the initial cost of the whole project [9].

As for the pile foundation GHEs, a great deal of research work has been conducted until nowadays. The behavior of a pile subjected to thermo-mechanical loads was studied in situ [10], therefore the increased loads on pile was investigated. Jun Gao etc. studied the thermal performance and underground temperature based on a district heating and cooling system in Shanghai, China [11], and they provided guidelines for better design. Christopher J. wood etc. researched the heat pump performance and underground temperature while pile foundation GHEs were employed for a residential building [12]. Fleur Loveridge etc. investigated the temperature response functions for single pile foundation

* Corresponding author.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.12.036
0017-9310/

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	speed in x-direction (m s^{-1})
S	dimensionless velocity
a	thermal diffusivity (m^2 s^{-1})
R	dimensionless radius
R_m	distance to heat source (m)
L_m	dimensionless distance to heat source
c_p	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})
b	pitch between adjacent coils
B	dimensionless pitch

Greek symbols

ρ	density (kg m^{-3})
τ	time (s)
φ	angular coordinate (rad)
Θ	dimensionless excess temperature
θ	excess temperature

Superscript

$'$	integration parameter

Subscripts

a	advection
c	conduction
i	infinite model
f	finite model

GHE [13], and they proposed a method for deriving G-functions for use with multiple pile foundation GHEs, pile spacing and corresponding number with any given arrangement were studied [14].

Since the pile diameter is always larger than that of boreholes and the pile depth is usually not so deep [15], high-density polyethylene (HDPE) spiral tubes rather than U-tubes can be placed within the concrete piles so as to occupy the external space fully. This material is chosen because of its high corrosion resistance and long service life characteristics so that the heat transfer efficiency is high and the cost is low. The pile foundation GHEs configuration is shown in Fig. 1.

The spiral tubes have higher thermal transmissivity than U-type tubes because of their larger heat transfer area. The spiral tubes can be placed inside a prefabricated hollow steel cage which is buried into the pile foundation before lowering the assembly into the drilled pile hole and pouring concrete. The length of the GHEs is governed by the depth of the pile foundation required for structural purpose. Generally, a pile foundation is also over ten meters deep up to dozens of meters. Groundwater transfusion may exist unavoidably and the transfusion degree is determined by the local hydraulic gradients. Thus, the heat dissipation of the pile GHEs is not just due to conduction and the whole heat transfer process is a combined case consisting of pure conduction and convection [16]. The temperature response at any point in the underground medium will be the synthetic contribution of the heat conduction and convection. It is worth studying the effect of the transfusion behavior on the heat transfers when the pile foundation GSHP system is considered because the heat accumulation around the GHEs in the underground medium can be relieved by this convection effect and the heat exchange is more effective. However, the current theoretical research on spiral-coil pile foundation GHEs with groundwater transfusion has not widely been reported. The cylindrical heat source models and ring-coil heat source models for pile foundation GHEs when groundwater transfusion is in existence were proposed by us before [17–19], but the cylindrical heat source models did not consider the effect of the pitches of spiral tubes because the whole tubes are simplified into a continuous cylindrical surface. The ring-coil heat source models are improved models compared with the previous models, but all the buried coils are considered as a series of separated coils without any connection between adjacent coils. In view of these shortcomings or defects; more accurate and precise models need to be proposed for further research. A more realistic spiral-coil model is thus reported in this paper where a real spiral-coil tube replaces the ring-coil tube in a pile foundation GHE. Besides the detailed heat transfer circumstance of the spiral-coil model with groundwater advection has not been reported until nowadays, it is desirable to account for the groundwater transfusion in the heat transfer model to avoid over-sizing of the GHEs. The paper describes the theoretical study of a true spiral-coil pile foundation in the presence of groundwater flow across the pile in which the tubes are embedded.

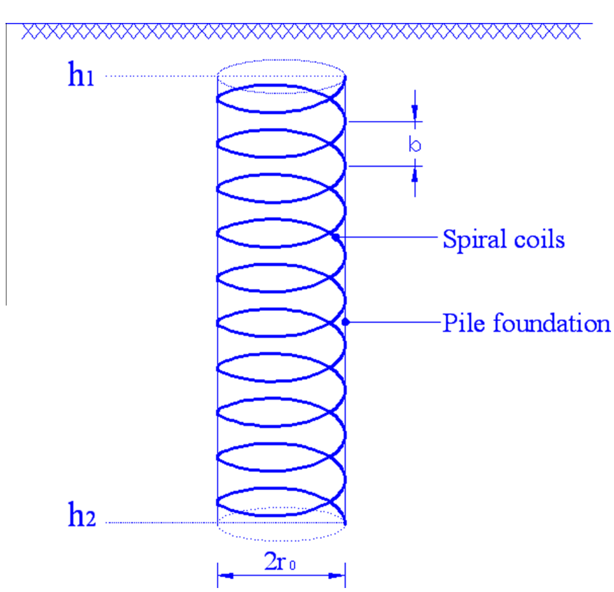

Fig. 1. The schematic diagram of a pile foundation GHE with spiral tubes.

2. The spiral-coil models without considering groundwater transfusion

To analyze heat transfer of the pile foundation GHEs with spiral coils the Green function [20–22] has been usually used, which is proven to be very potent and straightforward to obtain an analytical solution on the thermal response in a medium. The Green function can describe the temperature response of an instantaneous point heat source and unit heat intensity produced at any point