Energy 161 (2018) 920–938

Contents lists available at ScienceDirect

Energy

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

Thermo-mechanical behavior of cast-in-place energy piles

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ARTICLE INFO

Article history:
Received 10 October 2017
Received in revised form
14 June 2018
Accepted 13 July 2018
Available online 17 July 2018

Keywords:
Thermal stress
Cast-in-place energy pile
Numerical analysis
Thermo-mechanical coupled analysis
Ground heat exchanger

ABSTRACT

An energy pile induces heat exchange with the ground formation by circulating heat carrier fluid through a heat exchange pipe, which is encased in pile foundation. During heat exchange, temperature variation in energy pile generates thermally-induced stress due to the different thermo-mechanical behavior between the pile and surrounding ground, and the restriction of pile deformation. A series of full-scale field tests was performed to identify the thermo-mechanical behavior of a cast-in-place energy pile equipped with 5-pair-parallel U-type heat exchange pipe. During the field investigation, each cooling and heating test lasted for 30 days, including a 15-day operating period and 15-day resting period, and the thermal stress generated in the energy pile was monitored. The maximum thermal stress was evaluated to be 2.6 MPa in the cooling test, which is about 10% of the design compressive strength of concrete. In addition, a finite element (FE) numerical model was developed to simulate the thermo-mechanical behavior of the energy pile. In the numerical analysis, relevant boundary conditions and interface model were determined by comparing with the field measurement. Finally, a parametric study was performed to estimate the thermal stress and deformation of a cast-in-place energy pile for various ground conditions.

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1. Introduction

Recently, numerous studies have been made to develop new and renewable energy systems in response to the global need for overcoming energy scarcity and resolving the problem of climate change. Geothermal energy is one of the new and renewable energy sources that can effectively address the issue of considerable energy consumption in heating and cooling of buildings. The Environmental Protection Agency (EPA) in the USA reported that a Ground Source Heat Pump (GSHP) system is the most energy-efficient and environment-friendly system with significant cost saving among the existing cooling and heating technologies [1]. The GSHP system can utilize the surrounding ground as a heat sink or heat source for cooling and heating buildings with the aid of the stable underground temperature throughout a year. A typical GSHP system mainly consists of a water-source heat pump unit coupled with ground heat exchangers (GHEXs) where heat exchange occurs between a working fluid circulating through the heat exchange pipe and the surrounding ground formation. Among various types of GHEXs, the closed-loop vertical GHEX is the most popular system in practice. Since the conventional closed-loop vertical GHEX should be separately constructed independent of the building structure, it requires additional borehole drilling and extra construction area, which causes a relatively high construction cost [2]. Recently, several studies have been actively carried out for developing new types of GHEX to resolve the problem of high investment cost in the GSHP system. An energy pile induces heat exchange via heat exchange pipes installed inside an existing pile foundation [3]. As a practical alternative to the conventional closed-loop vertical GHEXs, the energy pile plays a multirole of a structural foundation and a heat exchanger. Several construction cases can be found where energy piles have been adopted in large-scale public buildings [4]; [5]; [6]; [7]; [27].

Even though the energy pile plays a multifunctional role, the main purpose of a structural foundation is supporting the upper building structure. Considering that all construction materials contract or expand corresponding to temperature change, it is obvious that the long-term or cyclic heating and cooling operation has a great impact on the thermo-mechanical behavior of an energy pile, which may cause structural defects. The temperature variation in an energy pile generates thermally-induced stress (i.e., thermal

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https://doi.org/10.1016/j.energy.2018.07.079
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stress) due to different thermo-mechanical behavior between the pile and surrounding ground formation, and the boundary condition of the pile that restricts the deformation. During cooling operation, a temperature increase in the energy pile causes volume expansion, and vice versa during heating operation. If free expansion or contraction in an energy pile is restrained by the surrounding ground and overlying structure, longitudinal stress occurs consequently within the pile, which is transferred to the ground by the skin friction or end bearing [8]. Therefore, thorough consideration on the thermo-mechanical behavior of energy pile should be performed in a design stage [9].

However, recent works and researches have paid most attention to the thermal performance of energy pile system. Yang et al. [10] experimentally conducted parametric studies on the thermal performance of coil-type energy piles with various influential factors such as the inlet fluid temperature, coil pitch, operation mode and structure material. Park et al. [11]; [12] investigated the relative constructability and thermal performance of coil-type cast-in-place energy piles by conducting in-situ thermal response and thermal performance tests. In order to compare the efficiency of different types of energy piles and suggest the design specifications of energy piles, Gao et al. [13] conducted in-situ thermal performance tests and numerical analyses to obtain the average heat resistance and heat injection rate, which derived analytical solutions to more accurately interpret the result of thermal performance tests. Bandos et al. [14] proposed a mean integral solution to the finite cylindrical source model to evaluate the thermal performance of energy piles. The solution is able to consider the heat capacity inside the borehole, which is found to be more accurate than the solution with the mid-depth temperature. Zhang et al. [15] suggested a spiral source heat transfer model to simulate heat transfer mechanisms of ground heat exchangers with consideration of groundwater transfusion. The model can capture the heat conduction and convection of groundwater, and is more accurate than preceding models such as the solid cylindrical model and ring-coil model.

On the other hand, field experiments for thermo-mechanical behavior of energy piles were relatively insufficient. Laloui et al. [16] carried out a full-scale in-situ experiment to estimate structural loads on an energy pile. The diameter and length of the test pile were 0.88 m and 25.8 m, respectively, being equipped with a single U-type heat exchange pipe. The field experiment was performed with two load conditions, i.e., mechanical and thermal loads. The mechanical load was applied by dead weights during building construction, and the thermal load was induced by controlling inlet fluid temperature. Consequently, Laloui et al. [16] concluded that a temperature increment of 1 °C resulted in an additional vertical force with the order of 100 kN. Another field investigation was performed by Bourne-Webb et al. [17]; in which the test pile had 0.6 m diameter and installed to a depth of 23 m. A series of field tests was carried out along with a mechanical load of 1200 kN. Contrary to Laloui et al. [16] where only cooling operation was considered, Bourne-Webb et al. [17] evaluated the thermo-mechanical behavior of the energy pile under both heating and cooling operation. In addition, the thermo-mechanical response of the energy pile showed reversible behavior (i.e., thermo-elastic linear behavior) in both references. Based on the field test results, advanced numerical studies have been successfully carried out by developing thermo-hydro-mechanical (THM) models [18]; [19]; [20].

However, the preceding studies on the thermo-mechanical behavior of energy piles were mainly focused on PHC (pre-tensioned spun high strength concrete) energy piles. Large-diameter cast-in-place concrete piles have been recently emerging as a promising energy pile type because of the high thermal storage capacity of concrete and the large borehole volume that increases the contact area between the heat exchange pipe and surrounding medium, which may enhance heat exchange [7]; [11]; [12]; [27]. In addition, the effect of different thermal and mechanical properties of layered ground formations on the structural behavior of energy piles was not experimentally investigated yet.

In this paper, experimental and numerical analyses were carried out in order to identify the thermo-mechanical behavior of a large-diameter cast-in-place energy pile. First, a comprehensive field investigation for temperature and thermal stress variation was carried out during the cooling and heating operation of the large-diameter cast-in-place energy pile equipped with 5-pair-parallel U-type heat exchange pipe. Each cooling and heating operation lasted for 30 days, including the 15-day operating and 15-day resting period. During the field tests, thermal stress in the longitudinal direction was continually monitored. Second, a finite element (FE) numerical model was developed for simulating the thermo-mechanical behavior of energy pile. A non-linear contact modeling was adopted to represent the interaction between the pile and ground, and a thermo-structural coupled analysis was conducted to handle the thermo-mechanical problem. The numerical model was verified by comparing with the field measurement data. With the developed numerical model, a parametric study was performed to investigate the thermo-mechanical behavior of energy pile with various ground conditions. In the parametric study, thermal stress and displacement distribution in the energy pile were estimated corresponding to various Young's moduli of the surrounding ground, when other parametric values were identical to the field test conditions.

2. THERMO-MECHANICAL behavior of energy pile

During energy pile operation, heat exchange between the energy pile and surrounding ground leads to temperature redistribution, which induces thermal stress as a result of different thermo-mechanical behaviors of the pile material and the surrounding ground formation. Bourne-Webb et al. [17] described the relationship between the thermal loading and mechanical behavior of an energy pile as follows (i.e., Eqs. (1)–(4)). The strain in the energy pile in the unrestrained boundary condition can be expressed as Eq. (1).

$$\varepsilon_{free} = \alpha_c \cdot \Delta T \tag{1}$$

where ε_{free} is the strain of energy pile in the unrestrained condition, α_c (mm/mm/K) is the coefficient of thermal expansion, and ΔT (K) is the temperature change in the energy pile during cooling or heating operation.

The strain should be restrained by the adhesion or friction between the energy pile and the surrounding ground, and also by the end bearing at the pile tip when a bed rock formation exists. Therefore, the strain observed in the field test (ε_{obs}) should be less than or equal to the strain in the unrestrained condition (ε_{free}), i.e., $\varepsilon_{obs} \le \varepsilon_{free}$. Then, the strain observed in the field investigation can be expressed by subtracting the strain restrained by the surrounding ground formation ($\Delta\varepsilon_{res}$) from ε_{free} as represented in Eq. (2).

$$\varepsilon_{obs} = \varepsilon_{free} - \Delta\varepsilon_{res} \tag{2}$$

Finally, the thermal stress in the energy pile that is generated by the resistance of surrounding ground formation can be calculated by the general Hooke's Law as shown in Eq. (3) and Eq. (4).

$$\sigma_T = -E \cdot \Delta\varepsilon_{res} \tag{3}$$

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