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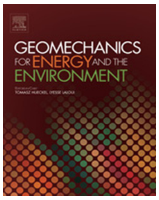

Investigation of potential dragdown/uplift effects on energy piles

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HIGHLIGHTS

- Axial strain data is reinterpreted from a pair of energy piles undergoing building heat pump operation over five years.
- A temporal dragdown effect is superimposed atop the thermal axial strains.
- The thermal and dragdown effects were isolated to evaluate axial stresses in the piles during heating and cooling.

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ABSTRACT

This study focuses on the interpretation of axial strains in a pair of full-scale energy piles beneath an 8-story building measured over the course of five years of geothermal heat pump operation. Although the cyclic temperature changes imposed upon the energy piles are consistent during each of the years of operation, the axial strains at different depths appear to show diverging trends. Evaluation of the profiles of thermal axial strain under different instances of extreme heating and cooling in each year of operation indicates that predominantly contractile strains are being superimposed atop the thermo-elastic expansion and contraction of the piles, especially near the toe of the piles. An evaluation of the trends in mobilized coefficient of thermal expansion during different heating and cooling cycles indicates that the superimposed contractile strains on the pile are not affecting the thermo-elastic expansion and contraction of the energy piles. Accordingly, the superimposed contractile strains were determined to be due to the effects of dragdown or uplift of the surrounding soil on the piles. The observed dragdown or uplift may be caused by thermal effects on the subsurface surrounding the piles or long-term mechanical compression of the subsurface under the applied building load, and deserve further study using more advanced analyses.

1. Introduction

Evaluation of instrumented energy piles in a field setting is the only way to fully consider the effects of installation, actual construction materials, subsurface stratigraphy, and restraints at the head and toe of the pile on the thermo-mechanical strains, stresses, and displacements induced by heating and cooling. Due to this fact, several field scale tests on instrumented energy piles have been performed that involved monotonic heating or cooling.[1–7] The details of these experiments have been summarized in detail by Olgun and McCartney.[8] Although very useful in interpreting soil–structure interaction phenomena in energy piles, one issue with monotonic heating or cooling tests is that time dependent effects that impact either the capacity of the energy pile such as setup or the stress distribution in the energy pile such as dragdown or uplift cannot be easily considered. These time-dependent effects are complex to analyze and predict even for conventional piles,[9–12] and may be more complex for energy piles in that temperature changes of the energy pile may affect the properties or cause volume changes of the surrounding subsurface,[13] lead to creep effects,[6] or cause ratcheting effects in heavily-loaded piles undergoing cyclic heating and cooling.[14–17] Although time-dependent effects can be assessed through long-term monitoring of embedded instrumentation in energy piles, fewer studies have been performed to assess the thermo-mechanical behavior of energy piles during long-term heating and cooling of energy piles associated with to operation of a geothermal heat pump used for building space conditioning.[18–20] This paper revisits the case history described by Murphy and McCartney[20] with

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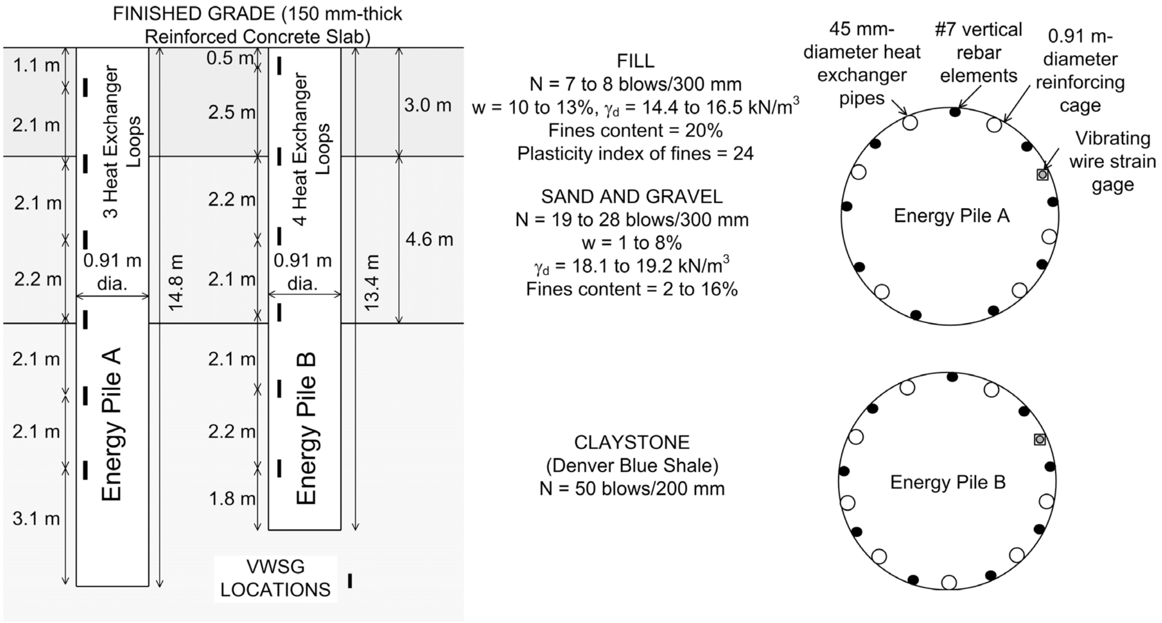

Fig. 1. Schematics of the energy piles including locations of instrumentation.

new instrumentation data to assess the potential effects of dragdown or uplift caused by thermal or mechanical effects on the interpretation of the thermo-mechanical behavior of two energy piles installed at the site.

2. Brief review of the case history details

McCartney and Murphy[19] and Murphy and McCartney[20] provide detailed information about two full-scale energy piles, referred to as Energy Pile A and Energy Pile B in this paper, constructed beneath an 8-story building in Denver, Colorado, USA. The site stratigraphy consists of urban fill atop a sandy gravel layer atop weathered claystone bedrock from the Denver Formation (locally referred to as Denver Blue Shale). The thicknesses of the soil layers along with measurements from in-situ site investigation tests are shown in Fig. 1. Energy Pile A was installed under an interior building column, and has a depth of 14.8 m and a diameter of 0.91 m, while Energy Pile B was installed under an exterior building wall, and has a depth of 13.4 m and a diameter of 0.91 m. Both energy piles serve as end-bearing elements in the claystone, and were designed to carry vertical loads of 3.84 and 3.65 MN, respectively. Each shaft contains a full-length reinforcing cage that is 0.76 m in diameter with nine #7 vertical reinforcing bars tied to #3 lateral reinforcing hoops spaced 0.36 m on center. A reinforced concrete slab-on-grade with a thickness of 150 mm was cast at grade level and connected to the energy piles to provide a stiff upper boundary condition, which is important for understanding the potential thermal restraint.[21] Energy Pile A includes three loops of polyethylene tubing having an inside diameter of 44 mm installed within the reinforcing cage, while Energy Pile B includes four loops of the same tubing. The energy piles were installed using a 10 m-long temporary casing through the urban fill and sandy gravel overburden and embedded into the claystone layer. Six concrete embedment vibrating wire strain gages (Model 52640299 from Slope Indicator of Mukilteo, WA) and co-located thermistors were incorporated into each energy pile at the depths shown in Fig. 1. The vibrating wire strain gages were oriented longitudinally parallel to the axis of the energy pile and were attached to the lateral reinforcing hoops. One of the vibrating wire strain gages at a depth of 3.2 m in Energy Pile A was damaged during installation, but all of the other sensors were functional over the duration of this project (including the thermistor at a depth of 3.2 m in Energy Pile A). Over the five years of monitoring, the different data acquisition systems malfunctioned for short intervals due to different issues, including battery power loss, programming issues, and memory issues. Nonetheless, sufficient data is available to understand the long-term behavior of the energy piles. More details of the site, the conventional geothermal system, and the drilled shaft installation process are provided in Refs. 19, 20.

3. Updated time series of temperature and strain

Time series of the temperatures of the heat exchanger fluids entering and exiting Energy Piles A and B are shown in Fig. 2. Although the focus of this paper is on the thermo-mechanical response of the energy pile, these fluid temperatures are an important boundary condition for the energy piles, with a temperature ranging from 7 to 37 °C based on the heating and cooling demands of the heat pumps in the building. A discussion on the heat transfer that can be estimated using the information in this figure can be found in Ref. 20, and no different conclusions on this topic are drawn in this study from the updated time series. The concrete temperature at different depths in Energy Piles A and B are shown in Fig. 3(a) and (b), respectively, and the corresponding changes in concrete temperature in Energy Piles A and B with respect to the initial condition corresponding to the start of heat pump operation are shown in Fig. 3(c) and (d), respectively. The energy pile temperatures follow the same trends as the heat exchanger fluids, and it can be observed that the changes in pile temperature are relatively constant with depth in the energy pile. The temperatures at the toe of the energy piles were not measured, although the heat exchanger tubing extended throughout the length of the reinforcing cages. The magnitude of the extreme changes in temperature during heating and cooling are approximately the same in each year of operation.

The thermal axial strains were calculated using the approach described in Ref. 20, with the initial temperature on December 29, 2011 used as the reference point for changes in pile temperature, and are shown in Fig. 3(e) and (f) for Energy Piles A and B, respectively. Because the strains in these figures were zeroed after all mechanical loading was applied (i.e., after the building was constructed and in operation), they should ideally only reflect the

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