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A novel truncated cone helix energy pile: Modelling and investigations of thermal performance

Guangqin Huang [a,*], Xiaofeng Yang [a], Yajiao Liu [a], Chunlong Zhuang [a], Hongyu Zhang [a], Jun Lu [b]

[a] Dept. of Military Installation, Army Logistical University of PLA, Chongqing, China
[b] Faculty of Urban Construction and Environmental Engineering, Chongqing University, Chongqing, China

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ABSTRACT

Cylinder helix energy pile (CyHEP) is a new popular ground heat exchanger which have the advantages of large heat exchange rate and low initial cost. However, severe thermal interferences exist in the radial and generatrix directions duo to the limited thermal heat capacity of pile and small ratio between coils pitch and radius of pile. Therefore, a novel truncated cone helix energy pile (CoHEP) is presented to weaken the thermal interferences and improve the heat transfer efficiency. Further, an analytical solution model for CoHEP is proposed based on Green's function to discuss the dynamic characteristics of thermal interferences and heat transfer performance. A laboratory experiment is carried out to validate the presented model. The results indicate that the generatrix thermal interference in the bottom of the novel energy pile is significantly weakened and the radius thermal interference in the top of the novel energy pile is also weakened. Therefore, the heat transfer of the novel energy pile is enhanced compared with CyHEP and better performance of novel energy pile can be obtained by setting bigger cone angle. Besides, the thermal response characteristics of helix energy piles are discussed under the influences of dynamic load and the results show that the average temperature rise on the pipe wall of CoHEP is lower than that of CyHEP in the period of heat rejections while the average temperature of CoHEP is higher than CyHEP in the period of heat extraction. It is indicated that the energy efficiency of ground source heat pump coupled with CoHEP is higher than that coupled with the popular CyHEP.

1. Introduction

Energy saving and environmental protection have been the symbols in the modern development. In china, "Strategic Action Plan for Energy Development (2014–2020)" was published in November 2014 in order to achieve the sustainable development. The plan points out that the non-fossil energy share of primary energy consumption would reach to 15% by 2020 and the utilized quantity of geothermal energy would run up to 50 million tons of standard coal. Ground source heat pump (GSHP) is an efficient technology to exploit the shallow geothermal energy and has been applied extensively in building energy conservation.

GSHP utilizes the ground maintaining a nearly constant temperature as the heat source or sink, and the particular underground temperature is appropriate for efficient operation of unit. The most important component for GSHP is the ground heat exchanger (GHE) and the borehole GHE with U-type tube is the most common form. However, the high installation and drilling cost restrict the application of borehole GHE, especially for the rocky areas. Therefore, energy piles [1] have been proposed and widely applied for its good economic and well heat transfer performance. The primary structure forms of energy piles consist of U-type [2–4] (such as single U-type, parallel double U-type, triple U-type and series U-type) and helix type [5–7], and the helix energy piles (HEP) are a promising GHE due to the characteristics of large heat exchange rate and no air chocking in the pipes. However, duo to the features of complex helix structure, shallow-burial and large diameter of pile, the heat transfer characteristics of HEP are completely different from the U-type borehole GHE and wouldn't be described by classical Kelvin's line source [8]. Hence, the heat transfer of HEP has formed an academic focus. Besides, the investigations of

* Corresponding author.
E-mail address: hgq880818@163.com (G. Huang).

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Nomenclature

x, y, z	Cartesian coordinate (m)
r, φ, z	Cylindrical coordinate (m)
R, φ, Z	Dimensionless cylindrical coordinate
h	Height (m)
H	Dimensionless height
r	Radial coordinate (m)
R	Dimensionless radial coordinate
q_l	Heating rate per length of pipe (W s^{-1})
τ	the time (s)
α_s	Thermal diffusivity (m^{-2} s)
d_p	Distance from the heat source point to the calculated point (m)
d_n	Distance from the heat sink point to the calculated point (m)
D_p	Dimensionless distance from the heat source point to the calculated point (m)
D_n	Dimensionless distance from the heat sink point to the calculated point (m)
ρ	Density (kg m^{-3})
c	Specific heat (J kg^{-1} K^{-1})
λ	Thermal conductivity (W m^{-1} K^{-1})
ΔT	the temperature rise (K)
R	Thermal resistance (m^{-1} K^{-1} W)
L	Length of helix pipe

Greek symbols

θ	Cone angle (rad)
φ	Spiral angle (rad)
Fo	Fourier number
η	Influence coefficient
Θ	Dimensionless temperature rise

Superscript

$'$	Integration parameter
ave	the average value
CyHEP	Cylinder helix energy pile
CoHEP	Truncated cone helix energy pile
t	Top surface of pile
b	Base surface of pile
mi	Middle surface of pile
i	the index of arc
j	the index of coil
k, n	the index of time
p	Pipe
f	Fluid
g	Ground

energy pile with U-tube also have been carried out [2–4,9–11]. It is worth noting that the spiral coils are fixed on the cylinder surface in the existing studies of HEP, which is named cylinder helix energy piles (CyHEP) to distinguish with the truncated cone helix energy pile (CoHEP) proposed in the manuscript.

Several analytical solution models of CyHEP were proposed, which have a great significance for engineering designs duo to the concise expressions of solutions.

The derivations of analytical solution models of CyHEP is a process of integrating Green's function [12] with respect to the time and heat source shape under specific assumptions. According to the assumed heat source shape, three pure conduction models ignoring the groundwater seepage were presented including "solid" cylindrical heat source model (CyM) [13], "ring-coils" heat source model (RcM) [14] and spiral coils heat source model (ScM) [15,16]. CyM regards cylinder surface of energy pile as heat source while RcM is simplified as a number of separated rings on the cylindrical surface and is capable to discuss the pipe wall temperature. A spiral coils heat source on the cylindrical surface is supposed in ScM and the circumferential heat transfer is considered. Recently, a composite-medium solution [17] and a double-layered ground model [18] are proposed on the basis of CyM and RcM, which respectively considers the thermal property difference between pile and soil, and the thermal property difference in the vertical ground. The above proposed models would further refine the heat transfer theory of CyHEP. However, the solution formulas of composite-medium model [17] and double-layered model [18] are quite complicated and the calculation process is difficult.

On the basis of pure conduction analytical solution models, several combined analytical solution models (CoSM) considering both conduction and advection were presented to discuss the influence of groundwater seepage on heat transfer of HEP [18–21] by Wenke Zhang et al. which consist of the line source model [19], cylindrical heat source model [20], "ring-coils" heat source model [21] and spiral coils heat source model [22]. Those new CoSM have made great contribution to investigate the effect of underground water flow. Ulteriorly,