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Heat transfer model and design method for geothermal heat exchange tubes in diaphragm walls

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ABSTRACT

The technology of embedding heat exchange tubes in diaphragm walls is a new direction for Ground-coupled Heat Pumps (GCHP). This paper examines the heat transfer model and design method for geothermal heat exchangers in diaphragm walls, which are seldom investigated in the world. Two-dimensional (2D) heat transfer models for diaphragm wall heat exchangers (DWHE) are established. A design method for DWHE is further developed to calculate the hourly heat exchange capacity of DWHE and to get the reasonable design parameter of DWHE. The DWHE model over the excavation line has the same changing trend with numerical solutions, and the relative errors between them are less than 2%. The relative errors of calculated heat exchange rate per meter using DWHE model and measured data are less than 6% after running 10 h. The relative errors of temperature between DWHE model under the excavation line and the measured data at different positions are no more than 9%, whereas the relative error between the tradition models in GCHP (line source model and finite-line source model) and the measured data may reach as much as 40%.

1. Introduction

In recent decades, ground-coupled heat pumps (GCHPs) have been increasingly used worldwide because of their economic and environmental advantages. However, certain drawbacks prevent the large-scale application of this technology, such as the need for large space. Every 1 KW heat exchange rate requires approximately 37 m^2–93 m^2 of surface area in horizontal ground heat exchanger projects. Even for vertical ground heat exchanger projects, a surface area of 1.6 m^2–10.5 m^2 per KW is needed. Such a requirement is sometimes difficult to satisfy in built-up urban areas. Another issue is the high initial cost. The initial investment in GCHP is 20%–45% higher than that in traditional heating and air-conditioning systems due to the high cost of drilling holes. The extra investment can only be recovered after five to ten years. To overcome these challenges, energy geotechnical engineering has been proposed. This is an energy-saving technology that embeds heat exchange tube loops directly in underground structures such as base slabs, bored piles, and diaphragm walls, forming heat exchangers with part of the geotechnical engineering structures. With the advantages of good stability, durability, and heat transfer performance, the new technology has the potential to be used widely in densely populated urban areas [1]. The technology of embedding heat exchangers in diaphragm walls is under the category of energy geotechnical engineering. Heat exchange tube loops were first embedded in diaphragm walls as heat exchangers in Austria and Switzerland in 1996 [2]. In 2003, heat exchange tubes were buried in diaphragm walls, base slabs, and linings of sector tunnels as heat exchangers in sections of the Vienna Metro Line Extension U2 [2,3]. The technology was also adopted in the newly built Shanghai Museum of Natural History in China [4].

A schematic diagram of geothermal heat exchangers embedded in diaphragm walls is presented in Fig. 1. The diaphragm wall heat exchangers (DWHEs) are different from borehole heat exchangers (BHEs) in three aspects. First, the buried depth of a DWHE is about 15 m–40 m restricted by the depth of the diaphragm wall, whereas the depth of a BHE may reach 80–120 m. Generally speaking, a smaller depth of heat exchangers means a higher heat exchange rate per meter. Second, the borehole diameter is only about 110–150 mm, which is considerably less than the depth of the borehole. Therefore, the line source heat transfer model and the finite-line source heat transfer model, which ignore the heat capacity of the borehole and treat the temperature field inside the borehole as a steady state, are widely applied in the calculation of BHEs. However, the diaphragm wall is 0.8–1.2 m wide, so its heat capacity is too large to be neglected. Third, given that the surrounding stratum of the BHE is uniform soil, the diaphragm walls are divided into two parts by the excavation line. Over the excavation line, the diaphragm walls connect with soil on the soilward side

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Nomenclature

T	temperature (°C)
k	heat conductivity (W/m K)
q	heat exchange rate per meter (W/m)
c_p	specific heat capacity (J/kg K)
h	Convective heat transfer coefficient (W/m^2 K)
$f(t)$	air temperature (°C)
L	length (m)
a, b	x and y coordinate (m)
v	water velocity (m/s)
d	diameter (m)
H	total length of a set of heat exchange tube (m)
M	the mass flow rate of water (kg/s)

Greek symbols

α	thermal diffusivity (m^2/s)
ρ	density (kg/m^3)
δ	Dirac function
μ	dynamic viscosity coefficient of water (Pa s)

Subscripts

w	water
inner	inner diameter
outer	outer diameter
in	inlet
out	outlet
o	over the excavation line
u	under the excavation line
h	highest
initial	at the beginning of the cooling season
run	duration time of the cooling season
p	pipe wall
f	water in the heat exchange tube
1,2	diaphragm wall and soil, respectively, in the model over the excavation line
1′,2′,3′	soil on the left of the diaphragm wall, the diaphragm wall itself, and soil on the left of the diaphragm wall, respectively, in the model under the excavation line

and with air on the excavation side. Under the excavation line, the diaphragm walls connect with the soil on both sides. In accordance with the aforementioned factors, it is necessary to establish a new and more suitable heat transfer model and design method based on the actual situation of DWHEs instead of copying the model and method for BHEs. Therefore, the heat transfer problem of composite medium (diaphragm wall and soil) under convective boundary conditions should be considered in the calculation of DWHEs.

Brandl performed the related in situ test of DWHE based on the practical project of the Vienna Metro Line Extension U2 in Austria [2]. Adam and Markiewicz optimized the spacing of DWHE by using the numerical simulation method [3]. However, they did not propose the heat transfer model or design method for DWHEs. Cao proposed a slab heat transfer model for DWHEs [5], which assumes diaphragm walls to be a slab heat source, and that the whole slab injects and extracts heat to and from the surroundings. However, DWHEs are discrete with an interval of dozens of centimeters, and the diameter of the DWHE is much less than the size of the diaphragm walls. Therefore, the sum total of the areas of heat exchangers simply accounts for a tiny portion of the diaphragm walls, and it is not suitable to assume the diaphragm walls as a whole slab heat source.

This study established the 2D heat transfer models of DWHEs over and under the excavation line according to the structural

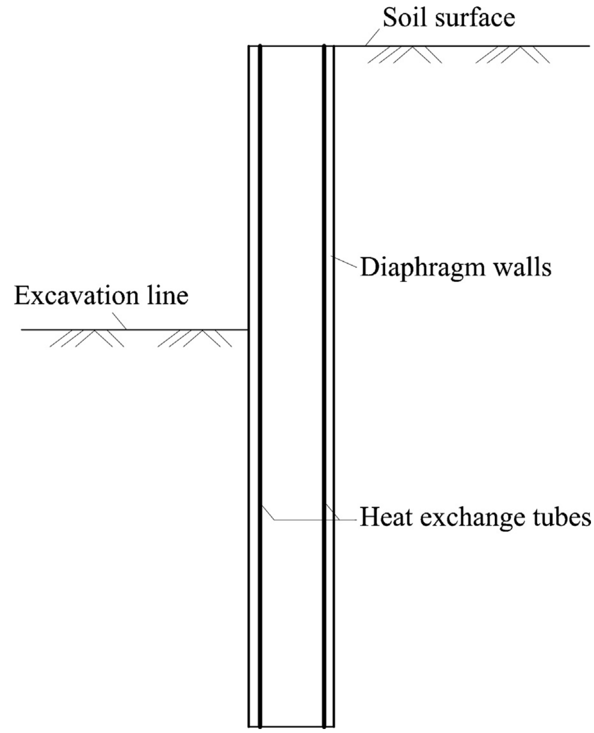

Fig. 1. Section plan drawing of geothermal heat exchangers embedded in diaphragm walls.

features of DWHEs. The analytical solutions of heat transfer models with variable heat exchange rates were conducted based on Green's function method and variables separation method [6]. A calculation method of the hourly heat exchange capacity and a design method for DWHE were proposed according to iterative methodology, flowing temperature field in DWHE, and the analytical solution of the proposed DWHE model. The calculation reliability of the proposed model was verified by comparisons between the numerical solutions, line heat source model, the finite-line source model, and the field experimental data.

2. Heat transfer models and analytical solutions

2.1. Model assumptions

The proposed models were established based on the following assumptions:

(1) No thermal contact resistance exists between the heat exchange tubes and the diaphragm wall, and between the diaphragm walls and the soil.
(2) Over the excavation line, the diaphragm wall connects with air directly on the excavation side, forming a convective boundary condition.
(3) The heat transfer in a vertical direction is ignored to simplify the vertical thermal gradient in the ground and the effect of the ground surface boundary condition.
(4) The thermal physical parameters do not change with temperature.
(5) Compared with the size of the diaphragm wall, the heat exchange tube is so small in diameter that each of its branches is assumed to be a point heat source.
(6) Hundreds of heat exchange tubes will operate simultaneously when the GCHP system is running. If each of the two adjacent sets of heat exchange tubes is assumed to have the same spacing, then one set can be chosen as the research object. Based