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Foundation heat transfer analysis for buildings with thermal piles

Luis Enrique Almanza Huerta, Moncef Krarti *

Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, CO, United States

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ABSTRACT

Thermal piles or thermo-active foundations utilize heat exchangers embedded within foundation footings to heat and/or cool buildings. In this paper, the impact of thermal piles on building foundation heat transfer is investigated. In particular, a simplified analysis method is developed to estimate the annual ground-coupled foundation heat transfer when buildings are equipped with thermal piles. First, a numerical analysis of the thermal performance of thermo-active building foundations is developed and used to assess the interactions between thermal piles and slab-on-grade building foundations. The impact of various design parameters and operating conditions is evaluated including foundation pile depth, building slab width, foundation insulation configuration, and soil thermal properties. Based on the results of a series of parametric analyses, a simplified analysis method is presented to assess the impact of the thermal piles on the annual heat fluxes toward or from the building foundations. A comparative evaluation of the predictions of the simplified analysis method and those obtained from the detailed numerical analysis indicated good agreement with prediction accuracy lower than 5%. Moreover, it is found that thermal piles can affect annual building foundation heat loss/gain by up to 30% depending on foundation size and insulation level.

1. Introduction

Thermo-active foundation systems offer innovative and sustainable alternatives to ground-source heat pumps (GSHPs) and other conventional heating, ventilating, and air-conditioning (HVAC) systems to heat and cool commercial as well as residential buildings. Thermo-active foundations have a dual function since they are installed within elements that are already needed for structural and geotechnical purposes. Studies, carried out mostly in Europe and Japan, have shown that thermo-active foundation systems can save up to 75% of energy used to heat and cool both residential and commercial buildings compared to conventional HVAC systems [1–3]. These systems have been reported to be more energy efficient than geothermal borehole ground-source heat pumps since concrete has higher thermal conductivity than most soil types. In addition, thermo-active foundation systems do not require any land availability which is one of the main challenges for conventional geothermal borehole heat pumps especially those using horizontal heat exchange loops.

While, there are several analysis studies reported for conventional GSHP systems [4–8], few models of thermo-active foundations are available in the literature [9–11]. However, these models are based on simplified assumptions and do not account for the thermal interactions between thermal piles and building thermo-active foundations. Ground-coupled heat transfer can be significant especially for low-rise residential and commercial buildings when the foundation heat transfer can contribute up to 30% of the total building heating and cooling loads [12]. Unlike the case of above grade building envelope, heat losses or gains from building foundations are difficult to estimate due to the multiple dimensional nature of ground-coupled heat transfer. Several solution techniques have been proposed to reduce the computational efforts required to determine foundation heat transfer [13–14]. The addition of heat exchangers in the foundation piles can significantly affect ground-couple heat transfer thermal piles. Indeed, ground coupled heat transfer occurs mostly only the joints between slab floor and foundation piles and thus can varies significantly depending on the heat exchanger operating mode. No detailed analysis is reported in the literature on the magnitude of the thermal interactions between the building foundations and thermal piles especially under dynamic operation conditions.

In this paper, a numerical model of thermal pile and building slab foundation is developed and used to assess the impact of various design parameters and operating conditions on ground coupled heat transfer. The level of thermal interactions can then be utilized to assess the optimal design specifications in order to reduce the thermal loads of buildings served by thermo-active foundations. Ultimately, a simplified analysis method is developed

* Corresponding author.
E-mail address: krarti@colorado.edu (M. Krarti).

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Nomenclature

A	correlation coefficients for Eq. (19)
a	half width of the slab (m)
b	depth of the ground (m)
C	specific heat capacity (J/kg K)
D	thermal pile depth (m)
d	dimensional group at the right side
d_p	diameter of heat exchanger pipe (m)
f	dimensional group at the left side
$GSHP$	ground source heat pump
H	length of the domain
k	thermal conductivity (W/m K)
L	distance far away from the building (m)
L_{ins}	partial insulation length (m)
$NTHB$	normalized total heat with respect to the baseline
NX	number of nodes in x direction
NY	number of nodes in y direction
Nu	Nusselt umber
P	dimensionless parameter
Pr	Prandtl number
q	heat (W)
R	resistance value
Re	Reynolds number
S	source term
T	temperature (K)
t	time (day)
V_a	mean velocity (m/s)
V_x	mean velocity in x direction (m/s)
V_y	mean velocity in y direction (m/s)
V	magnitude of velocity, $V = \sqrt{V_x^2 + V_y^2}$ (m/s)
x	displacement in x direction (m)
y	displacement in y direction (m)

Subscripts

amp	amplitude
HE	heat exchanger
NHE	no heat exchanger
m	mean
max	maximum
now	current time
o	outdoor
$shift$	time with minimum ground surface temperature

Greek Symbols

Γ	diffusion coefficient
ω	angular frequency
ρ	density (kg/m^3)
β	clustering parameter
δ	differential
α	thermal diffusivity
μ	dynamic viscosity (Pa s)
φ	parameter to choose the location of a clustered zone

to help architects and engineers in the early design phase to assess the impact of the thermal piles on the annual heat fluxes to or from the building foundations. First, the numerical model is presented with a verification analysis of its prediction accuracy. Then, select results of a comprehensive parametric analysis are summarized. Finally, a simplified analysis method is developed and validated to predict thermal interactions between thermal pile and foundation heat loss and gains.

2. Model description

Fig. 1 shows a two-dimensional model for a building slab foundation equipped with thermal piles. Methods to extrapolate 2-D analysis to 3-D analysis of building foundation heat transfer can then be utilized [12]. It should be noted that the ground beneath the building foundation is modeled using a layered soil medium to account for variation of thermal properties. As shown in Fig. 1, each soil layer is assumed to have a thickness of c, while b denotes the depth of the soil and L is the horizontal extension for the ground medium so that the boundaries $x = \pm L$ can be considered to be unaffected by the presence of the building. The half width of the building slab is denoted by a.

The temperature field with the foundation and soil medium can be determined by solving the two dimensional heat equation with a heat source:

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + S \tag{1}$$

To take into account the effect of the working fluid flowing at a defined velocity, V, within the heat exchanger pipes located in the foundation piles, the convection–diffusion equation is considered [9].

$$\frac{\partial}{\partial t}(\rho C T) + \frac{\partial}{\partial x}(J_x) + \frac{\partial}{\partial y}(J_y) = S \tag{2}$$

where J represents the fluxes which are defined as:

$$J_x = (\rho C V_x)T + \Gamma\frac{\partial T}{\partial x} \tag{3}$$

$$J_y = (\rho C V_y)T + \Gamma\frac{\partial T}{\partial y} \tag{4}$$

with V_x and V_y denote the velocity components in the x and y direction, respectively while Γ is the diffusion coefficient.

As illustrated in Fig. 1, the slab-thermal pile model is symmetric at $x = 0$ which means that it is possible to analyze only the half of the model to analyze the thermal performance of the building foundation. For the present analysis the domain from (0, 0) to ($-L$, 0) is analyzed. Such symmetry condition may be written as:

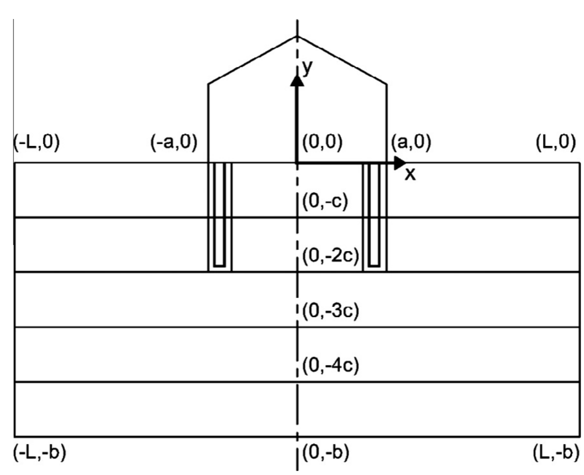

Fig. 1. Model and associated dimensional parameters for a building slab with thermal piles.