Geomechanics for Energy and the Environment 5 (2016) 1–15

Contents lists available at ScienceDirect

Geomechanics for Energy and the Environment

journal homepage: www.elsevier.com/locate/gete

Parameterization of a calibrated geothermal energy pile model

Robert Caulk[a,*], Ehsan Ghazanfari[a], John S. McCartney[b]

[a] Department of Civil and Environmental Engineering, University of Vermont, Burlington, VT, USA

[b] Department of Structural Engineering, University of California San Diego, San Diego, CA, USA

HIGHLIGHTS

- We model conductive heat transfer and pipe flow in four geothermal energy piles.
- We calibrate the model using field data from in-situ geothermal energy piles.
- Optimal cross-sectional heat exchanger geometry determined by sensitivity analysis.
- Theoretical thermal axial strains are computed using field-developed relationships.

ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form 14 October 2015
Accepted 1 November 2015
Available online 1 December 2015

Keywords:
Geothermal energy
Energy pile
Numerical modeling
COMSOL
Calibration
Thermo-active foundation

ABSTRACT

This paper describes the calibration and parameterization of a numerical model for conductive heat transfer from a group of geothermal energy piles into the soil surrounding the piles. Calibration was performed using Thermal Response Test (TRT) data collected from a group of full-scale in-situ geothermal energy piles in Colorado Springs, CO. The calibration of the three dimensional model incorporated field data to represent boundary conditions including inlet temperature, atmospheric temperature, and subsurface temperatures at different locations within the pile group. Following calibration, the model was parameterized to understand the role of heat exchanger configuration with a given energy pile as well as the role of pile spacing in an energy pile group. Parametric combinations were compared using heat transfer per unit length of the energy pile (W/m). The results of the parametric study indicate that heat transfer increases by up to 8% for an even heat exchanger layout compared to an uneven layout when considering a 15.2 m long, 0.61 m ⌀ energy pile configured with a W-shape heat exchanger. These results also provide useful insight into the cross-sectional temperature distribution of the aforementioned energy pile configuration. Energy pile temperature was observed to vary by up to 20% across the core of the pile during heating for various heat exchanger layouts. This uneven temperature distribution may have implications on the estimation of in-situ thermal axial stresses in energy piles. Specifically, using measurements at strain gage locations may underestimate thermal axial stress during heating.

1. Introduction

Indoor climate control accounts for almost 50% of America's residential energy consumption.[1] As energy prices rise with increased demand and short supply, global communities will need clean renewable alternatives to heat/cool

* Corresponding author.
E-mail address: Rob.Caulk@gmail.com (R. Caulk).

http://dx.doi.org/10.1016/j.gete.2015.11.001
2352-3808/

residential and commercial buildings. Although ground source heat pumps are a well-established energy efficiency technology, their coupling to building foundations provides a new way to transfer heat to or from the ground for lower installation costs. Heat is transferred by circulating heated or cooled fluid through closed-loop heat exchangers embedded in the foundations. In this way, geothermal energy piles serve two purposes, first to transfer building loads into the subsurface, but also to extract thermal energy from surrounding soils.

Concrete energy piles are a natural fit for geothermal energy. Since concrete foundation piles are generally longer than 6 m,[2] they provide access to the constant subsurface temperatures necessary for an efficient ground source heat pump (GSHP) system. Another benefit is the reduced heat exchanger installation cost compared to traditional vertical borehole heat exchangers. Since the installation of foundation piles requires drilling equipment, heat exchangers do not require additional installation (drilling) cost. Also, geothermal energy piles are easily coupled with solar panels to provide grid-independent climate control. Finally, the concrete protects the heat exchangers from damage and contains potential ground water pollution.[2]

The initial geothermal energy pile design controls the heat transfer and thermal stresses associated with the thermal soil–structure interaction for the lifespan of the foundation.[3] The cross-sectional temperature distributions within energy piles not only reflect the transient heat transfer characteristics of the geothermal energy pile, but may also have an important impact on the in-situ thermal axial stress within the energy pile.[4] This study seeks to understand different aspects of geothermal energy pile behavior using a numerical model calibrated with field data. The specific objectives are to understand the role of heat exchanger configurations on heat transfer within the pile and on the thermal stress calculations. Concrete cover, shank distance, and pile spacing contribute to both the amount of heat transferred from an energy pile into surrounding soils, as well as the cross-sectional temperature/thermal axial stress distribution.

In an attempt to provide insight into geothermal energy pile behavior, the present study details the calibration, validation, and parameterization of a model followed by a discussion of results and concluding remarks. COMSOL Multi-physics software and high-performance computing (HPC) enabled the construction of the full-scale three-dimensional finite element model. The model was calibrated with respect to an experimental field investigation conducted at the United States Air Force Academy (USAFA) in Colorado Springs, CO.[5] Accordingly, all geometries within the model reflect full-scale, in-situ geometries of the experimental energy piles and surrounding soil strata. The full-scale model coupled conductive heat transfer and non-isothermal pipe flow physics to estimate temperatures at any time/location within the model. Calibration was performed by comparing these model temperatures to field temperatures. Following calibration, the model was parameterized to understand the roles of concrete cover, shank distance (defined as the downwards U loop Fig. 1), and pile spacing on heat transfer from energy piles into surrounding soils. The heat transfer performance of the energy pile group was evaluated and relationships between construction specifications and performance were quantified. These relationships verified the model and enabled the investigation of the cross-sectional temperature distribution within the energy pile. These results were used to examine the implications of strain gage location on in-situ thermal axial stress estimation. In summary, this study exhibits the variation of energy pile performance with respect to construction specifications and the evolution of cross-sectional temperature distribution. Additionally, the study demonstrates the strength and flexibility of the finite element based model and the capabilities of COMSOL coupled with HPC.

2. Background

Evaluating heat transfer between geothermal energy piles and surrounding soils remains a key area of research numerically[6–14] and in the field.[15–19,5,20,21] Field experiments performed by Hamada et al.[16] and Gao et al.[6] were designed to evaluate the most efficient heat exchanger layout within energy piles. With respect to thermo-mechanical processes, Bourne-Webb et al.[17] used an experimental pile embedded in London Clay to investigate energy pile behavior during cyclic heating. More recently, Murphy et al.[5] and Murphy and McCartney[4] detailed the thermo-mechanical response of in-situ energy piles in different soil profiles. The interest in energy pile behavior has motivated the development of energy pile design guidelines.

A state of practice paper by Bourne-Webb et al.[3] emphasized the current need for advanced finite element models in addition to field studies to improve existing design guidelines for geothermal energy piles. Existing energy pile design guidelines are contained within GSHPA,[22] however these guidelines focus on sizing and installation "best practices". In an attempt to move towards energy pile design guidelines that incorporate the thermally influenced pile–soil interface, Mimouni and Laloui[23] conducted a combined numerical–experimental study. The study demonstrated the dynamic loading, expansion/contraction, and associated friction mobilization inherent to energy piles. Another key numerical study relating to the design of energy piles was performed by Cecinato and Loveridge.[24] The study investigated the influences of design parameters on energy pile efficiency using an analytically-validated numerical model and parametric statistical methods. These methods enabled the quantified contribution of several key design parameters including pile length, number of heat exchangers, and concrete cover. Cecinato and Loveridge[24] expressed the importance of increasing the number of heat exchanger tubes to maximize efficiency. Different from the study of Cecinato and Loveridge,[24] this study incorporates full soil and foundation material calibration with the investigation of the role of design parameters on the cross-sectional temperature distribution for energy piles with W-shaped heat exchanger layouts.

Several other studies have focused on numerically and analytically modeling heat exchangers embedded within