Thermo-Mechanical Behavior of Energy Foundations

Comportement thermo-mécanique des pieux énergétiques

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ABSTRACT: This paper focuses on the impact of the upper boundary condition on the thermo-mechanical response of end-bearin g energy foundations during heating. To support this discussion, results from tests performed on a centrifuge-scale energy foundation and a full-scale energy foundation beneath an 8-story building in Denver, Colorado are compared. Although the soil profiles differ in both tests, the centrifuge-scale foundation involved heating during a load-controlled (free displacement) scenario, while the full-scale foundation involved heating during the constraint associated with a real building. The stress distribution in the centrifuge test showed greater stresses near the toe of the foundation than near the head of the foundation, while those in the full-scale foundation were closer to being uniform along the length of the foundation. The soil in the centrifuge-scale test was unsaturated, compacted silt with uniform strength, while the soil in the field included unsaturated urban fill with relatively low side shear resistance underlain by claystone. This indicates that the constraint of the reinforced grade beams within the building foundation led to the higher thermally-induced stresses within the full-scale energy foundation.

RÉSUMÉ : Cet article met l'accent sur le rôle de la condition imposée à la limite supérieure pour la réponse thermo-mécanique des pieux énergétiques travaillant en pointe pendant le chauffage. Pour cette étude, les résultats de tests effectués sur des systèmes de fondations en centrifugeuse et à échelle réelle pour un immeuble de 8 étages à Denver sont comparés. Les profils de sols diffèrent dans les deux essais : la fondation utilisée dans la centrifugeuse nécessite de chauffer sous chargement contrôlé avec déplacement libre, tandis que la fondation à échelle réelle implique un chauffage sous la contrainte associée au bâtiment réel. La distribution des contraintes dans le test de centrifugation a montré des contraintes plus fortes à la base de la fondation que près de la tête du pieu, tandis que ceux de la fondation à grande échelle étaient plus uniformes sur toute la longueur de la fondation. Le sol de l'essai en centrifugeuse était saturé et constitué de limon compacté avec une résistance uniforme, tandis que le sol in situ était un remblai urbain de faible résistance au cisaillement surmontant une couche d'argilite. Ceci indique qu'il est nécessaire de prendre en compte les contraintes induites thermiquement dans les pieux énergétiques.

KEYWORDS:Energy foundations, soil-structure interaction, centrifuge physical modeling.

1 INTRODUCTION

Energy foundations are drilled shafts that incorporate ground-source heat exchange elements, which can be used to transfer heat to or from the ground to a building (Brandl 2006; Laloui et al. 2006; McCartney 2011). Ground-source heat exchange (GSHE) systems exploit the relatively constant temperature of the ground to improve the efficiency of heat pump systems for heating and cooling of buildings. Traditional GSHE systems typically require a network of boreholes installed outside of the building footprint, which can be cost-prohibitive (Hughes 2008). To counter this problem, heat exchange elements can be incorporated into deep foundation elements during construction to minimize GSHE installation cost. Although energy foundations may not provide all the energy required to heat and cool residential or commercial buildings, they may provide sufficient heat exchange to supplement a conventional system for little extra cost.Studies on full-scale foundations have established the efficiency of heat extraction and thermal properties of energy foundations (Ooka et al. 2007; Wood et al. 2009; Adam and Markiewicz 2009; Ozudogru et al. 2012).

Although important information has been collected regarding the thermo-mechanical behavior of energy foundations during heating and cooling, there are still questions to be answered. Several experimental studies have been performed in the laboratory using centrifuge-scale models of energy foundations which identified mechanisms of soil-structure interaction in energy foundations (McCartney et al. 2010; McCartney and Rosenberg 2011; Stewart and McCartney 2012). Further, several full-scale energy foundations have been installed throughout Europe and Asia, including two well-documented thermo-mechanical tests on full-scale foundations published to date; in Switzerland (Laloui et al. 2006), and in the UK (Bourne-Webb et al. 2009; Amatya et al. 2012). In these studies, proof load tests along with heating/cooling tests were used to evaluate the thermo-mechanical stress-strain response in the foundations. Data from these tests were used to develop soil-structure interaction design tools (Knellwolf et al. 2011). This paper addresses an important topic identified by Knellwolf et al. (2011), specifically the impact of the head boundary conditions on the distribution in thermally-induced axial stresses in energy foundations. This topic is investigated by comparing strain gauge data from two energy foundations having different head constraints (load-control and actual building constraint).

2 BACKGROUND

As a structural element is heated and cooled, thermally induced axial strains are superimposed onto already present mechanical strains. Thermal strains are induced in energy foundations due to thermoelasticity, although a combination of end bearing, side shear resistance, and head stiffness may provide constraint to the foundation, leading to the development of thermally induced stresses. A load transfer analysis may be used to represent these different features. A schematic of a load transfer analysis developed by Plaseied (2012) based on the work of Knellwolf et al. 2011) is shown in Figure 1. Different from a mechanical load transfer analysis, a spring at the head of the foundation is used to represent the constraint of a foundation by the overlying building and grade beams. During heating, the foundation will expand about a null point, the location of which depends on the distribution of side shear values (K_s) and the magnitude of the end stiffness (K_{base}) and head stiffness (K_h). An iterative approach can be used to ensure equilibrium between forces Q and compatibility between displacements ρ.

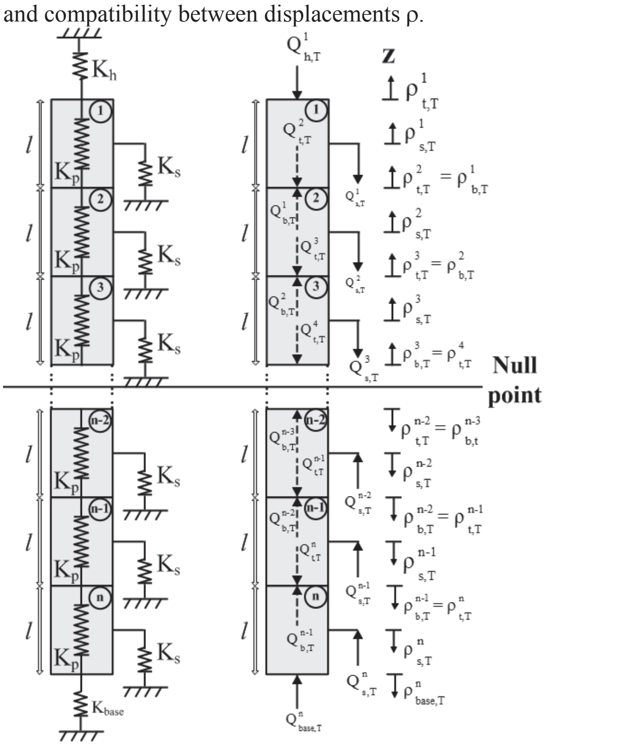

Figure 1. Thermo-mechanical load-transfer analysis (Plaseied 2012)

If strain gauges are used to monitor strains in the foundations, the thermal axial strains within a foundation can be obtained by subtracting the mechanical strains occurring due to an applied load (i.e., the weight of a building). Depending on the type of strain gauge, different thermal correction factors may need to be applied (McCartney and Murphy 2012; McCartney and Stewart 2012). The thermal axial stresses at any point in the foundation σ_T can be defined as follows:

$$\sigma_T = E(\varepsilon_T - \alpha_c \Delta T) \quad (1)$$

where E is the Young's modulus of reinforced concrete, ε_T is the measured thermalaxial strain, α_c is the coefficient of thermal expansion of reinforced concrete, and ΔT is the change in temperature. The value of $\alpha_c\Delta T$ represents the maximum axial strain possible in the energy foundationfor unrestrained conditions, and is negative (expansive) during heating.

3 FOUNDATION CASE STUDIES

3.1 *Centrifuge-Scale Energy Foundation*

The centrifuge-scale energy foundation evaluated in this study has a length of 533.4 mm and a diameter of 25 mm, and was installed in the center of a cylindrical container filled with a layer of unsaturated Bonny silt. The base of the foundation rests on the base of the container, providing a zero-displacement or end-bearing bottom boundary condition. The centrifuge test was performed at acentrifugal acceleration of 24, so the model-scale foundation is intended to represent a prototype-scale foundation having a length of 12.8 meters and a diameter of 1.2 meters. Although it is understood that heat flow cannot be scaled in a similar manner to geometry, stresses and strains, the thermally-induced stresses and strains are governed by the restraint provided by the surrounding soil, which depends on the stress state. Accordingly, it is expected that the thermally-induced stresses and strains will scale in a similar manner to mechanical stresses and strains. Accordingly, centrifuge tests involved maintaining the foundation at a constant temperature and waiting for thermally induced stresses and strains to stabilize.

The model energy foundation was precast outside of the soil layer due to the large amount of instrumentation, cables, and heat exchanger tubing within the assembly. This also permits the foundation to be tested outside of the soil layer to characterize their thermal and mechanical properties. The reinforcing cage for the model foundationwas constructed from a hoop of reinforced wire mesh. A cardboard tube having an inside diameter of 50.8 mm was used as a form for the foundation, permitting a concrete cover of 5 mm on the sides and 12.7 mm on the top and bottom. A total of three heat exchanger loops (3 inlets and 3 outlets) was installed in the foundation so that the distribution of heat across its circumference would be as uniform as possible. Embedded strain gauges and thermocouples were attached to the reinforcement cage of the model foundation at the locations shown in Figure 2. Linearly-variable deformation transformers were used to measure the axial displacement of the foundation and the soil surface. The distribution in temperature was measured using thermocouple profile probes and dielectric sensors (also used to monitor changes in volumetric water content of the soil). Additional details of the instrumentation are presented by McCartney and Stewart (2012).

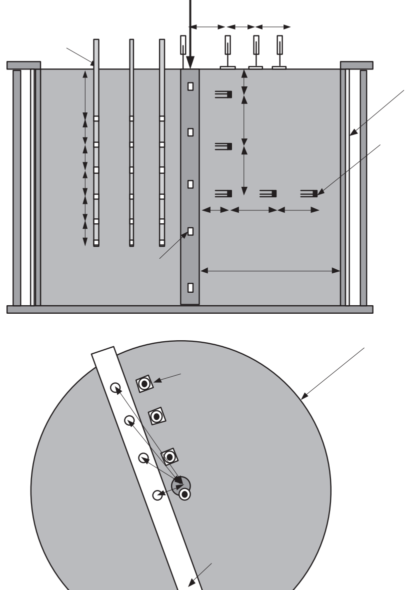

Figure 2.Schematics of the centrifuge-scale energy foundation test

A comprehensive set of characterization tests were performed on the pre-cast drilled shaft outside of the soil in a load frame at 1-gravity to determine the mechanical and thermal properties of the reinforced concrete. These results from these tests are reported in detail by Stewart (2012). The first test involved application of incremental axial loads under room temperature conditions, taking care to properly level the foundation and center the load to avoid bending. The mechanical strains encountered during application of an axial load of 700 kPa were variable. The Young's modulus determined using the corrected strain data was 7.17 GPa. The foundation was then heated to a temperature of 62 °C by circulating fluid through the heat exchange tubes within the foundation while maintaining a constant axial stress of 439 kPa. The foundation was permitted to freely expand under this axial stress, permitting definition of the coefficient of linear thermal expansion of the foundation (α_c = -7.5 με/°C, where με is micro-strain, with compressive strain defined as positive).

Heating tests were performed on the energy foundation in the layer of Bonny silt (USCS classification of ML) compacted at a gravimetric water content of 14% to a dry density of 1451 kg/m^3. An axial stress of 384 kPa was applied to the head of the foundation using a feedback-controlled electric motor. This motor permits the load to be maintained constant but permits free displacement. This implies that the value of K_h for the centrifuge-scale foundation should be close to zero. A heat pump, operated outside the centrifuge, was used to control the temperature of the fluid being circulated through the scale-model foundations. Details of the heat control system are provided by Stewart (2012).

3.2 *Full-Scale Energy Foundations*

Two drilled shaft foundations installed as part of the new Denver Housing Authority senior residential facilitywere converted into energy foundations. The energy foundations were coupled into a conventional GSHE system which was already being incorporated into the building. This paper focuses on the results of one of the drilled shafts,having a length of 14.8 meters and a diameter of 0.91 meters, that includes 3 heat exchanger loops. The shaft consists of a full-length reinforcing cage with nine #7 vertical reinforcing bars tied to #3 lateral reinforcing hoops spaced 0.36 meters on center. A schematic of the drilled shaft within the soil profile is shown in Figure 3. The drilled shaft functioned as rock-socketed, end-bearing elements in bedrock, with an expected load of 3.84 MN.The grade beams attached to the top of the foundation likely provided a non-zero stiffness to the head of the foundation (K_h> 0).

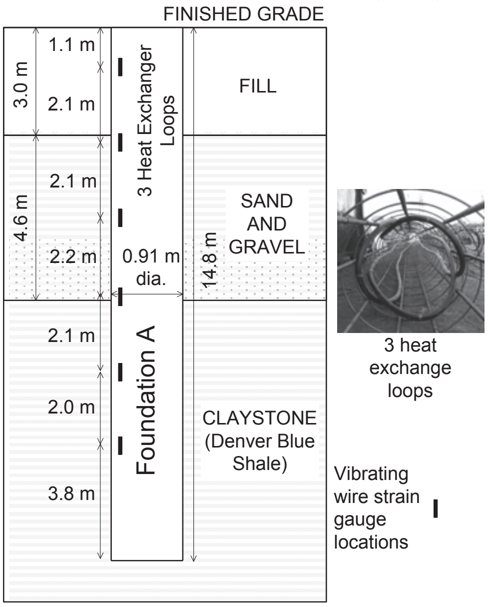

Figure 3.Soil stratigraphy and layout of foundation instrumentation

At the site, urban fill extends from grade to a depth of approximately 3 meters and consists of slightly moist, medium dense, clayey sand with gravel. Beneath the fill, non-expansive, medium dense, silty, sand and gravel extended to a depth of approximately 7.6 meters below grade. Following the sands and gravels, the subsurface conditions consisted of hard sandy claystone bedrock from the Denver formation. Because of the potential for caving during drilling through the overburden and possible perched ground water conditions, a cased-hole method was chosen for installation of the drilled shaft foundations at the site. Groundwater was observed near the depth of the claystone.

The heat exchanger system in the energy foundation consists of 44 mm-diameter polyethylene tubing attached to the inside of the reinforcing cages. The drilled shaft contains a total of 82.3 linear meters of tubing configured into three loops running the length of the reinforcing cage. The heat exchanger tubing was routed along the inside perimeter of the reinforcing cage to avoid crossing the diameter of the cage, which could block concrete flow or cause segregation of concrete. Equal angular spacing of the tubing was maintained to ensure relatively uniform temperature along the circumference of the shafts. Six vibrating wire concrete-embedment strain gauges with attached thermistors were incorporated into the foundation to monitor temperature and axial strain distributions with depth, although one gauge was damaged. The supply and return temperatures of the heat exchanger fluid were also monitored. More information is provided by McCartney and Murphy (2012).

4 STRAIN DISTRIBUTIONS

4.1 *Centrifuge-Scale Energy Foundations*

The axial thermal strain distributions in the centrifuge-scale energy foundation after heating to different changes in temperature above the ambient temperature of 20 °C are shown in Figure 4(a). Heating leads to a relatively uniform increase in negative axial strain throughout the foundation, indicating thermal expansion. The smallest strains are located near the toe of the foundation, which is as expected due to the rigid end restraint. The axial strains at the very top of the foundation represent the thermal strain for free expansion of the foundation ($\alpha_c\Delta T$). The measured strains are consistent with these theoretical values, and confirm that the top of the foundation can expand freely. An upward displacement in prototype scale of 1 mm was observed. The thermal axial stresses were calculated from the thermal strains using Equation 1. The location of minimum strain (and maximum stress) reflects the null point for the foundation, which is approximately at the bottom of the foundation. The trend in stress approaches zero at the top of the foundation, supporting the conclusion that K_h = 0.

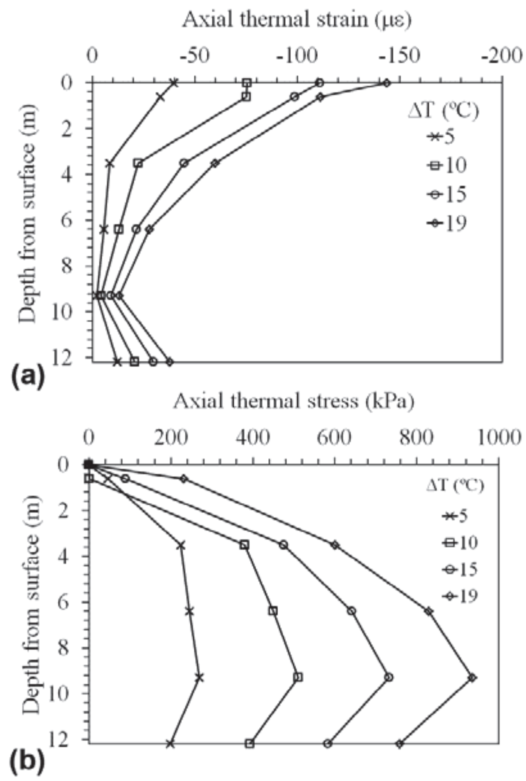

Figure 4. Centrifuge results: (a) Axial strains; (b) Axial stresses

4.2 *Full-Scale Energy Foundations*

During operation of the heat pump between March and May 2012, the temperature of the foundation was relatively uniform, and involved both heating and cooling. The strains induced in the foundation during different average changes in foundation temperature are shown in Figure 5(a). Similar to the centrifuge-scale foundation, the greatest strains were noted near the top of the foundation, resulting from the end-bearing boundary conditions at the toe. It was not possible to measure the displacement at the top of the foundation, but integration of the strains indicates that an upward displacement of approximately 0.18 mm occurred during a change in temperature of 3°C. Although the strain at the top of the foundation during heating is close to that expected for free expansion, this is not the case during cooling, where the strains are about 50% of free expansion conditions. During cooling of the foundation (heating of the building), the smaller axial strains are possibly due to the reinforcement connection to the grade beams at the ground surface. This indicates that K_h may be different for heating and cooling. The thermal axial stresses calculated using Equation 1 are shown in Figure 5(b). The coefficient of thermal expansion for the reinforced concrete was not measured, but is assumed to be -10 με/°C for the concrete mix design used in Colorado (Quartz aggregate with high slump). Similar to the centrifuge-scale energy foundation, the maximum stress is located near the toe of the foundation. In contrast to the results in Figure 4(b), the trend of the axial stresses indicates that the stresses do not tend toward zero at the top of the foundation. Based on the magnitude of stresses during heating, it is possible that the value of $K_h$is approximately half the stiffness of the end bearing spring at the toe of the foundation.

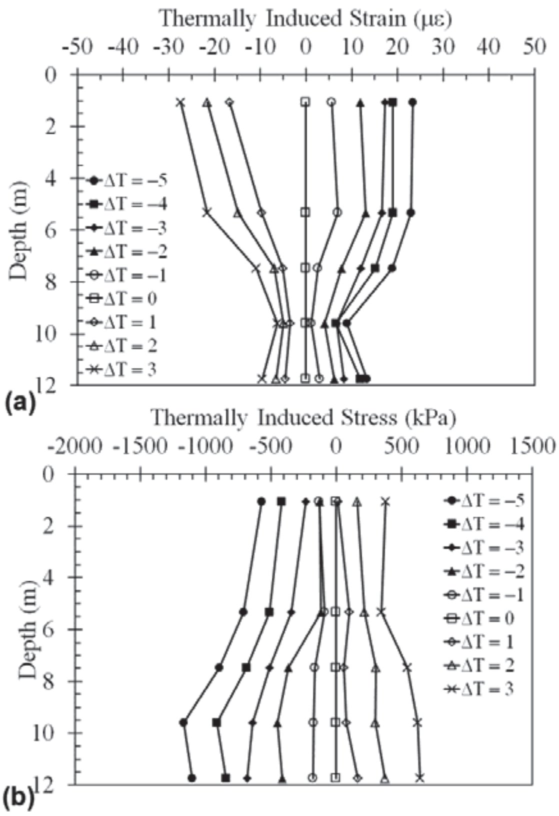

Figure 5.Full-scale results: (a) Axial strains; (b) Axial stresses

5 CONCLUSIONS

The results presented in this study indicate that the head boundary conditions of energy foundations have an important effect on the magnitude and shape of stress distributions in energy foundations. The results from an end-bearing centrifuge-scale foudation heated in load-controlled conditions indicate a similar shape to the thermal stress distribution but with negligible stresses at the head of the foundation. The results from a full-scale, end-bearing energy foundations during typical operation of a building in Denver, Colorado indicate that the thermal stresses are the greatest near the toe of the foundation, although the stresses near the head of the foundation are non-zero. The results indicate that even though a building applies a constant load to an energy foundation, the grade beam connections provide constraint to the head of an energy foundation, potentially with different magnitudes depending on whether the foundation is being heated or cooled.This is a subject of continued research being evaluated through further comparison of centrifuge- and field-scale foundations.

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