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Evaluation of Head Restraint Effects on Energy Foundations

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ABSTRACT: This paper presents an evaluation of the impact of head restraint on the thermo-mechanical response of centrifuge-scale energy foundations. Specifically, the head movement and axial strain response of an end-bearing energy foundation installed in a dry sand layer was evaluated during thermal response tests with both load-control and stiffness-control head restraint conditions. During the thermal response test, an axial load is applied to the head of the foundation in either load- or stiffness-control after spin-up of the centrifuge, then heated fluid with a controlled temperature is circulated through heat exchanger tubing embedded in the foundation. In both tests, the foundation was heated from a temperature of 23 to 33 °C then was maintained until foundation head displacements and axial strains had stabilized. The test performed under stiffness-control conditions was found to expand by a slightly lower amount, and had lower axial strains and higher axial stresses near the ground surface. The axial strain distributions lower in the two foundations were similar.

INTRODUCTION

Although incorporation of heat exchangers into deep foundation elements (energy foundations) helps reduce the installation costs of ground-source heat exchange systems (Brandl 1998; Ennigkeit and Katzenbach 2001; Brandl 2006), an issue encountered is the potential for foundation movements due to thermal expansion and contraction of the foundation element or surrounding soil. Further, soil-structure interaction may restrain movement of the foundation, leading to generation of thermally induced stresses. This behavior has been documented in several field-scale case histories (Laloui et al. 2006; Bourne-Webb et al. 2009; Amatya et al. 2012; McCartney and Murphy 2012). Although thermo-mechanical soil-structure interaction analyses permit prediction of changes in axial stress or strain during heating and cooling operations (Knellwolf et al. 2011; Plaseied 2011), they require empirical data for calibration of model parameters and verification of predictions.

In these analyses, a variable of particular interest is the stiffness of the spring at the top of the foundation that represents the restraint to thermal displacements imposed by the overlying superstructure. Although the stiffness of the spring attached to the head of the foundation can be estimated through back-analysis, there have not been

studies that focused on the measurement of this variable or evaluated its effect in a controlled environment. Characterization of this variable is important for the development of methodologies for energy foundation design. For example, the design methodology proposed by Burlon et al. (2013) uses the stiffness of the head restraint to characterize the maximum thermal stresses in an energy foundation. Accordingly, the objective of this study is to understand the role of the head stiffness of an end-bearing energy foundation under the same testing conditions. The approach used in this study was to perform a thermal response test on a centrifuge-scale end-bearing foundation first in load-control conditions, then in stiffness-control (restrained head movement) conditions and to measure changes in axial strain and head displacement.

MATERIALS

Model Scale Foundation

A scale-model energy foundation was fabricated to study the impact of mechanical loading and heating on the internal strain distribution in energy foundations. The foundation has a diameter of 63.5 mm, and a length of 533.4 mm. A centrifuge acceleration of 24g was used so that the prototype-scale foundation would have a length of 12.8 m and a diameter of 1.5 m. The foundation is tested in a soil layer having a thickness of 533.4 mm. Although drilled shafts are typically cast-in-place, the model foundation was precast in a cardboard mold to ensure quality construction considering the fact that extensive embedded instrumentation was to be incorporated. The foundation has a larger diameter than that of Stewart (2012) to provide more space around embedded instrumentation. Further, the larger diameter permitted a larger fraction and size of coarse aggregates to be incorporated into the concrete mix design. This led to a Young's modulus of reinforced concrete that was closer to that of drilled shaft foundations in the field than obtained by Stewart (2012). The mechanical and thermal properties of the precast foundation were also characterized outside of the centrifuge. The details of the calibration are described in detail by Goode (2013).

The reinforcing cage was formed from welded steel hardware cloth that simulates the longitudinal and lateral members of a steel reinforcing cage. The cage has 12.7 mm-square openings, with 19 gage wire thickness. The cage diameter is 48.5 mm with 7.5 mm of concrete cover on the sides. The cage has 6.35 mm of concrete cover on the top and bottom. A schematic of the foundation is shown in Figure 1. Seven strain gages and thermocouples were embedded within the foundation to characterize the strain response and temperature distribution within the foundation. The strain gages were model CEA-13-250UW-350 from Vishay Precision Group, and were bonded using M-Bond AE-15 to 50.8 mm-long, 12.7 mm-wide steel plates. The plates have two 6.1 mm-diameter holes at top and bottom to provide good contact with the concrete. The zinc plating on the steel was sanded off to provide a smooth steel surface. M-Bond AE-15 was used as the bonding agent due to its ability to withstand cyclic temperatures. The bonded gages were cured under pressure for 4 hours at 57.2 °C. A Teflon strip was placed over the cured gage, which was then covered

using a waterproof epoxy (Gagekote #5). Miniature thermocouples (Omega fine wire Type K Model STC TT K 36 3C) were attached to the steel plates next to the strain gages. Heating tests under a constant tensile stress were performed on the gage-steel assembly to define the coefficient of thermal expansion of the steel, which was found to be $\alpha_{\text{steel}} = -13.2 \mu\epsilon/^{\circ}\text{C}$, and to define calibration parameters for the strain gages. The finished strain gages were then attached to the inside of the reinforcing cage using thin wire thread. The placement of the gages is also shown in Figure 1.

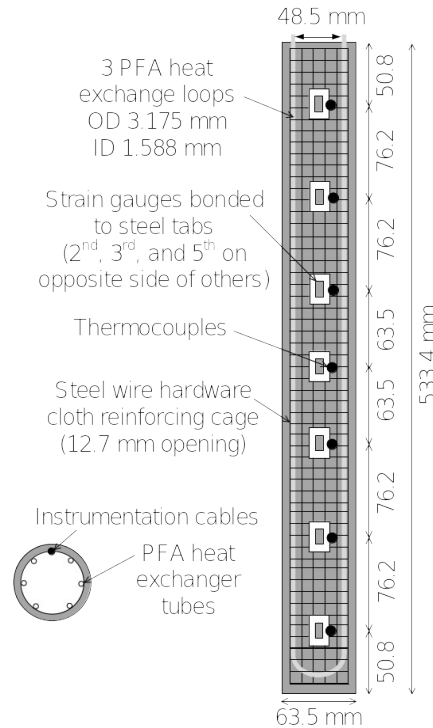


FIG. 1. Cross section of the model-scale energy foundation

Three heat exchanger loops were affixed to the reinforcement cage. The loops were equally spaced around the circumference of the cage and affixed to the cage with small cable stays. Perfluoroalkoxy (PFA) tubing with a 3.175 mm-inside diameter was used for the heat exchange loops, with the bottom loops held tight to the cage in order to avoid loops crossing the bottom of the cage.

A cardboard tube with a 63.5 mm inside diameter was used as the form for the concrete. The cage was centered in the form, and concrete having a 1:2:1.5:1.5 water:cement:sand:coarse aggregate mixture was poured into the form using a miniature tremie pipe. This approach prevented damage of strain gages during concrete placement and ensured that the concrete was reaching the bottom of the form. Concrete placement was performed on a large vibrating table to guarantee the concrete was flowing to all areas of the form as well as extruding entrapped air. When the concrete had reached the top of the form, a set screw was placed in the middle of the foundation to provide a good centering point for mechanical loading of the foundation. The foundations were cured in a fog room for 14 days, after which 14 more days of curing were permitted after removing the form. The calibration tests

reported by Goode (2013) indicate that the coefficient of thermal expansion of the reinforced concrete foundation is $\alpha_c = -15.0 \mu\epsilon/^\circ\text{C}$ and the Young's modulus was 33 GPa. These parameters are useful to convert the thermal axial strain to thermal axial stress (McCartney and Murphy 2012).

Soil

The soil used in this study is dry Nevada sand having a relative density of 60% (void ratio of 0.75). This soil was selected as its shear strength will increase with depth, in contrast to the uniform shear strength with depth of the compacted silt used by Stewart (2012). The sand consists of uniform angular particles, with characteristic grain size values of $D_{10} = 0.085$ mm, $D_{30} = 0.110$ mm, and $D_{60} = 0.160$ mm. The sand has a friction angle of 35° , a shear modulus of 30 MPa, and a Poisson's ratio of 0.3 at this relative density and a mean stress 100 kPa. The thermal conductivity measured using a KD2Pro thermal needle was found to be 0.25 W/mK.

EXPERIMENTAL SETUP

Two loading systems were fabricated to evaluate the effect of both load and stiffness control conditions on an end bearing foundation. In load control conditions, loads were applied to the foundation using a pneumatic Bellofram loading piston mounted to a reaction frame above the container, as shown in Figure 2(a). The compressed air line connected to a regulator in the laboratory was connected to the slip-ring stack, the passed to the end of the centrifuge basket where it was attached to the loading piston. The piston rod extended through the reaction frame to a coupler which was then attached to an 8896 N Futek LSB 350 S-type load cell. A double-threaded stud was then attached to the load cell, and an acorn nut was attached to the bottom of the stud to apply point loads. Displacements were measured using linearly variable differential transformers (LVDT) mounted on a rack connected to the top of the container. The stiffness-control setup involved replacing the pneumatic piston with a threaded rod connected to the loading frame, as shown in Figure 2(b). Loads are applied in this setup by tightening nuts to put the rod and load cell under compression, so loads had to be applied initially at 1-g. Besides this, the setup was the same as in the load-control test. Pictures of the loading apparatus in both load-control and stiffness-control modes are shown in Figures 3(a) and 3(b), respectively.

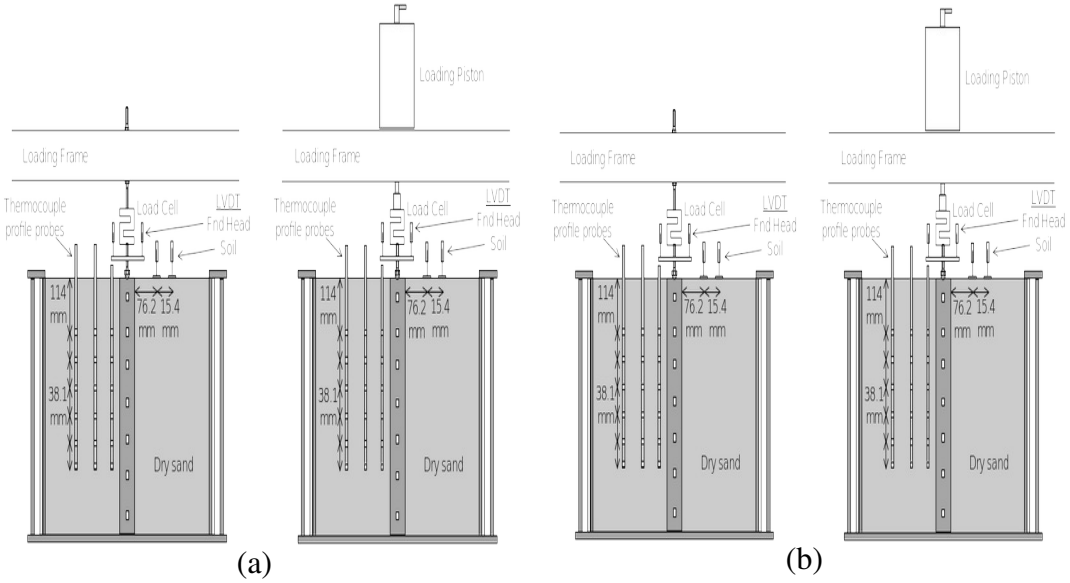


FIG. 2. Testing container schematics: (a) Load control; (b) Stiffness control



FIG. 3. Top end constraint loading setup: (a) Load control; (b) Stiffness control

PROCEDURES

The two separate sets of procedures were developed to evaluate the thermo-mechanical response of the same foundation in the same soil profile in either load-control or stiffness control conditions. The same setup was used for both tests as elastic, small displacements were expected, and dry sand is not expected to have thermo-plastic behavior. For the load-controlled test, after achieving the target g-level and all sensors stabilized, a model-scale 2200 N load was applied to the foundation head. After the load stabilized, the foundation was heated to an average temperature of 33 °C. After finishing the load-control test, the pneumatic piston was removed and the stiffness setup was installed. In stiffness-control conditions the load was applied prior to centrifugation by tightening the bolts on the threaded rod connected to the loading frame. Although efforts were made to apply the same axial load as the load-control test, this was difficult as the foundation compresses during centrifugation leading to a drop-off in load. After several iterations, an initial load of

2350 N was applied to the foundation. Once deformations stabilized, the foundation was heated to 33 °C. The ideal testing procedure for the applied load at the foundation head and the foundation temperature with time in either test is presented in Figure 4.

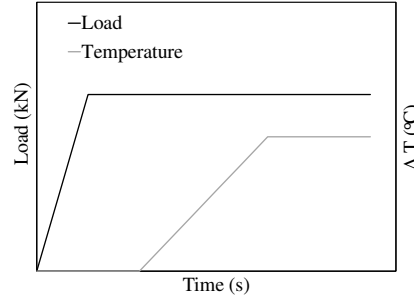


FIG. 4. Idealized procedure for applying axial load and foundation temperature

RESULTS

Time series of temperature and axial load from the two tests are shown in Figure 5. The heating rate differed slightly for the two tests, although the foundation reached approximately the same final temperature. As expected, the load-control test had a constant load during the test, while the stiffness-control test showed an increase in load with increasing foundation temperature. Initial prototype-scale axial loads of approximately 1270 to 1350 kN were applied to the foundation (axial stress of 690 to 740 kPa) in the two tests, which are in the range of expected building dead loads.

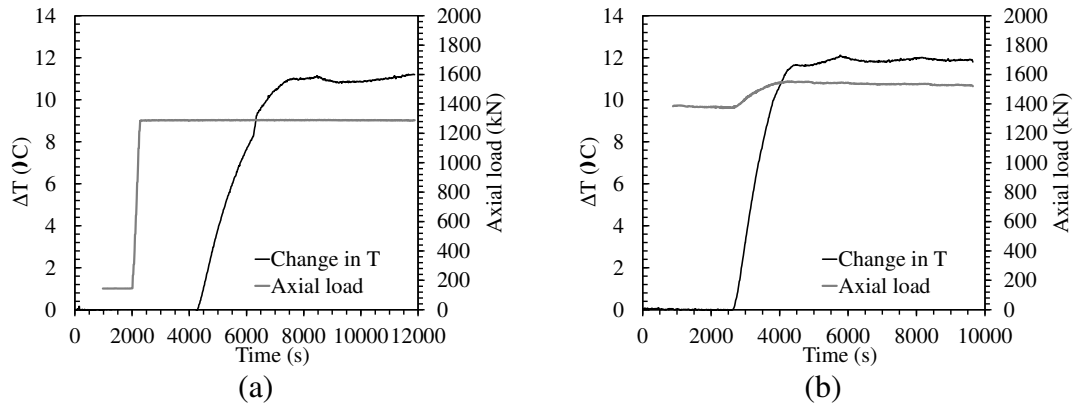


Fig. 5. Time series of axial load and foundation temperature (prototype-scale): (a) Load-control test; (b) Stiffness-control test

The time series of foundation head settlement and axial load for both tests are shown in Figures 6(a) and 6(b). The total settlement was obtained by zeroing the average reading of the two LVDTs on the head of the foundation at the end of spin-up of the centrifuge. A distinct downward settlement is observed in Figure 6(a) after application of the mechanical load. As the mechanical load was applied before spin up of the centrifuge for the stiffness-control test, no mechanical settlements are noted

in Figure 6(b). Further, the thermal settlement due to heating is also shown in these figures, obtained by zeroing the settlement at the beginning of heating. As the foundation is heated, the head of the foundation was observed to expand upwards (negative settlement values) in both tests. In the case of the stiffness-control test, the thermal expansion of the foundation was observed correspond with the increase in axial load, indicating that the load cell acts as a spring with a constant stiffness.

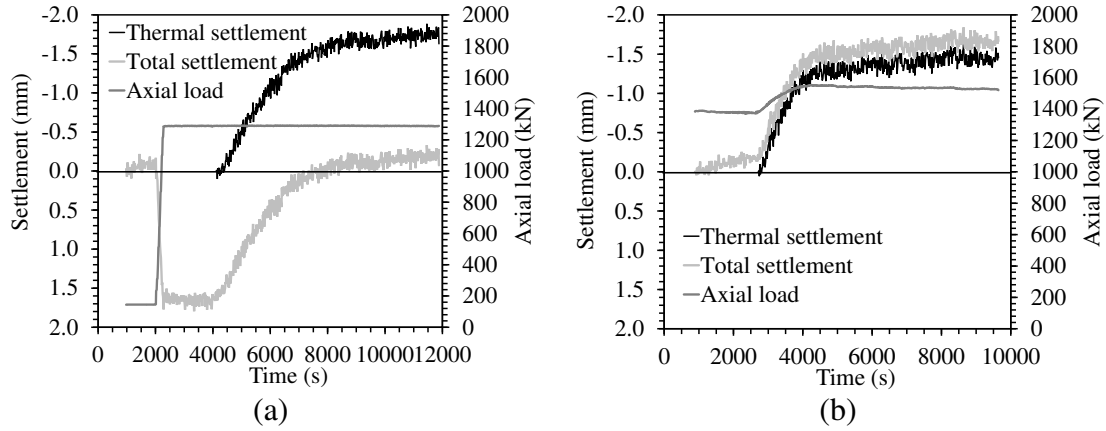


Fig. 6. Axial load and foundation head displacement (prototype-scale): (a) Load-control test; (b) Stiffness-control test

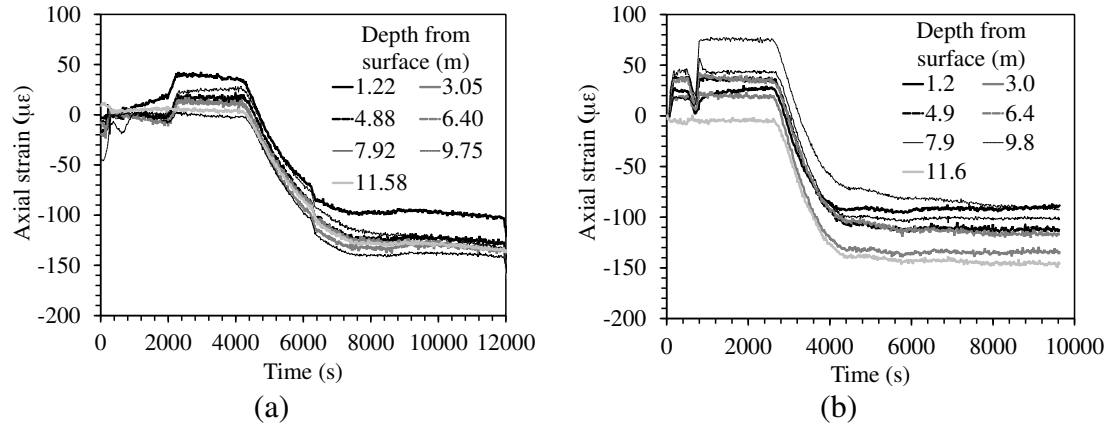


Fig. 7. Axial strain time series: (a) Load-control test; (b) Stiffness-control test

ANALYSIS

Several instances throughout the duration of the test that correspond to a different average change in temperature ΔT_{ave} were selected for plotting profiles of different variables. Profiles of actual temperature in both foundations for different average changes in temperature are shown in Figures 8(a) and 8(b). Because both end-bearing foundations are touching the bottom of the container, the temperature at the base of the foundations is slightly lower than the rest of the foundation. Also, the top of the foundation was slightly cooler due to interaction with the air above the soil surface.

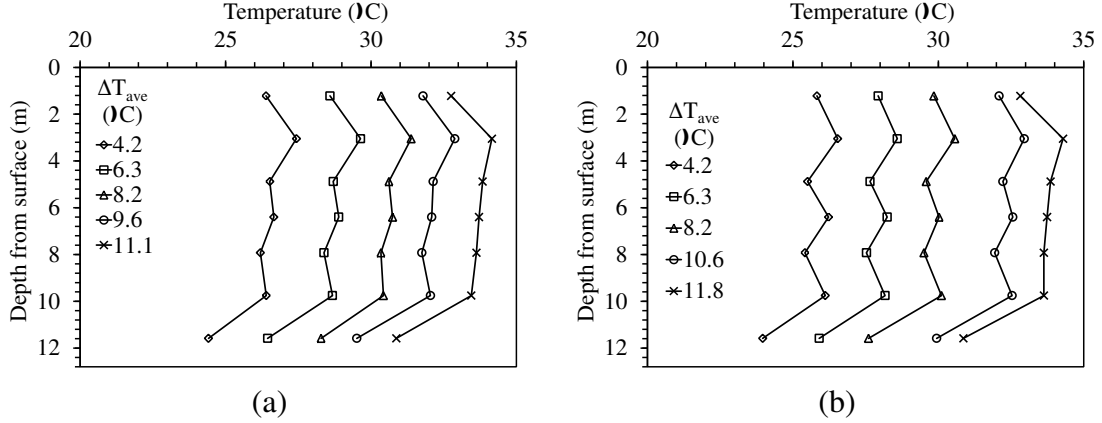


Fig. 8. Temperature profiles: (a) Load-control test; (b) Stiffness-control test

The thermal axial strain values were defined by zeroing the axial strains shown in Figure 7 at the beginning of heating. The profiles of thermal axial strain corresponding to the same average changes in temperature in Figure 8 are shown in Figure 9. In both cases the thermal axial strain is relatively constant with depth except near the top and bottom of the foundation. The foundation in load-control conditions should be able to expand freely at the top, so the thermal axial strains at a depth of zero in Figure 9(a) correspond to the theoretical free expansion strains calculated using $\varepsilon_{T,free} = \alpha_c \Delta T$, where $\alpha_c = -15 \mu\epsilon/^\circ\text{C}$.

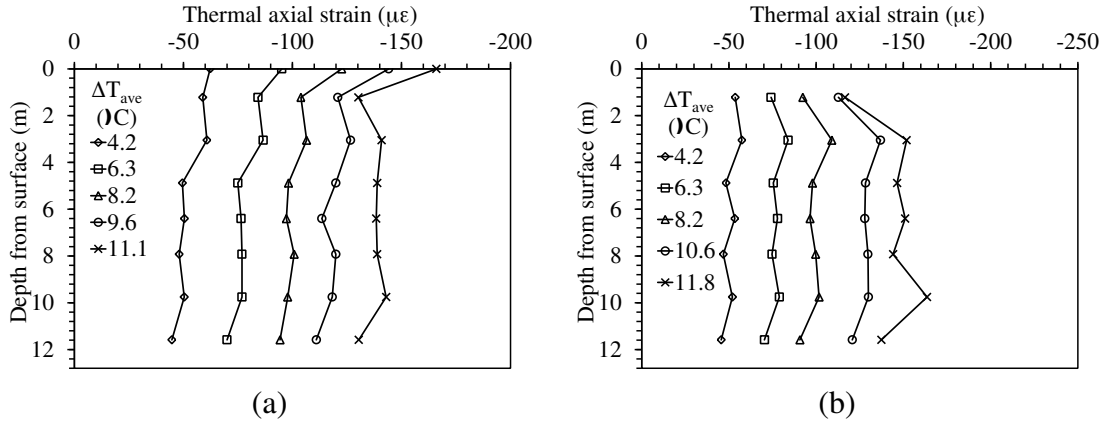


Fig. 9. Thermal strain profiles: (a) Load-control test; (b) Stiffness-control test

The thermal axial stresses were calculated from the measured thermal axial strains ε_T from Figure 9, as follows:

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

where E is the Young's modulus of reinforced concrete, α_c is the coefficient of linear thermal expansion for the reinforced concrete foundation, and ΔT is the change in temperature of the foundation at the location of the strain measurement. The thermal axial stresses in both foundations are shown in Figure 10. By definition, the thermal axial stress at the head of the foundation in load-control conditions is zero. The thermal stresses were greater in the foundation during the stiffness-control test,

especially near the top of the foundation. The thermal stresses at the bottom of the foundation were expected to be the greatest, but the actual change in temperature at this depth was lower than in the rest of the foundation (Fig. 8), contributing to the lower stress values calculated.

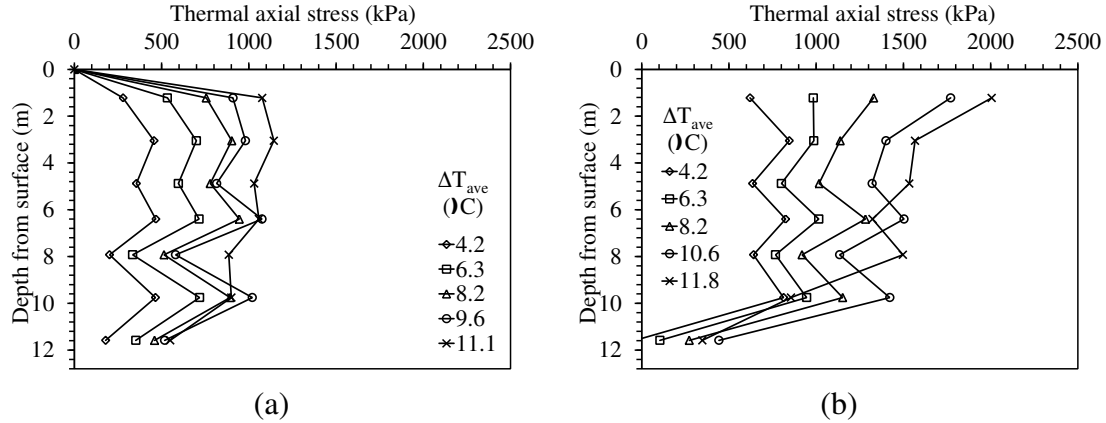


Fig. 10. Thermal stresses: (a) Load-control test; (b) Stiffness-control test

The thermal axial displacements as a function of depth were calculated by assuming that the toe of the foundation was not able to move due to the end-bearing boundary condition (i.e., the location of the null point is at the bottom of the foundation). The strains were integrated with depth to define the thermal axial displacements, as shown in Figure 11. The thermal head displacements at a depth of zero in Figure 11 were obtained using the average displacement of the two LVDTs on the top of the foundation. The trends in displacements calculated from the strain measurements correspond well with the LVDT measurements, except during the transient heating phase of the foundation in the stiffness control test.

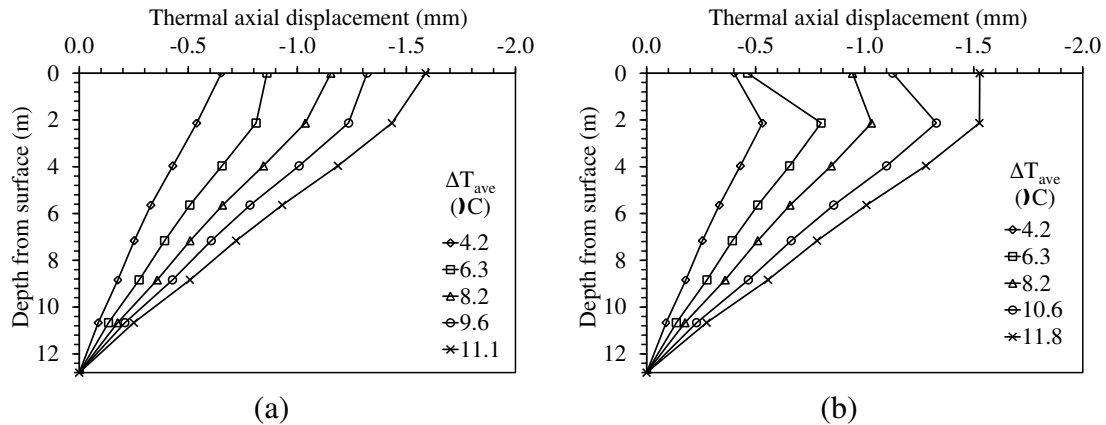


Fig. 11. Thermal displacements (prototype-scale): (a) Load-control test; (b) Stiffness-control test

A comparison of the thermal settlements measured by the LVDTs for the foundation in the load-control and stiffness-control tests as a function of the average

change in temperature of the foundations are shown in Figure 12. As expected, the foundation behaves in a thermo-elastic manner during the heating process. Because of the linear behavior and the relatively small thermal strains observed in Figure 9, it is assumed that the first test does not have a major impact on the second test. It is clear that the head stiffness induced by the load cell is not very high, as the foundations expanded by similar amounts. The slope of the axial load as a function of temperature for the stiffness-control test shown in this figure confirms that the load cell was being linearly compressed during heating due to the expansion of the foundation. The stiffness of the load cell was calculated from the measured displacement and change in axial load to be 113 kN/m (prototype-scale).

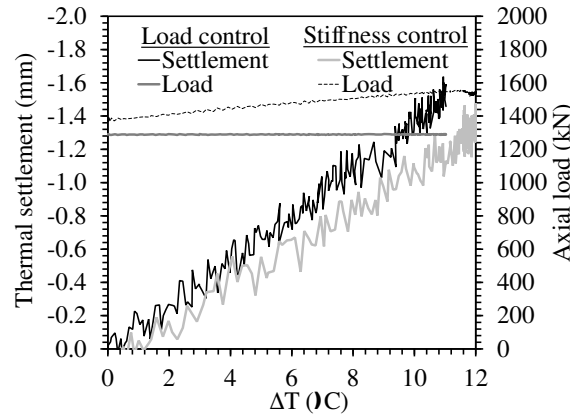


Fig. 12. Comparison of load and stiffness control head thermal expansion and axial load with change in temperature (prototype-scale)

CONCLUSIONS

This paper presents an evaluation of the impact of head restraint on the thermo-mechanical head movement and axial strain response of centrifuge-scale energy foundations installed in dry sand layers during a thermal response test. The test performed on the end-bearing foundation under stiffness-control conditions (i.e., restrained head expansion) indicates a smaller amount of expansion than in the test performed under load-control conditions (i.e., free head expansion). The foundation in stiffness-control conditions had lower thermal axial strains near the ground surface and nearly 50% greater thermal axial stresses on average. These results indicate the relevance of properly estimating the head stiffness in thermal load transfer analyses.

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