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# Response of an Energy Foundation to Temperature Fluctuations

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**ABSTRACT**: This paper focuses on the evaluation of the thermo-mechanical response of a 15.2 m-long energy foundation in dry sandstone over a 4-month period. Although the foundation was not actively heated or cooled using a heat pump, the fluctuations in the temperature of the heat exchange fluid occurred due to seasonal variations in the mechanical room temperature. Although these fluctuations only led to small changes in foundation temperature (from -1 to 1 °C), these were sufficient to evaluate the mobilized coefficient of thermal expansion of the foundation. Further, the trends in the thermal axial stress and strain with depth in the foundation were evaluated, along with the mobilized side shear stress and axial displacement.

## INTRODUCTION

Energy foundations are structural elements used for the purpose of exchanging heat between the subsurface and a building. Heat is exchanged by circulating fluid through closed-loop heat exchanger tubes embedded in the reinforced concrete. This change in temperature leads to a thermo-mechanical response. This paper presents data from a 4-month period involving an assessment of the thermal and thermo-mechanical response of an energy foundation installed beneath a 1-story building at the US Air Force Academy. This energy foundation has been characterized in three previous studies involving monotonic heating: Murphy et al. (2014a) performed a short-term heating test, Murphy et al. (2014b) performed a full thermo-mechanical characterization of the foundation response during heating and ambient cooling, and Murphy et al. (2014c) evaluated the role of the horizontal run-out length between the energy foundation and the heat exchange manifold on the thermal response. This paper provides novel contributions by presenting data collected over a 4-month period where fluid was circulated through the foundation, during which time heat was exchanged with the mechanical room without the assistance of a heat pump. Data monitored during this period includes the temperatures of the heat exchange fluids measured using thermistors, profiles of foundation temperatures and thermal axial strains measured using thermistors and vibrating wire strain gages embedded within the foundations at different depths, and profiles of temperatures within the subsurface surrounding the foundation. This data is suitable to assess the transient response of the energy foundations cyclic temperature changes.

## BACKGROUND

The full-scale response of energy foundations has been assessed in several studies to evaluate their thermo-mechanical response under different conditions (Brandl 2006; Laloui et al. 2006; Bouazza et al. 2012; Amatya et al. 2012; McCartney and Murphy 2012; Olgun et al. 2012; Murphy et al. 2014a; Murphy et al. 2014b; Murphy and McCartney 2014). Data from some of these tests were used to successfully validate soil-structure interaction design tools (Knellwolf et al. 2011) and thermo-elastic finite element models (Laloui et al. 2006; Ouyang et al. 2012). However, the thermo-mechanical response of energy foundations under frequent reversals in temperature has not been studied in detail. Stewart and McCartney (2013) evaluated the transient response of a centrifuge-scale end-bearing type energy foundation installed within a layer of unsaturated silt during heating and cooling, and did not observe a significant change in thermal axial strain after four cycles of heating and cooling. The thermo-mechanical performance of two end-bearing energy foundations in claystone overlain by cohesionless soil over the course of two years of heat pump operation was studied by Murphy and McCartney (2014), who found that seasonal heating and cooling operations lead to changes in the mobilized coefficient of thermal expansion that do not follow thermo-elastic behavior. They also observed issues in the interpretation of the thermal axial strains due to transient differences between the temperatures of the strain gages and the heat exchange fluid.

## ENERGY FOUNDATION SYSTEM

### Building

This study involves evaluation of results from an energy foundation beneath a new building at the US Air Force Academy (USAFA), which was completed in January 2014. The building includes a conventional gas-powered heating system as well as a ground-source heat pump system coupled with eight energy foundations installed around the perimeter of the building. The eight energy foundations are 0.61 m-diameter, 15.2 m-deep drilled shafts. Each shaft contains a 0.46-m-diameter steel reinforcing cage that extends the full length of the shaft. The reinforcing cages are composed of six #7 longitudinal bars with #5 radial hoops spaced at 0.3 m on center throughout the length of the cage. The top of the shafts are spliced into a 0.91 m-deep by 0.61 m-wide grade beam that extends around the perimiter of the building. The shafts were constructed using the dry hole method as no groundwater was observed and because the subsurface material was deemed competent upon excavation.

Each foundation contains a closed-loop heat exchanger constructed from 19 mm-diameter high density polyethylene (HDPE) tubing. The details of the heat exchnage tubing within the different foundations is explained in the plan view of the foundation system in Figure 1. The tubing is routed from the foundation to the mainfold in the mechanical room through the grade beam. The heat exchange tubing was attached to the inside of the reinforcing cages with zip-ties at a distance of at least 70 mm from the vertical reinforcing members. The inlet and outlet tubes were seperated diametrically by at least 90° to minimize thermal short-circuiting where heat is transfered by direct transmission from the inlet to outlet tubes. U-shaped couplings were used at the bottom of the foundations to connect the inlet and outlet tubes so that the tubing does not cross the bottom of the cage, where it could cause concrete segregation. A concrete pump truck was used to place high-slump concrete having a compressive strength of 21 MPa in the holes following placement of the reinforcing cages. This study is focused on the behavior of Foundation 4, which contains 61 m of heat exchange tubing connected in a UU shape to form two continuous loops (i.e., fluid will circulate through the length of the foundation twice).

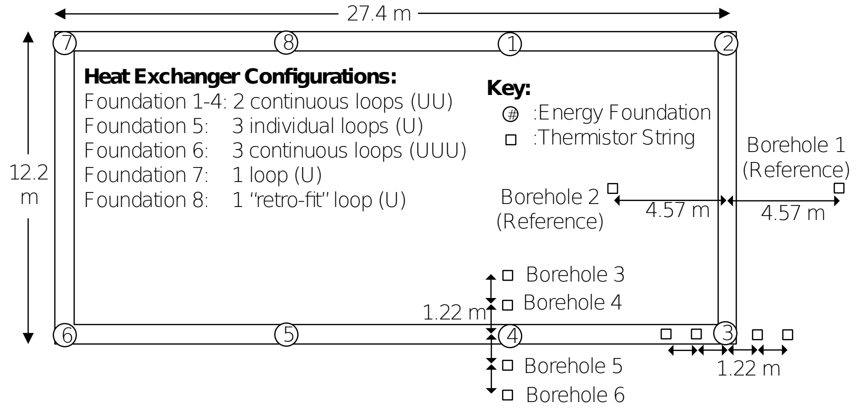


Figure 1: Heat exchanger loop configurations in the energy foundations

## Subsurface Conditions

Relevant data from a site investigation within the building footprint is shown in Figure 2 with respect to the instrumentation plan for Foundation 4. Three strata were identified: an approximately 1 m-thick layer of sandy fill, underlain by a very dense 1 m-thick sandy gravelly layer, underlain by Dawson-Arkose sandstone bedrock. Field classification tests indicate that all materials are non-plastic and non-expansive. The thermal conductivity of disturbed samples recovered from a split-spoon sampler for each layer were measured on site using a thermal needle (KD2Pro from Decagon Devices of Pullman, WA). The thermal conductivity values were 1.12 W/mK for the sandy fill, 0.79 W/mK for the dense sandy gravel, and 1.23 for the sandstone.

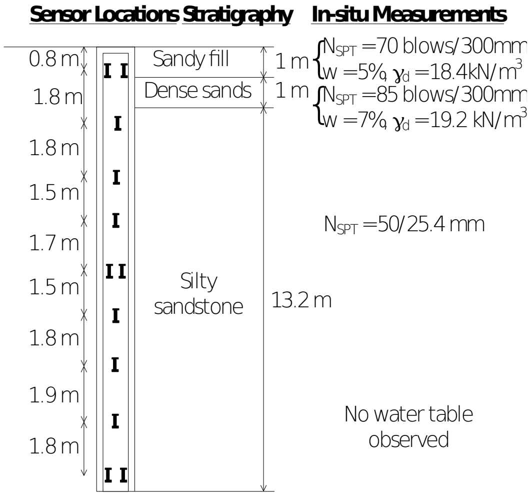


Figure 2: Subsurface stratigraphy and Foundation 4 instrumentation layout

## Instrumentation

Vibrating wire strain gages and thermistors were incorporated into Foundation 4 at different depths in order to capture the distribution of temperature and axial strain with depth. The locations of the sensors are shown in Figure 2. All of the thermistors were attached to brackets welded to longitudinal steel reinforcing bars. The sensor leads were routed to the mechanical room where they are connected to the data acquisition system. Temperature variations in the subsurface around the energy foundations were monitored using a series of ten Geokon model 3810 thermistor strings that each have six sensors, installed in boreholes that were then backfilled with CETCO high thermal conductivity grout at the locations shown in Figure 1. The subsurface temperatures around Foundation 4 are monitored using four thermistor strings, with two under the slab and two outside. Two thermistor strings are used to monitor ground temperatures under the center of the slab and outside of the building.

## Experimental Setup and Procedures

After the set of thermal response tests on all of the foundations performed by Murphy et al. (2014b; 2014c) in July 2013, construction continued on the heating and cooling system for the building. Although the building envelope was closed and the heating/cooling system was installed by January 2014, only the conventional heating and cooling system will be used in the first year of operation to provide a baseline for efficiency comparisons. Accordingly, the heat pump has not yet been activated. However, the circulation pump for the geothermal system was activated in January of 2014, and a 20% propylene glycol-water mixture was circulated through the foundations without active heat exchange. The temperature of the fluid fluctuates by a small amount during interaction with the mechanical room, whose temperature fluctuates with the outside air temperature. Fluid properties of the glycol mixture are shown in Table 1. The heated fluid passed into the supply header, circulated through the foundation, and then passed out of return header back to the pump. The P/T port includes a Venturi balancing valve for calculation of the flow rate from the differential pressure. The fluid rate out of the foundation was measured to be 200 ml/s using a differential pressure meter inserted into a pressure and temperature port (P/T ports). During testing, the inlet and outlet fluid temperatures for each foundation were monitored using pipe plug thermistors installed in the P/T ports.

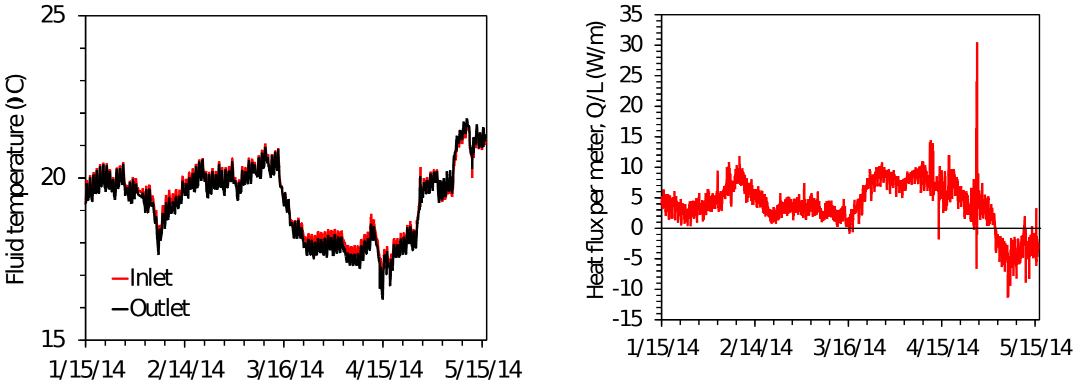
**Table 1: Heat exchange fluid properties**

| Water to Propylene Glycol Ratio | Molar Heat Capacity (J/molK) | Molecular Weight (g/mol) | Specific Heat Capacity (J/kgK) | Fluid density (g/ml) |
|---|---|---|---|---|
| 5:1 | 98 | 30 | 3267 | 1.008 |

The measured values of the supply and return fluid temperatures and the mass flow rate through each foundation can be used to calculate the heat flux, as follows:

$$\dot{Q}=\Delta T\,\dot{V}\,\rho_{fluid}C_{fluid} \tag{1}$$

where $\dot{Q}$ is the heat flux in W, ΔT is the difference between the supply and return fluid temperatures in K ($T_{supply}$ and $T_{return}$, respectively), $\dot{V}$ is the fluid flow rate in ml/s, $\rho_{fluid}$ is the mass density of the fluid kg/ml, and $C_{fluid}$ is the specific heat capacity of the fluid in J/(kgK). The inlet and outlet fluid temperatures during the ambient temperature circulation are shown in Figure 3(a). In addition to the fluctuation in the mean fluid temperature from 16 to 22 °C, the inlet fluid was greater than the outlet fluid during the winter, indicating injection of heat from the ground. The heat flux per unit meter of foundation length is shown in Figure 3(b). It is clear that a relatively small amount of heat is being transferred during the ambient circulation of the heat exchange fluid, as the value from the thermal response test for this foundation reported by Murphy et al. (2014c) were approximately 88.16 W/m.

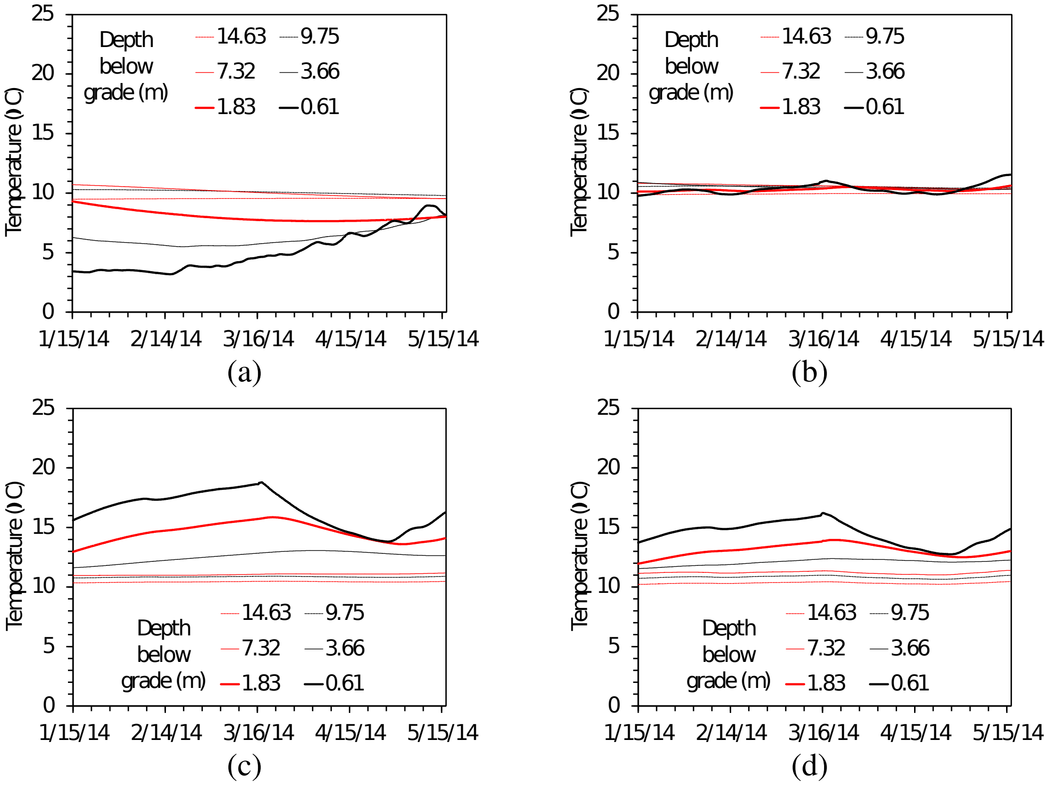


(a) (b)

**Figure 3: Heat exchange fluid details: (a) Fluid temperatures; (b) Heat flux**

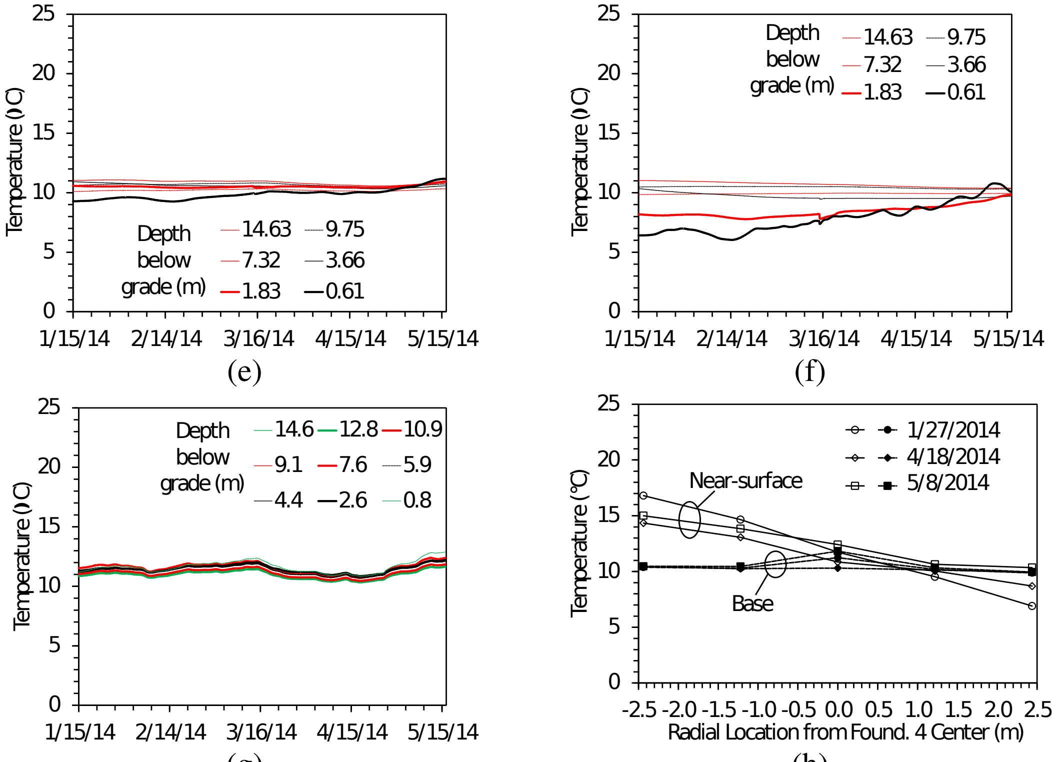
## RESULTS

Temperatures of the subsurface and Foundation 4 at different depths below grade (i.e., below the bottom of the 0.91 m-deep grade beam) were monitored during the 4-month period. The results from reference Borehole 1 in Figure 4(a) outside of the building footprint indicate that the near-surface soils are relatively cold due to the interaction with the atmosphere, but at deeper depths the temperature is relatively constant. This is in contrast to the results from reference Borehole 2 in Figure 4(b) under the building footprint, where no change in temperature with depth is noted due to the insulating effect of the building. Relatively high temperatures were observed under the building footprint in Boreholes 3 and 4 next to Foundation 4 in Figures 4(c) and 4(d). This may be because the heating test performed on Foundation 4 in summer 2013 heated up the soil. It may take a long time for the subsurface beneath the building footprint to change in temperature due to the relatively low thermal conductivity of the dry sandstone. The subsurface temperatures in Boreholes 4 and 5 in Figures 4(e) and 4(f) show a transitional behavior that is closer to that observed in Borehole 1. The temperatures of Foundation 4 in Figure 4(g) closely mimic those of the heat exchange fluids, albeit with a smaller magnitude of 10 to 13 °C. The radial distributions in temperature around Foundation 4 at different depths and times of the year are shown in Figure 4(h), and show that the temperature is relatively constant at the bottom of the foundation, but that a decreasing trend in temperature is noted near the ground surface. These transient fluctuations in ground temperature may affect the thermo-mechanical response.



(a) (b)

(c) (d)

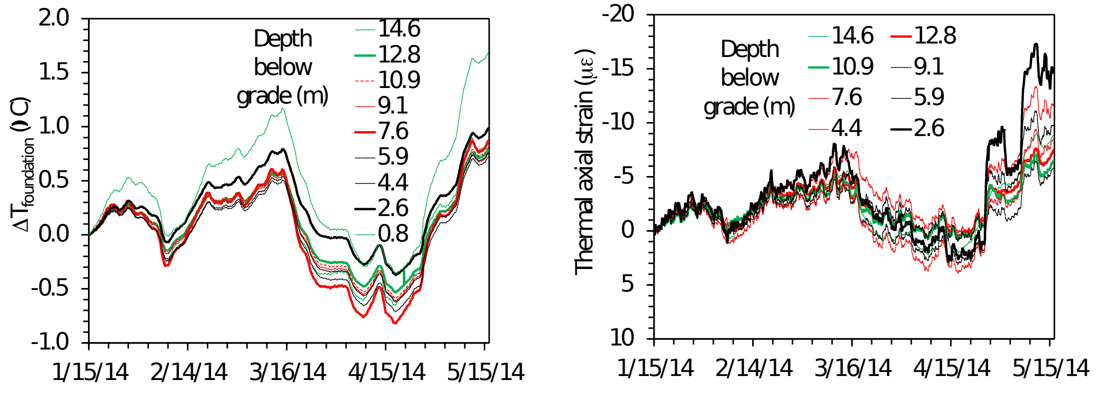


(e) (f)

(g) (h)

**Figure 4: Temperatures: (a) Reference borehole 1 outside slab; (b) Reference borehole 2 under slab; (c) Borehole 3; (d) Borehole 4; (e) Borehole 5; (f) Borehole 6; (g) Foundation 4; (h) Radial temperature distribution around Foundation 4**

The change in temperature of Foundation 4 after the start of fluid circulation is shown in Figure 5(a). The thermal axial strains in the foundation were calculated by subtracting off the mechanical strains at the beginning of fluid circulation and applying the manufacturer-recommended correction to account for the thermal expansion of the steel wire, and are shown in Figure 5(b). The thermal axial strains generally show expansion (negative strains) during positive changes in temperature, and contraction (negative strains) during cooling. More details about the calculation of thermal axial strains in energy foundations can be found in Murphy et al. (2014b).

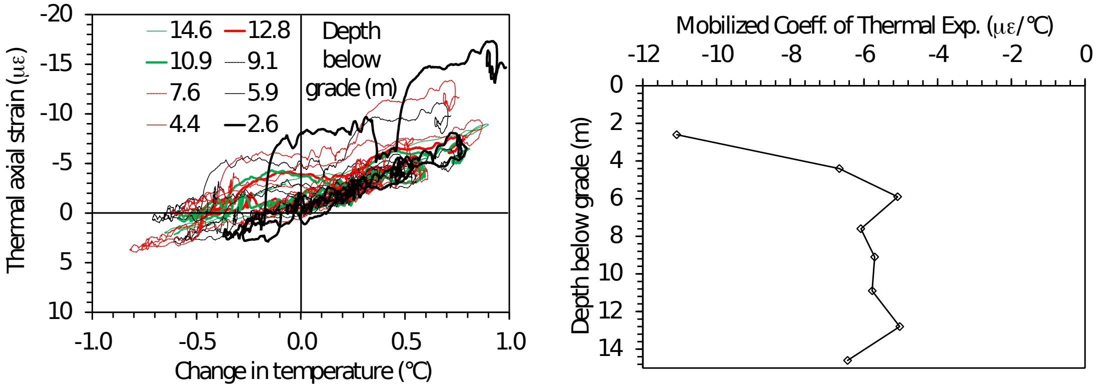


(a) (b)

**Figure 5: Thermo-mechanical response: (a) Changes in foundation temperatures; (b) Changes in thermal axial strain**

## ANALYSIS

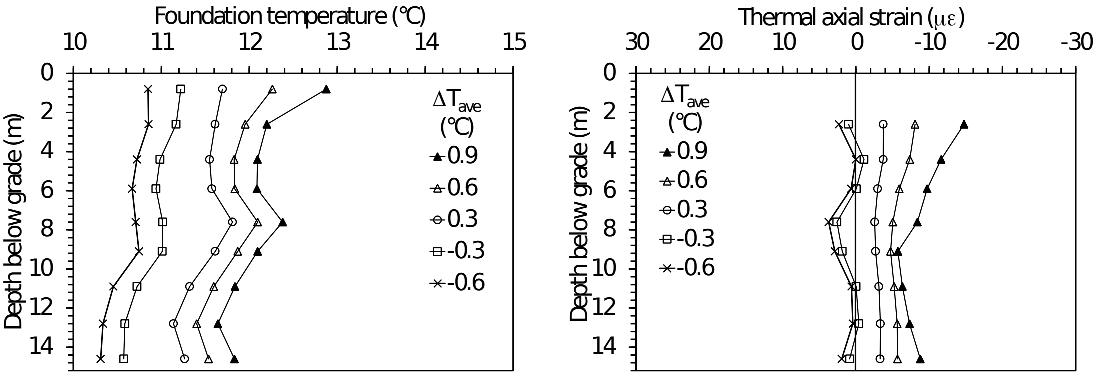
The first step in evaluating the thermo-mechanical response of the energy foundations is to plot the thermal axial strain as a function of the change in temperature at the location of each gage, as shown in Figure 6(a). The average slope of each hysteresis loop indicates the mobilized coefficient of thermal expansion at the depth of each gage. The strain gage closest to the ground surface did not show a stable response during this time period so it is not shown. Although it appears that the mobilized coefficients of thermal expansion are shifting upward slightly, similar to observations of Murphy and McCartney (2014), the hysteresis loops are relatively linear. The more nonlinear the hysteresis loops, the more likely that other soil-structure interaction processes are superimposed on top of the thermo-elastic response of the reinforced concrete foundation. The magnitudes of the mobilized coefficients of thermal expansion shown in Figure 6(b) are consistent with those observed by Murphy et al. (2014b), and the trend with depth reflects end-bearing conditions with strong restraint near the toe. The coefficient of thermal expansion for the reinforced concrete is approximately -12 με/°C, which indicates that the top of the foundation is under nearly free-expansion conditions.



(a) (b)

**Figure 6: (a) Thermal axial strain at different depths versus temperature change at those depths; (b) Mobilized coefficient of thermal expansion**

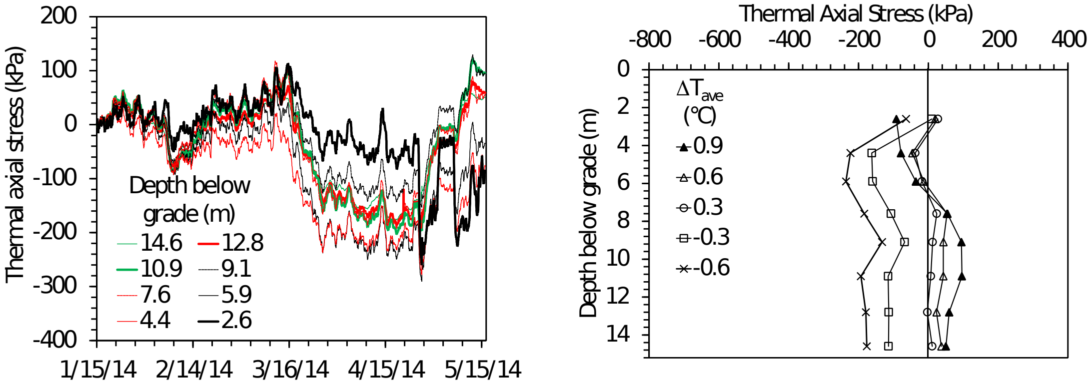
Moments in time when the foundation had reached different average changes in temperature with depth were identified from the time series. Different from the case when the foundation is actively heated (Murphy et al. 2014b), the temperatures are not uniform with depth during ambient circulation of fluid, as shown in Figure 7(a). The thermal axial strains at these times are shown in Figure 7(b). Different from the results of Murphy and McCartney (2014), the strain profiles do not retain the same shape during transitions from heating to cooling, although greater temperature changes may be needed to observe this effect. The thermal axial strains are consistently positive or negative during cooling or heating, respectively.



(a) (b)

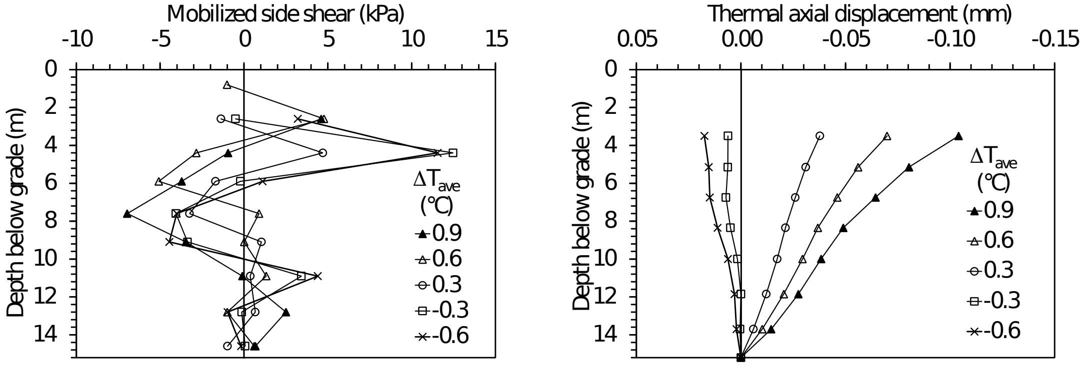
**Figure 7: (a) Temperature profiles for different average changes in foundation temperature; (b) Profiles of thermal axial strain during heating and cooling**

The thermal axial stresses were then calculated using the approach described by Murphy et al. (2014b), using a coefficient of thermal expansion of -12 με/°C and a Young's modulus of 30 GPa for the reinforced concrete. The thermal axial stresses as a function of time shown in Figure 8(a) follow the opposite trend of the thermal axial strains in Figure 5(a). Profiles of thermal axial stresses in Figure 8(b) generally show that the foundation is in compression during heating and tension during cooling, but unexpected behavior is noted near the surface. Specifically, the thermal axial strains in Figure 7(a) for $\Delta T = 0.9$ °C were greater than the free expansion strain, which leads to an error in the calculation of the thermal axial stress. This may have been caused by movement of the near-surface soil layer in response to combined changes in temperature and water content, an issue that needs to be studied in more detail. Nonetheless, the stresses deeper in the foundation are consistent with expectations for end-bearing energy foundations (Amatya et al. 2012). The mobilized side shear stresses in Figure 9(a) were calculated from the axial stress profiles. Although the greatest side shear stresses were observed near the top of the foundation, these are affected by the inaccuracy in the axial stress calculations at these depths. The thermal axial displacements shown in Figure 9(b) were calculated by integrating the strain profiles in Figure 7(b) with depth, and indicate that the foundation head expands upward during heating than downward during cooling. Larger temperature changes are required to evaluate if bias toward expansion has an effect on the response.



(a) (b)

**Figure 8: Thermal axial stresses: (a) Time series; (b) Profiles**



(a) (b)

**Figure 9: (a) Mobilized side shear resistance; (b) Foundation displacements**

## CONCLUSIONS

This paper focuses on the evaluation of the thermo-mechanical response of a 15.2 m-long energy foundation in dry sandstone during circulation of heat exchange fluid without the use of a heat pump. The foundation was observed to show consistent expansion and contraction during heating and cooling, respectively, indicating a thermo-elastic response. However, the top of the foundation was observed to show inconsistent thermo-mechanical stress-strain behavior during transient temperature fluctuations. Although the inconsistencies may be due to the relatively small changes in temperature observed in the foundation, they may indicate that a more advanced analysis is needed to interpret the thermo-mechanical axial stresses in the foundation.

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