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Numerical modelling of thermal regimes in steel energy pile foundations: A case study

E. Hassani Nezhad Gashti[a,*], V.-M. Uotinen[b], K. Kujala[a]

[a] Faculty of Technology, FIN-90014, University of Oulu, Finland
[b] Ruukki Construction Oy, FIN-13300 Hämeenlinna, Finland

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ABSTRACT

Heating/cooling operations of ground heat exchangers (GHEs) incorporated with steel pile foundations were simulated in a 3D numerical model using the Comsol Multiphysics package. Acceptable agreement between numerical and experimental results denoted high ability of the finite element method utilised in the model to predict system operation. Use of the model to compare the performance of several GHEs in terms of their efficiency revealed that double U-tube systems have greater productivity than single U-tube systems at a particular fluid flow rate. The model was further used to analyse thermal regimes generated in pile shaft in different heating/cooling modes, in which two zones with different thermal profiles (steady state and transient) were identified over the pile length, with the transient zone dominating. The final stabilised temperature in the pile shaft was found to be around 25–33% difference with the inlet fluid temperature. The results showed that the constant temperature assumption over the pile length utilised in some literature is not very realistic and can prevent correct prediction of mechanical behaviour in energy piles, in particular in the vicinity of the U-curve of polyethylene tubes at the end of piles.

1. Introduction

With high energy prices and new environmental policies, the use of geothermal energy has become increasingly popular. The EU, including Finland, aims to increase the use of renewable energy resources, become more self-sufficient and reduce carbon emissions [1–3]. Geothermal energy pile foundations, so-called energy piles, are considered as alternative technologies for producing energy instead of traditional systems. Statistics show that there is high increasing interest in using this relatively new technology worldwide (around 80 countries around the world have been using geothermal energy for different heating and cooling objectives since 2000) [4]. The system is based on absorbing/rejecting heat from/to the ground during winter/summer, respectively. This means that the ground acts as a heat source during cold seasons in providing heat energy and as a heat sink during hot seasons in affording cooling to buildings (Fig. 1).

Heat transfer in energy piles results in thermal fluctuations in the pile shaft. Detailed study of these fluctuations is highly important due to their ability to affect the mechanical behaviour of energy piles by generation of extra stresses and deformations [5]. Energy piles can have great potential for heating/cooling applications in terms of their long-term performance as regard sustainability, economics and flexibility [6] if pile durability (both mechanical and geotechnical aspects) remains in the ranges recommended by current codes. Correct prediction of thermal stresses and deformations in energy piles is impossible unless thermal regimes generated from heat transfer regarding the real operations of ground heat exchangers (GHEs) are first accurately taken into consideration. A classic method in modelling the thermal regimes around GHEs is that presented by Carslaw and Jaeger [7], which is based on cylindrical heat source theory, extended for an infinite pipe length surrounded by a homogeneous soil. This method has been utilised by a number of researchers in numerical analyses of GHE performance [8–10]. It has also been used in an extended form in some analytical models, e.g. those presented by Ochifuji and Kim [11] and Bernier [12]. However, all these models are based on constant cylindrical shape of GHE by assuming constant diameter at depth. Hence, they are unable to analyse the effect of heat exchanger U-pipe shape inside the piles, which could prevent correct prediction of GHE performance and thermal regimes generated around the system.

With the appearance of softwares based on finite element theory, many analyses of complex mathematical problems have been conducted. In recent years, a number of numerical models have been applied to simulate the performance of ground-source heat pump (GSHP) systems based on this theory and the data obtained have been compared with experimental results [13–19]. Nam et al. [20] used a numerical finite element model to calculate heat exchange rate in a GSHP systems in China. In that model,

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[*] Corresponding author. Tel.: +358 417248344.
E-mail address: ehsan.hassani@oulu.fi (E.H.N. Gashti).

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Nomenclature

ρ	density of heat-carrier-fluid (kg/m^3)
u	heat-carrier-fluid velocity vector (m/s)
p	heat-carrier-fluid pressure (Pa)
μ	heat-carrier-fluid dynamic viscosity (Pa s)
F	body force vector (N/m^3)
C_p	fluid heat capacity at constant pressure (J/kg K)
T	absolute temperature (K)
q	heat flux by conduction (W/m^2)
τ	viscous stress tensor (Pa)
Q	heat sources other than viscous heating (W/m^3)
S	strain-rate tensor (1/s)
E	elastic contribution to entropy (J/m^3 K)
$(\rho C_p)_{eq}$	equivalent heat capacity at constant pressure (J/kg K)
k_{eq}	equivalent thermal conductivity (W/m K)
θ_p	solid material's volume fraction
θ_L	liquid material's volume fraction (Porosity) in saturated conditions
ρ_p	density of solid (kg/m^3)
$C_{p,p}$	solid heat capacity (J/kg K)
k_p	solid thermal conductivity (W/m K)
k	liquid thermal conductivity (W/m K)
L	pile length (m)

heat transfer in surrounding domains was modelled based on GHE performance in concrete piles with unsteady state analysis. The numerical results were then compared with experimental values and their good agreement was found. Much experimental work has concentrated on analysis of GSHP system performance and evaluation of productivity in different climates (e.g. examination of coefficient of performance, COP). However, there are far fewer numerically validated studies concentrating on the thermal regimes generated in the energy pile shaft, which reflects the actual operation of the system in 3D real-scale based on the exact shape of U-tubes inside the piles.

In the present study, the thermal operation of common steel energy piles utilised in Finland was numerically analysed based on real conditions of system performance in heating and cooling operations in this climate. For the analysis, a 3D model based on finite element theory was defined in the Comsol Multiphysics package. The model operated in real scale of the pile and surrounding environment and reflected the exact shape of the polyethylene (PE) U-tubes in the system. The model simulated heat transfer by coupling forced convection and conduction processes from the heat-carrier fluid inside the pipes into the ambient materials. Model results were then compared with experimental values measured in a pilot test conducted at Hämeenlinna in southern Finland to validate the numerical model. GHE power for some different U-tube types was then determined and the values compared in order to identify the most efficient tube type. Temperature variations in vertical and horizontal axes along the pile length in a single U-tube system were determined in different heating and cooling operations and the results were compared with the constant temperature assumption along the entire pile length. The results obtained from this thermal regime analyses can be used for calculating extra thermal stresses and deformation in energy piles. Furthermore, the numerical model is sufficiently flexible to be extended for further investigations of thermal regimes in energy piles under various climates and GSHP operations.

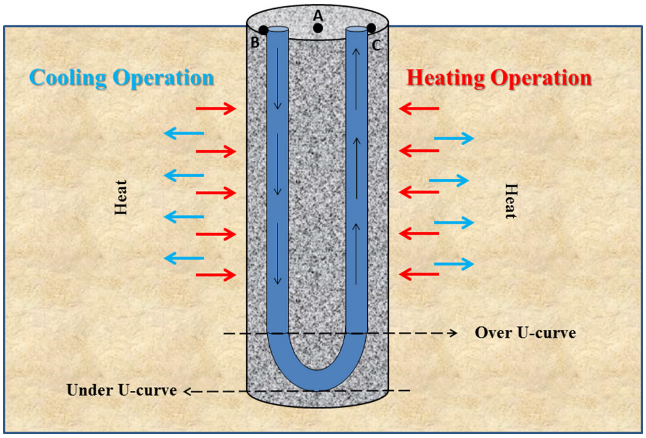

Fig. 1. Heating/cooling operation of energy piles by absorbing/rejecting heat from/to the ground during winter/summer modes.

2. Governing equations of model

The software employed for the analysis is able to simulate heat transfer processes in GSHP systems using computational fluid dynamics (CFD) with forced convection of heat-carrier fluid inside the pipes, conduction in pipe walls to pile materials and conduction and convection in porous media. The finite element method used for software analysis has been employed extensively in analysis of such systems, e.g. Zanchini et al. [21] utilised it to calculate groundwater flow effects on performance of a borehole heat exchanger under different unbalanced conditions. Non-isothermal laminar flow conjugated with heat transfer is included in the analysis, based on main formulations of continuity, momentum and energy equations [22].

For calculation of fluid convection inside the pipes, the following equations are used:

$$\frac{\partial}{\partial t}u+\nabla\cdot(\rho u)=0 \qquad (1)$$

$$\rho\frac{\partial}{\partial t}u+\rho u\cdot\nabla u=-\nabla p+\nabla\cdot\left\{\mu(\nabla u+(\nabla u)^T)-\frac{2}{3}\mu(\nabla\cdot u)I\right\}+F \qquad (2)$$

The fluid heat equation is solved as:

$$\rho C_p\left(\frac{\partial}{\partial t}T+(u\cdot\nabla)T\right)=-(\nabla\cdot q)+\tau:S-\frac{T}{\rho}\frac{\partial\rho}{\partial T}|_p\left\{\frac{\partial p}{\partial t}+(u\cdot\nabla)p\right\}+Q \qquad (3)$$

$$S=\frac{1}{2}(\nabla u+(\nabla u)^T) \qquad (4)$$

The interface supports heat transfer in solid media, e.g. pipe walls:

$$\rho C_p\frac{\partial}{\partial t}T=-(\nabla\cdot q)-T\frac{\partial E}{\partial t}+Q \qquad (5)$$

while heat transfer in porous media uses the following equation (Darcy porous medium):

$$(\rho C_p)_{eq}\frac{\partial T}{\partial t}+\rho C_p\cdot u\cdot\nabla T=\nabla\cdot(k_{eq}\nabla T)+Q \qquad (6)$$

where u is the fluid velocity field which is acquired from Darcy velocity and other variables in Eq. (6) are calculated as follows:

$$K_{eq}=\theta_p\cdot k_p+\theta_L\cdot k \qquad (7)$$

$$(\rho C_p)_{eq}=\theta_p\cdot\rho_p\cdot C_{p,p}+\theta_L\cdot\rho\cdot C_p \qquad (8)$$

$$\theta_p+\theta_L=1 \qquad (9)$$