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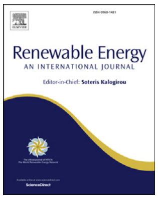

A new approach to estimating temperature fields around a group of vertical ground heat exchangers in two-dimensional analyses

Eleonora Sailer[*], David M.G. Taborda, Lidija Zdravković

Department of Civil and Environmental Engineering, Imperial College London, UK

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ABSTRACT

Vertical ground heat exchangers (VHEs), in the form of either Borehole Heat Exchanger (BHE) or thermo-active piles, are increasingly being deployed to provide low cost and sustainable heating and cooling to buildings. These are often installed within densely built urban environments, where adjacent foundation systems and underground structures can be affected by soil temperature changes induced by the heat exchangers. Therefore, they need to be considered in the geotechnical design of such structures, which typically involves carrying out two dimensional finite element plane strain analyses in order to assess their stability and performance. In such a scenario, it is common to model a line of heat exchangers as a planar source with one infinite dimension and a heat flux rate calculated by dividing the design extraction rate of a single heat exchanger by their spacing in the out-of-plane direction. This study shows that this approach largely overestimates the generated temperature field and proposes a simplified but accurate procedure to estimate the required heat flux to be applied to the planar heat sources in a 2D analysis. For this purpose, a correction factor, T^*, is introduced which is shown to depend on geometric parameters and thermal ground properties.

1. Introduction

Ground source energy is widely recognised as being a renewable, efficient and cost effective energy source for residential and commercial space heating and cooling. A ground source heat pump (GSHP) system consists of a heat pump connected to a ground heat exchanger, in which pipes are buried in the ground, injecting (cooling mode) or extracting heat (heating mode) by circulating a fluid at a temperature higher or lower than that of the ground, respectively. This is possible because the ground, below a certain depth (usually around 10–15 m [1]), presents a constant temperature throughout the year, and can therefore be used as a heat sink during summer or a heat source during winter [2]. Different types of ground heat exchanger exist, either directly installed within the ground or placed within geotechnical structures, such as pile foundations, retaining walls and tunnel linings. The most commonly used type of vertical ground heat exchanger (VHE) is the borehole heat exchanger (BHE), where pipes are placed within a vertical borehole, typically backfilled with grout. Alternatively, multiple ground loops can be placed in a similar manner within pile foundations, which is often advantageous since these structures are in any case required in order to provide stability to civil engineering structures. Moreover, for both BHEs and thermo-active piles, the vertical installation of ground loops means that they require less surface area compared to horizontal configurations (e.g. slinky systems).

The need to meet continuously stricter sustainability requirements implies that the installation of BHEs/thermo-active foundations often takes place within densely built environments, which undergo continuous development. New structures are likely to require the design and construction of new basement and foundation systems, which rely on the shear strength of the ground for stability and are typically sensitive to considerable ground movements. Moreover, early studies by Campanella and Mitchel [3] showed that temperature has a significant effect on the thermo-hydro-mechanical properties of soil. Indeed, further research on this aspect of soil behaviour was carried out for a variety of materials, such as Pontida and Pasquasia clays [4], Boom clay [5], Kaolin [6] and soft Bangkok clay [7]. The gathered experimental evidence suggests that, unlike most engineering materials, normally and lightly overconsolidated clays tend to contract when heated. For heavily overconsolidated samples, contraction was observed only

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[*] Corresponding author. Skempton Building, Imperial College London, South Kensington Campus, London, SW7 2AZ, UK.
E-mail address: eleonora.sailer13@imperial.ac.uk (E. Sailer).

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Nomenclature

a	coefficient for the calculation of T^*
a_1	coefficient for the calculation of T^*
a_2	coefficient for the calculation of T^*
$a_{2,1}$	coefficient for the calculation of T^*
$a_{2,2}$	coefficient for the calculation of T^*
b	coefficient for the calculation of T^*
b_1	coefficient for the calculation of T^*
$b_{1,1}$	coefficient for the calculation of T^*
$b_{1,2}$	coefficient for the calculation of T^*
b_2	coefficient for the calculation of T^*
$b_{2,1}$	coefficient for the calculation of T^*
$b_{2,2}$	coefficient for the calculation of T^*
c	ground specific heat capacity $[J/Kg\ K]$
$erfc$	complementary error function
H	depth of heat source $[m]$
h	integrating parameter
L	length of finite plane source $[m]$
l	integrating parameter
n_i	number of in-plane heat exchanger
n_o	number of out-of-plane heat exchanger
Q	heat flux $[W]$
q_A	heat extraction rate per unit area $[W/m^2]$
q_{VHE}	heat extraction rate per unit depth $[W/m]$
q_{2D}	heat extraction rate for 2D analyses $[W/m^2]$
q^*	corrected heat extraction rate for 2D analyses $[W/m^2]$
r	distance to the point source $[m]$
r^+	distance to original point source $[m]$
r^-	distance to virtual point source $[m]$
s	spacing between heat exchanger $[m]$
T	ground temperature $[°C]$
T_0	initial ground temperature $[°C]$
T^*	proposed correction factor
t	time $[s]$
x	coordinate in in-plane direction
y	coordinate in out-of-plane direction
z	coordinate in depth

Greek letters

α	ground thermal diffusivity $[m^2/s]$
β	coefficient for the calculation of T^*
γ	coefficient for the calculation of T^*
δ	coefficient for the calculation of T^*
ε	coefficient for the calculation of T^*
ζ	coefficient for the calculation of T^*
η	coefficient for the calculation of T^*
θ	coefficient for the calculation of T^*
ι	coefficient for the calculation of T^*
κ	coefficient for the calculation of T^*
λ	ground thermal conductivity $[W/m\ K]$
μ	coefficient for the calculation of T^*
ν	coefficient for the calculation of T^*
ξ	coefficient for the calculation of T^*
ρ	ground density $[Kg/m^3]$
σ	coefficient for the calculation of T^*
ω	coefficient for the calculation of T^*

when the temperature was increased beyond values considered typical of GSHP systems (usually limited to around 40 °C). Furthermore, these studies showed that saturated soils subjected to temperature changes lead to the development of excess pore water pressures, due to the coefficient of thermal expansion of water being larger than that of the solid particles. Naturally, this modifies the effective stress state within the ground, thus affecting its strength and stiffness. Hence, when performing the geotechnical analysis of structures adjacent to fields of VHEs, it is important to predict accurately the generated three-dimensional temperature field, which can typically be done using relatively simple methods like the finite line source. However, in practice, given the complexity of the computational methods required to simulate accurately soil-structure interaction phenomena, two-dimensional plane strain finite element analyses are commonly employed in design, especially when simulating the response of geotechnical structures where one dimension is considerably larger than the other two (such as retaining walls, cut slopes, road and rail embankments and tunnels), leading to considerable savings in computational time [8]. As a consequence, a two-dimensional representation of the field of VHEs is required.

This paper proposes a method to determine the heat flux that should be applied in two-dimensional simulations of vertical heat exchangers (VHEs), such as borehole heat exchangers (BHEs), in order to obtain temperature changes in the soil similar to those calculated when considering the three-dimensional nature of the problem. Equally, the method is applicable to groups of thermo-active piles, as well as thermal drains used to accelerate the consolidation process beneath embankments (e.g. [9]). The frequently employed practice of simply dividing the heat extraction rate of the individual vertical heat exchanger (q_{VHE}) by their out-of-plane spacing (s) [10,11] is shown to lead to inaccurate estimates of temperature changes in the ground. Indeed, analyses presented herein demonstrate that this approach tends to overestimate the temperature field around a group of VHEs, especially with a low number of heat exchangers and a small spacing (less then 10 m). The proposed method suggests the application of a correction factor to the equivalent two-dimensional extraction rate ($q_{2D} = q_{VHE}/s$), which is a function of geometrical parameters of the VHE field and the ground thermal conductivity.

2. Modelling of borehole heat exchangers

Different analytical and numerical methods exist for the evaluation of the temperature changes generated by a VHE when only heat conduction is considered. A commonly used tool for this purpose is the finite line source (FLS) model [12,13]. This approach is particularly adequate for long term simulations where axial effects become important, an aspect which other procedures, such as the infinite line source (ILS), are unable to predict. Indeed, when using the latter method, steady state conditions are not reached, with the temperatures increasing indefinitely with time [14]. Perhaps the greatest limitation of the FLS model is its inability to consider the radial dimension of the heat exchanger, which may reduce the accuracy of the predicted temperature changes in the vicinity of large-diameter heat exchangers (e.g. within groups of large diameter thermo-active piles). Possible improvements in accuracy in such scenario could be achieved by using the cylindrical heat source (CHS) model, either in its infinite [15,16] or finite [17] forms, as it takes into account both the radial dimension and heat capacity of the heat exchanger. In recent years, further research has been carried out leading to the development of analytical