Engineering performance of energy foundations

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ABSTRACT
Drilled shaft foundations with embedded heat exchangers (energy foundations) have gained attention by employing materials to not only provide structural support but also improve the energy efficiency of heat pump systems. Data on the thermal and mechanical performance of energy foundations obtained through analysis, field testing, and centrifuge modeling will be summarized. Focus will be provided on the modification and validation of soil-structure interaction analyses needed to predict thermally-induced movements and changes in ultimate capacity. Relevant issues to consider in the design and construction of energy foundations will be discussed, along with methods to define material properties for analysis.

RÉSUMÉ
Fondations de l'énergie ont retenu l'attention en employant des matériaux non seulement de fournir un soutien structurel, mais aussi d'améliorer l'efficacité énergétique des systèmes de pompe à chaleur. Les données sur les performances thermiques et mécaniques des fondations de l'énergie obtenue par l'analyse, essais sur le terrain, et la modélisation centrifugeuse seront résumés. L'accent sera fournie sur la modification et la validation des analyses d'interaction sol-structure nécessaire pour prévoir les mouvements thermiquement induits et des changements dans la capacité ultime. Les questions pertinentes à considérer dans la conception et la construction des fondations de l'énergie seront abordées, ainsi que des méthodes pour définir les propriétés du matériau pour l'analyse.

1 INTRODUCTION

1.1 Motivation

Development and characterization of new technologies to reduce building energy consumption are important goals for the world from both environmental and economic perspectives. In the United States, commercial and residential buildings consume approximately 39% of the primary energy, of which heating and building systems consume 20% of this fraction (EIA 2008). Ground source heat pumps (GSHPs) have been used for many years as an energy efficiency strategy as they often require less energy to heat and cool buildings than conventional heating and cooling systems, including air-source heat pumps (Lund et al. 2004). This is because GSHPs exchange heat with the subsurface soil and rock, which has a relatively steady temperature throughout the year compared with that of the outside air. Although subsurface temperatures vary with geologic setting, the average temperature of the ground below a depth of 1.3 meters is approximately 10 to 15 °C year-round (Omer 2008).

Despite the established performance record of GSHPs, their relatively high installation costs have led to less significant rates of implementation than other energy efficiency technologies (Hughes 2008). A common GSHP installation technique involves insertion of polyethylene loops into boreholes up to 150 m deep spaced 6-10 m apart, filled with sand-bentonite. Not only does this require significant labor, but requires open space outside the building footprint to install the boreholes, trenching beneath the frost depth to connect the heat exchangers, and potential horizontal directional drilling to connect the borehole field to heat pumps within the building.

To counter the high installation cost of GSHPs (or to provide supplemental heat exchange to conventional GSHPs), drilled shaft foundations can be used as an alternate pathway to the subsurface for heat exchangers (Brandl 2006). These energy foundations may not only be more cost-effective to install because they use construction materials for multiple purposes, but they may be more efficient heat exchangers due to the high thermal conductivity and heat capacity of concrete compared to soil. Energy foundations have been successfully implemented in structures in Canada (ENR 2003); Europe (Brandl 2006; Laloui et al. 2006; Adam and Markiewicz 2009; Bourne-Webb et al. 2009; Wood et al. 2009), Japan (Ooka et al. 2007), and more recently in the US (Redmond Reporter 2010; Zitz and McCartney 2011). Brandl (2006) reported that there are currently over 25,000 energy foundations in Austria, with installations dating as early as the 1980's. Over the past five years, the installation of energy foundations has grown exponentially in the UK (Amis et al. 2008). There were approximately eight times more energy foundations installed in 2008 than in 2005. The reason for this rise in production is mainly driven by the code for sustainable buildings that requires the construction of zero-carbon buildings by 2019 (Bourne-Webb et al. 2009). Similar targets are being set across the globe suggesting a continued increase in production of such systems throughout the world.

This theme paper focuses on the key thermal, mechanical, and construction issues for energy foundations, from the perspectives of laboratory material characterization, analysis, and field observations. With respect to mechanical response, heat exchange leads to interesting thermo-elastic movements in the foundation materials. Evidence from both field investigations as well as centrifuge-scale tests will be presented and discussed.

1.2 Energy Foundations

Energy foundations are essentially a closed-loop system which transfers heat to or from the ground by circulating a heat exchange fluid (i.e., propylene glycol) through a polyethylene "U" tube attached to the inside of the reinforcement cage of the foundation. Heat from this fluid is exchanged through a baffled coupling with a refrigerant circulating through the heat pump. Commercial buildings may have several heat pumps connected in parallel to the heat exchanger loop in the ground. The heat exchange of this system will depend on the circulation rate of the fluid in the ground loop, the thermal conductivity of the system, and the entering and exiting water temperatures. The entering and exiting water temperatures are a function of the refrigerant temperature. A schematic showing the interaction between the different heating loops in an energy foundation is shown in Figure 1.

In heating mode, the refrigerant in the heat pump absorbs heat from the ground loop in the foundation, after it is compressed to increase its temperature. Heat from the hot refrigerant is transferred to the building through an air handler or hydronic system in the floors, as well as to a hot water storage tank. The refrigerant then goes through an expansion valve, which leads to a decrease in its temperature and the process repeats. This process can be reversed to supply cooling.

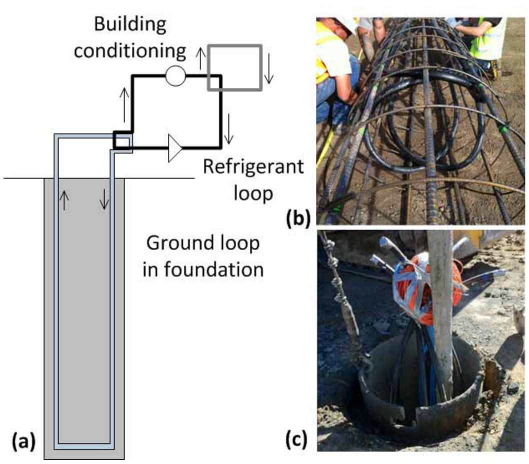


FIG. 1: Energy foundations: (a) Closed-loop heat exchange system; (b) Heat exchangers attached to reinforcement cage; (c) Concrete placement

The primary usage costs associated with heat pump systems are associated with the operation of the circulation pump for the ground loop (which must have sufficient horsepower to result in turbulent flow conditions in the ground loop) and the frequency at which the compressor must be powered to expand or contract the refrigerant. In air source heat pumps, the compressor operation depends on the exterior air temperature, which can be highly variable over time. The goal of a GSHP system is to reduce the frequency at which the compressor must be powered on average throughout the year by evening out the extreme seasonal variations in temperature.

While conventional heat exchange systems employ convective air flow to exchange heat between the refrigerant loop and the atmosphere, heat flow between the ground loop and the surrounding foundation and soil is a function of convective transfer in the heat exchange fluid and conduction through the foundation and ground. Because of the particular thermal conductivity values of soil and concrete, this may potentially require a significant length of heat exchanger tubing to meet a certain heat exchange demand from the building. In conventional GSHPs, the total piping requirements range from 60 to 180 meters per cooling ton (approximately 11.5 kW) depending on local soil types, groundwater levels, and temperature profiles (Omer 2008; McCartney et al. 2010). The use of propylene glycol as a heat exchange loop permits heat to be extracted from the ground even under sub-freezing conditions. The required flow rate through the primary heat exchanger is typically between 1.5 and 3.0 gallons per minute per system cooling ton (0.027 and 0.054 L/s-kW) (Omer 2008). The maximum temperatures in the heat exchanger fluid for GSHPs range from -5 to 50 ºC (Brandl 2006), although in most applications this range is narrower (3 to 35 ºC).

A picture of the heat exchanger tubing attached to the inside of the reinforcement cage is shown in Figure 1(b). The diameter of energy foundations typically ranges from 0.6 m to 1.5 m (Ooka et al. 2007), and each foundation typically accommodates 2-3 "U" tube loops. The number of loops in a given foundation does not increase the heat exchange capacity of a given foundation significantly, but helps to ensure uniform temperatures across the perimeter of the foundation to avoid differential thermal expansion. A picture of concrete being tremied into the bottom of an energy foundation is shown in Figure 1(c). The fact that the heat exchangers are embedded in concrete helps ensure intimate contact with the heat exchanger. The boreholes in conventional GSHPs are backfilled with sand-bentonite, which may deform away from the heat exchanger above the ground-water table after repeated heating and cooling cycles. Most energy foundations are 10 to 50 m deep, depending on the building size. In many applications, the length of heat exchanger for a conventional borehole GSHP system sized to meet the full thermal demand of a building will be longer than the length available for heat exchange in the foundations (which is a function of the building size and column spacing). In this case, energy foundations can be used to supplement the heating and cooling system for the building. In a supplemental application, energy foundations can still play a critical role in reducing energy costs. If they are able to cover the base load for heating and cooling of the building, then the electricity required to heat or cool the building during peak load applications will be significantly lower. As electricity costs are typically higher during peak periods, this may translate to significant savings.

Heat exchange loops are typically fused together with header pipes within the grade beams at the ground surface. These header tubes are designed such that all loops in the foundations receive equal circulation rates from the heat pump system in the building. A distinct advantage of energy foundations over conventional borehole GSHP systems is that land is not needed outside of the building footprint for heat exchange, and the heat pump infrastructure and connections are within the building footprint. This can be a major advantage in metropolitan areas. When comparing installation costs between conventional GSHPs and energy foundations, the cost of boring attributed to the heat exchanger is essentially zero for energy foundations. The capital cost of the heat exchange component of an energy foundation is that of the HDPE tubing and the labor cost of connecting the tubing to the steel reinforcement of the drilled shaft foundation. Additional costs come from quality assurance testing (i.e., pressurized leak tests) needed for energy foundations to avoid punctures in heat exchange loops during assembly or installation (Brandl 2006).

2 THERMAL BEHAVIOR

2.1 Measurement of System Thermal Conductivity

The thermal conductivity λ of a drilled shaft system is a key design variable for the thermal performance of energy foundations. The individual thermal conductivity values of different constituents are given in Table 1. These values were measured using the thermal needle or heat flux measurement techniques (Brandon and Mitchell 1989; Abuel-Naga et al. 2008). The primary variable which affects the thermal conductivity of soil is the dry density, as this reflects the packing of particles and the available pathways for conductive heat transfer (Brandon and Mitchell 1989; Abuel-Naga et al. 2008). The groundwater table may have implications on the required length of heat exchangers in deep foundations as the degree of saturation can affect the thermal conductivity of soils (Brandon and Mitchell 1989; Abu-Hamdeh and Reeder 2000). The soil mineralogy may also play an equally important role to the degree of saturation. Tarnawski et al. (2009) observed that the quartz content has a significant effect on soil thermal conductivity.

Table 1: Thermal properties of constituent materials in energy foundations

Material	λ (W/m°C)	α_T (x 10^{-6} m/m °C)	E (MPa)
Steel	1.70	11.7	200,000
Concrete	0.10-1.70	6-14.5	20,000-28,000
Polyethelene	0.51	101	800
Propylene glycol	0.15	100	N/A
Water	0.61	69	N/A
Sand	0.3-2.5	10-12	10-200
Silt	0.2-1.6	10-12	5-100
Clay	0.3-1.4	8-12	0.5-150

As many sites have several different soil layers with varying mineralogy and density it is often important to evaluate the thermal conductivity of the entire foundation system. Careful analytical and experimental studies have been performed to extend the line-source thermal conductivity analysis to GSHPs, which is possible but requires several assumptions (Shonder and Beck 1997). In these experiments, a constant amount of energy is used to heat the fluid circulating in the ground loop, and the temperature is recorded as a function of time. The thermal conductivity of the energy foundation system can be measured using a constant rate of heating test. The assumptions of a line source heating test may not be fully justified for energy foundations even if the temperature of the entire foundation is assumed to be the same as the circulating water, mainly due to the large diameter of the foundation compared to the rate of heat flow. Brettmann and Amis (2011) performed a heating test on a group of three foundations, and measured a thermal conductivity of 2.66 W/m°C using the line source equation shown in Figure 2. This is a relatively high conductivity due to the saturated clay soils at the site, indicating that it will have excellent thermal performance.

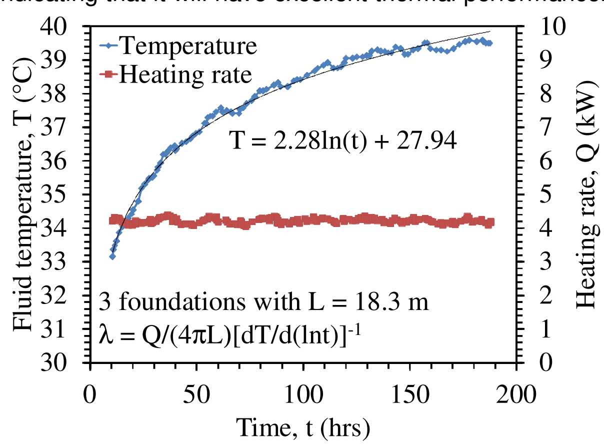
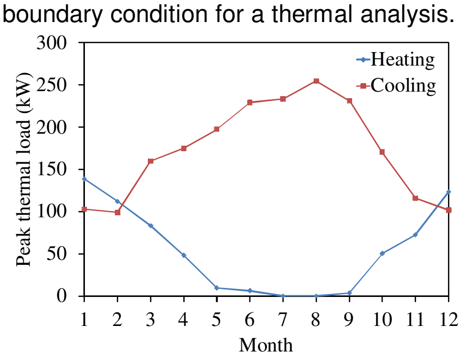


FIG. 2: Results from a constant heating rate test (Brettmann and Amis 2011)

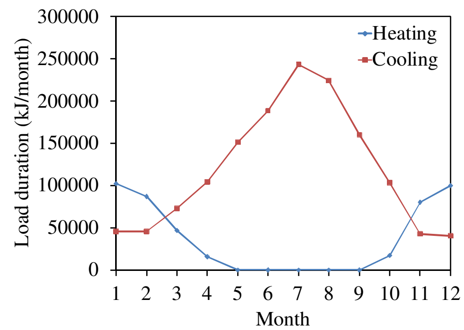
2.2 Simulation of Thermal Performance

Modeling of the thermal response of energy foundations is challenging due to the need to understand the heating and cooling load for a particular building design and climate. For example, a poorly insulated building in a cold climate may have little chance of having successful thermal performance with a GSHP or ASHP system. The state-of-the-art in thermal modeling is to use simplified quasi-analytical solutions to quantify the length of heat exchanger needed for a given building load (Eskilson 1987; Kavanaugh et al. 1997), which are incorporated into available GSHP design software (GLHEPro, EQuest, ECA, etc.). However, the quasi-analytical solutions available consider only a few conventional GSHP heat exchanger configurations (spacing and diameters), and do not consider conditions representative of energy foundations. Advanced heat exchange models such as EnergyPlus have been used to evaluate building slab heat losses (Krarti 1995), and are being evaluated for use in modeling heat exchange in energy foundations (Kaltreider 2011). These tools are computationally intensive, so design tools consistent with those for GSHPs are still needed for the thermal analysis of energy foundations to ensure sufficient thermal mass to heat and cool the building in a sustainable fashion.

Significant efforts have been made to predict the performance of GSHPs. This is a complex boundary value problem, because heat transfer between the heat exchanger and the ground is through conduction, while the heat exchange fluid transfers fluid between the through conduction and convection. The temperature of the heat exchange fluid depends on the programming of the heat pump system, and the compressor will work to maintain the desired temperature in the house. Depending on the size of the structure and the insulation, the thermal load required for the ground will vary throughout the year. A typical design peak thermal load for a building in Colorado is shown in Figure 3(a), and the duration of thermal loading is shown in Figure 3(a). These loads depend on the climate and building characteristics. The peak thermal load is typically used to design the capacity of the heat pump, while the thermal loading duration is reflects the total amount of energy needed to be extracted from the ground. This information is required by most conventional GSHP systems as the boundary condition for a thermal analysis.



(a)



(b)

FIG. 3: Heating demand for design: (a) Peak thermal load; (b) Thermal load duration

The main approach used to design the thermal behavior GSHP systems is the g-function approach developed by Eskilson (1987). This approach assumes that the heating loads for the building can be approximated by a series of thermal pulses having different durations. A g-function is an analytical solution to the heat flux equation for a given geometry of GSHP heat exchangers (i.e., number of heat exchanger tubes, tube spacing, tube and borehole diameters) which can be combined with the heat pulse and soil thermal properties to predict the response of the heat exchanger to the design heat pulses. This information is used to define the maximum length of heat exchanger required to meet the heating load, which is defined in a closed-form equation described by Kavanaugh et al. (1997). This approach cannot be used for energy foundations without making several assumptions, as g-functions have not yet been developed for the geometry of energy foundations.

Thermal evaluations of GSHPs in different settings using the g-function approach are useful to demonstrate that energy foundations have a strong likelihood of functioning properly in a range of settings. A recent study by Krarti and Studer (2009) used the eQuest3D interface for the DOE-2 software package to show that GSHPs reduce electricity peak demand, energy use, and CO_2 emissions by 10-30% in a typical Colorado home compared to conventional heating and cooling systems. McCartney et al. (2010) extended this analysis to houses and GSHP design for locations throughout the country, and found that GSHPs have adequate thermal performance in many parts of the country. In locations with a heavy heating demand (i.e., Duluth), heat from solar collectors can be injected into the subsurface during summer months in addition to the cooling activities.

Recent efforts have been made to evaluate the heat exchange performance of energy foundations (Rouissi et al. 2011; Kaltreider 2011; Abdelaziz et al. 2011). Kaltreider (2011) performed a series of 3D Finite Volume Method analyses to evaluate the heat exchange from buildings, and validated his results using laboratory-scale measurements of heat exchange in energy foundation by Rosenberg (2010). Kaltreider (2010) used the model geometry and boundary conditions shown in Figure 4 to predict the heat transfer from the slab of a building throughout the year. The results, shown in Figure 5, indicate that energy foundation operation leads to different amounts of heat loss from the building slab.

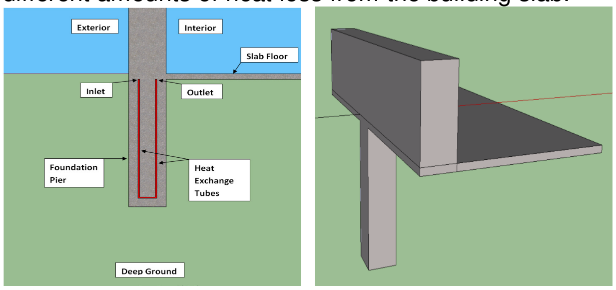


FIG. 4: 3D heat exchange model details (Kaltreider 2011)

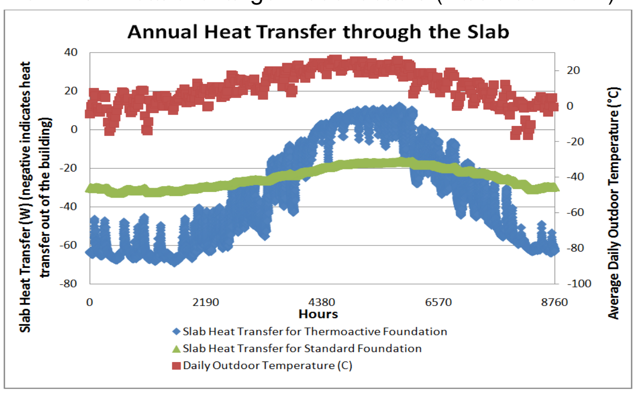


FIG. 5: Heat transfer through the building slab for energy and standard foundations (Kaltreider 2011; 0 hrs = Jan 1)

The results for the energy and standard foundation are compared in Figure 5, in terms quadrants showing heat loss during the heating and cooling seasons. Heat transfer out of the building is designated as negative. For example, decreased heat loss during the cooling season reflects that the heat exchange due to energy foundation operation leads to less loss of heat from the slab. For the particular geometry and climate settings evaluated, energy foundations lead to an overall negative impact on the slab heat loss during the heating and cooling seasons.

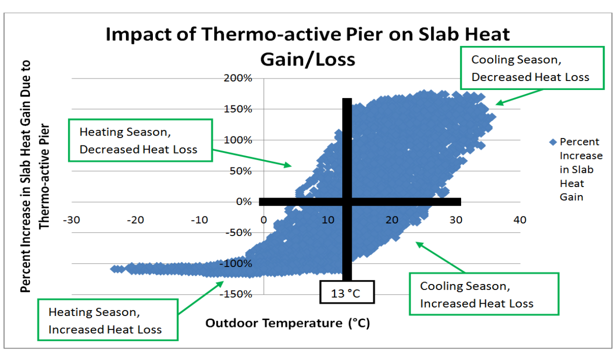
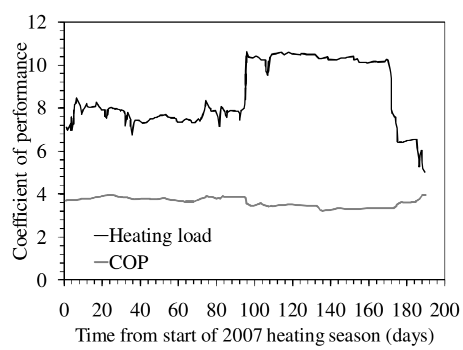


FIG. 6: Hourly increase or decrease in heat gain or loss from the building for an energy foundation as compared to a standard foundation (Kaltreider 2011)

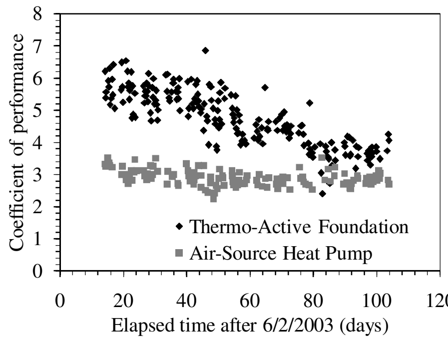
2.3 Field Assessment of Thermal Performance

A few full-scale energy foundation projects have provided some energy usage data (Ooka et al. 2007; Adam and Markiewicz 2009; Wood et al. 2009), proving the feasibility of this approach to provide sustainable heat output and long-term reductions in heating and cooling costs. The thermal efficiency of GSHPs is typically defined using the Coefficient of Performance (COP), which is equal to the thermal energy delivered by the system divided by the electricity input to operate the system. A typical COP value for air-source heat pumps (ASHPs) is 1-3 (Brandl 2006), although this varies with climate. GSHPs typically have a COP greater than 3, although this number may be lower for particular energy applications.

Wood et al. (2009) constructed a test plot consisting of 21 energy foundations which were 10 meters deep. A heat rejection setup was devised to simulate the heat load of a two-story, modern residential building with a ground floor area of 72 m^2. Testing of the energy foundations was performed over a heating season, with two different heating loads. The heating load and COP for the system is shown in Figure 7(a). The COP of the system was relatively consistent throughout the test, and equal to approximately 3.75. Ooka et al. (2007) compared the COP of an energy foundation and an air-source heat pump over the period spanning cooling and heating seasons, as shown in Figure 7(b). The COP of the energy foundation was found to be twice as high as the ASHP during the cooling season (early times), but decreases to 1.5 times greater during the heating season (late times). Adam and Markiewicz (2009) evaluated the performance of several different thermally-active geotechnical systems, including foundations, tunnel linings, sewers, and diaphragm walls. For an energy foundation used to support a cut-and cover tunnel, they observed a COP of approximately 2 for the period of several years. This system was exposed to the air in the tunnel, which may explain its lower COP.



(a)



(b)

FIG. 7: Thermal performance of energy foundations: (a) Coefficient of performance during different heating loads (after Wood et al. 2009); (b) Coefficient of performance over a summer and winter (after Ooka et al. 2007)

3 MECHANICAL BEHAVIOR

3.1 Experience from Field Analyses

In addition to the heat exchange design for energy foundations, geotechnical design is also required. Geotechnical design requires consideration of the complex interaction between temperature change and induced stresses and strains in the foundation, which may affect building performance. Specifically, contraction or expansion of the foundation during cooling or heating may lead to mechanical distress of the building or the concrete itself, or even changes in foundation side friction (and ultimate foundation capacity). Further, extreme conditions issues such as frost heave and subsequent settlement upon melting may occur if heat exchanger fluid temperatures are reduced below freezing for extended periods of time. Although freezing conditions in the heat exchanger can be avoided by programming of the control system for the heat pump, malfunctions may occur.

Deformations may occur in energy foundations due to thermo-elastic expansion, in which thermal strain ε_T occurs during a change in temperature proportionally to a coefficient of thermal expansion ($\varepsilon_T = \alpha_T\Delta T$). The coefficients of linear thermal expansion for the different materials in energy foundation analyses are presented in Table 1, along with typical Young's moduli values, which are needed to interpret thermally induced stresses. The coefficient of linear thermal expansion α_T of concrete can be as high as 14.5 x 10^{-6} m/m °C, while that of the steel used as reinforcement is 11.9 x 10^{-6} m/m °C (Choi and Chen 2005; Bourne-Webb et al. 2009). Because the two materials are compatible, differential thermal strains are not expected in reinforced concrete. The amount of thermal expansion or contraction for an energy foundation depends on soil-structure interaction, as the surrounding soil may provide a confining effect on the foundation.

The coupled thermo-mechanical loads in energy foundation produce unique stress and strain profiles, shown schematically in Figure 8 for the case of a floating foundation (no end restraint) (after Bourne-Webb et al. 2009). When a foundation is loaded under a mechanical load the largest stresses are seen at the top and diminish with depth. This loading profile is representative of the case in which the end bearing is not fully mobilized and when there are no residual stresses in the foundation from installation. Although the temperature distribution in energy foundations during heating is complex because heat is shed along the length of the heat exchanger tube, it can be assumed that the foundation changes in temperature uniformly for simplicity. In this case, the foundation will expand volumetrically about its mid-point, leading to a triangular profile of axial stresses due to the mobilized side shear. Accordingly, heating is expected to result in an increase in compressive stress throughout the foundation due to the axial expansion. The coupled response produces a uniform stress in the upper portion of the foundation, and the total stresses could be twice those from mechanical loading (Bourne-Webb et al. 2009; Laloui et al. 2006).

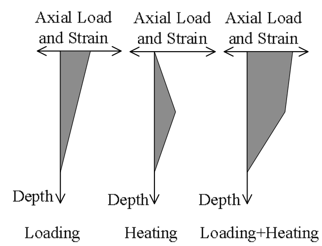


FIG. 8: Stress and strain response in energy foundations during heating (after Bourne-Webb et al. 2009)

As the foundation is cooled, it will tend to contract volumetrically. Because the mechanical load diminishes toward the bottom, tensile forces may occur if the cooling load is significant (Bourne-Webb et al. 2009). Further, contraction during cooling may lead to a reduction in radial stresses and possibly a decrease in side friction. Although cycles of heating and cooling may lead to a cumulative decrease in side friction if the soil does not respond elastically, this has not been fully investigated.

3.2 Experience from Field Analyses

The mechanisms of thermo-mechanical effects on energy foundations can be evaluated by assessing data presented by Bourne-Webb et al. (2009), who performed a series of thermal and mechanical loading tests on a full-scale foundation in England, and Laloui and Nuth (2006), who performed a series of thermal and mechanical loading tests on a full-scale foundation in Switzerland. Laloui (2011) also presented additional the field data from the site in Switzerland. The foundation tested by Bourne-Webb et al. (2009) was a 0.56 m diameter drilled shaft with a depth of 22.5 m, containing three polyethylene heat exchange loops. The lower 18.5 m of the foundation is in London clay with the rest of the foundation in cohesionless and fill material. The foundation tested by Laloui and Nuth (2006) was a 25.8 m-long drilled shaft having a diameter of 0.88 m. The upper 12 m of the foundation was in alluvial soils, while the lower part of the foundation was in glacial moraine material.

Bourne-Webb et al. (2009) loaded their foundation to 1200 kN, cooled it to -6 °C, and then heated it to 40 °C. Laloui and Nuth (2006) loaded their foundation to 2140 kN, increased the temperature by 21 °C above the natural ground temperature, then cooled it to 3 °C above the natural ground temperature. The strain distributions in the foundations tested by Bourne-Webb et al. (2009) and Laloui and Nuth (2006) after initial loading (data was only available from Bourne-Webb et al. 2009) and heating are shown in Figure 9(a). These strains were measured using fiber optic cables in the case of Bourne-Webb et al. (2009) and with strain gauges in the case of Laloui and Nuth (2006). The initial strain value at the bottom of the foundation measured by Bourne-Webb et al. (2009) indicates that there was a slight mobilization of end bearing during mechanical loading.

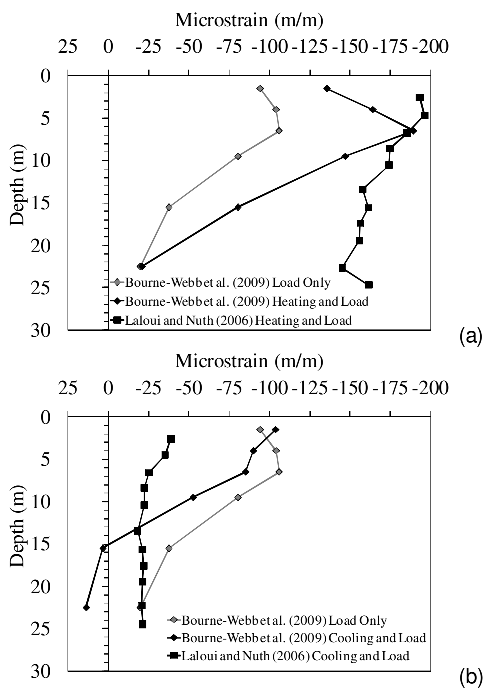


FIG. 9: Field data from energy foundations: (a) Loading with heating; (b) Loading with cooling

Similarly, the strain distributions after loading and cooling are shown in Figure 9(b). A small tensile stress was noted in the bottom of the foundation tested by Bourne-Webb et al. (2009) because the end bearing had not been fully mobilized. Overall, the observations from the field after loading then heating are consistent with the hypothetical response in Figure 8.

The impact of heating on the magnitude of thermally induced strains reported by Laloui (2011) is shown in Figure 10. These results indicate that a change in temperature from 5 to 20 °C leads nearly a 3 time increase in compressive strains in the foundation with no surface load. The changes in stress were primarily due to the frictional resistance from the soils.

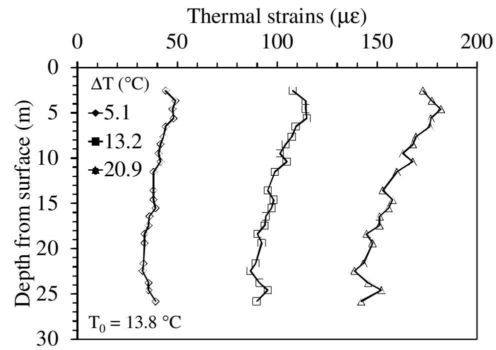


FIG. 10: Centrifuge-scale testing setup for energy foundations

The movement of the foundation associated with thermo-elastic expansion may lead to some heave or settlements of the foundation butt, and could potentially create down-drag on the foundation. The worst-possible scenario for thermally induced movement would be the case of thermo-elastic expansion of a foundation with a rigid end restraint and no side shear (Bourne-Webb et al. 2009). The presence of soil will resist the movement of the foundation, potentially making the surface movements negligible. For a foundation that was not loaded axially, Laloui et al. (2006) observed a butt heave of nearly 4 mm during an increase in temperature of 21 °C over the period of 1 day (Figure 11).

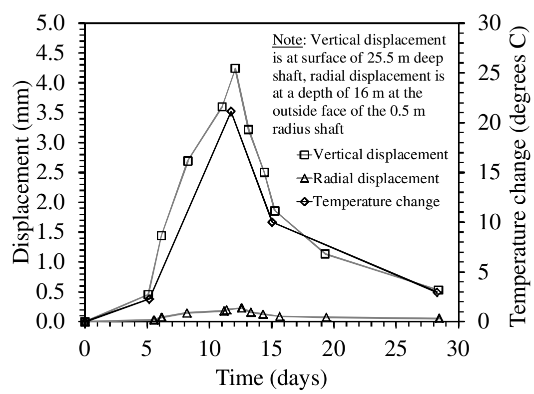


FIG. 11: Thermal deformations of an energy foundation (Laloui et al. 2006)

The foundation did not return to its original elevation upon cooling, but maintained an upward displacement of approximately 1 mm. Although the movements are minor, Laloui et al. (2006) indicated that the increase in temperature may have led to a plastic response in the clay. The soil was observed to partially recover deformations after cycles of heating and cooling, causing permanent foundation movement. A small amount of radial displacement was noted during heating.

3.3 Experience from Centrifuge Testing

The results of Bourne-Webb et al. (2009) and Laloui and Nuth (2006) are useful in identifying the mechanisms governing the structural performance of energy foundations. However, their tests required significant cost and time to perform. The field results are sensitive to the foundation installation process and the soil profile at each site, and subsequent testing may be affected by thermo-plastic strains in the surrounding soils. In order to build upon their experience, scale-model energy foundations may be evaluated in the geotechnical centrifuge. Centrifuge modeling permits parametric evaluation of the variables affecting the structural response of energy foundations under controlled conditions.

A setup used to evaluate the impact of heating on the ultimate capacity of energy foundations bearing in soil is shown in Figure 12 (Rosenberg 2010). The foundations were tested in silt, which was compacted around the foundations in lifts to a dry unit weight of 17.2 kN/m^3 at its optimum water content (13.6%) within a cylindrical, insulated aluminum tank with an inside diameter of 0.8 m and height of 0.7 m. Four foundations having diameters of 76.2 mm and lengths of 381 mm were placed within the container for these tests at a spacing of 3 diameters. This spacing was found to lead to minimal interference between foundations with respect to thermal and mechanical loading, while maintaining the same soil conditions for each of the foundations. The concrete foundations were cast outside the centrifuge using welded wire mesh as the reinforcement cage and an aluminum pipe as the heat exchanger. A heat pump outside the centrifuge was used to circulate fluid through the heat exchanger to heat and cool the foundation.

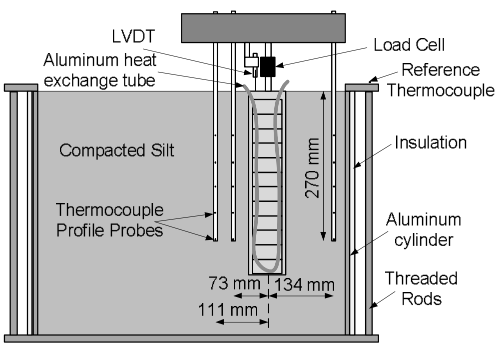


FIG. 12: Centrifuge-scale testing setup for evaluating the capacity of energy foundations

The foundations were tested at a g-level of 24. At this g-level, they represent prototype foundations with a length and diameter of 9.1 m and 1.8 m, respectively. Each of the foundations was tested individually after the soil and foundations had returned to ambient conditions from a previous test. Temperature profiles measured with thermocouple profile probes indicate that temperature did not extend to the soil in the vicinity of the other foundations. The load settlement curves (in prototype scale) for a series of different energy foundations are shown in Figure 13. The load-settlement curve for a baseline foundation was obtained by applying a constant displacement rate of 0.08 mm/min to the butt of the foundation and measuring the load. A second test indicated good repeatability [Figure 13(a)].

The impact of heating the foundations to different temperatures without a building load is shown in Figure 13(a). Because there is no building load in this case, the increase in capacity with temperature noted in this figure can be attributed to the increase in radial stresses during heating, which will lead to an increase in ultimate side shear capacity. The foundations that were heated from 15 to 60 °C then loaded axially to failure experienced an increase in side shear of 40% above that of baseline foundations tested at ambient temperature. A plunging-type failure was noted in the foundations tested under higher temperatures, possibly indicating that the foundation behaved in a more brittle fashion due to the greater lateral stresses induced by expansion of the foundation during heating.

The impact of heating and cooling after loading the foundation to a prototype building load of 800 kN was evaluated for two other foundations, shown in Figure 13(b). After reaching the building load but before increasing the temperature, some consolidation was noted. A force-displacement feedback loop was used to maintain the same load on the foundation. A greater amount of consolidation was observed in Test 3 than in Test 2, which may indicate that the compacted soil may have been slightly softer beneath this foundation. Nonetheless, the foundations all had similar initial slopes to their load-settlement curves. After stabilization under the building load, one of the foundations (Test 2) was heated to 50 °C (the centrifuge temperature was constant at 15 °C) then loaded to failure. The other foundation (Test 3) was heated to 50 °C, cooled down to 20 °C, then loaded to failure.

For simplicity, the ultimate capacities of the foundations heated to a constant temperature can be evaluated using Davisson's criterion:

$$(1)\quad Q_{ult} = 0.0038\ m + 0.01D + QL/AE$$

were D is the foundation diameter in prototype scale and QL/AE is the elastic compression of the foundation. The capacities for Tests 1 through 3 are 1380, 2150, and 1640 kN, respectively. The foundation that was heated then loaded to failure (Test 2) had a capacity that was 1.6 times greater than that of the baseline case. This is due to both consolidation of the soil at the tip of the foundation, as well as an increase in horizontal stresses and side friction along the length of the foundation. The foundation that was heated then cooled before being loaded to failure (Test 3) had a capacity that was 1.2 times greater than that of the baseline case. The difference between the capacities of the foundations in Tests 2 and 3 can be described by the fact that the foundations both expand during heating, causing consolidation of the soil at the tip of the foundation and along the sides of the foundation. After the foundation in Test 3 is cooled, the horizontal stresses will be less, leading to a lower side shear stress than in Test 2. However, the end bearing should be similar to that in Test 2 (and greater than in Test 1) because of the stiffer soil at the tip of the foundation.

to assess the impact of end restraint, as shown in Figure 15.

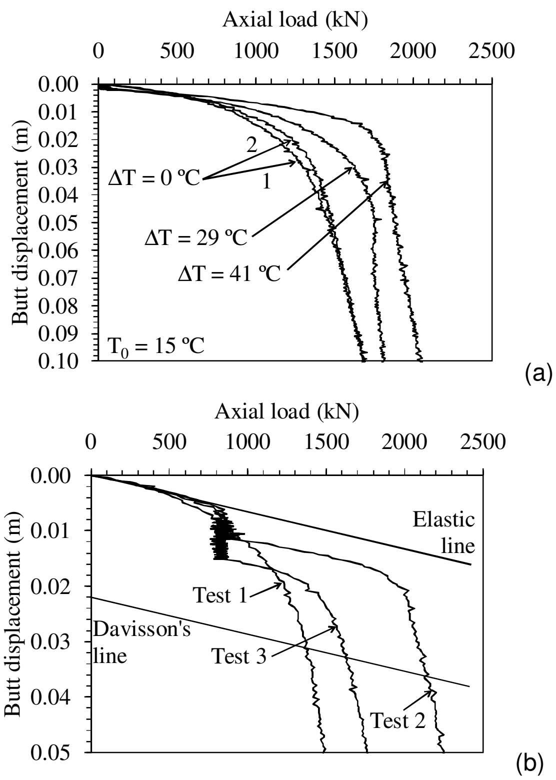


FIG. 13: Load-settlement curves for scale-model foundations in prototype scale (Rosenberg 2010): (a) Impact of heating without a building load; (b) Impact of heating with a building load (Test 1: Baseline loading at 15 °C; Test 2: Heating to 50 °C then loading; Test 3: Heating to 50 C°, Cooling to 20 °C then loading)

In many locations drilled shaft foundations are socketed into rock, which will not change significantly in end bearing. This implies that changes in side friction may still occur, but will likely not influence the performance of the foundation. However, the temperature-induced stresses in energy foundations socketed into rock may be a more important issue to consider.

Accordingly, a series of centrifuge modeling tests were performed on foundations with embedded strain gauges and thermocouples to assess strain distributions during mechanical and thermal loading. A schematic of the instrumentation layout for these more advanced centrifuge tests is shown in Figure 14. The soil conditions are the same as those for the capacity tests described in Figure 12. In addition to thermocouple profile probes, moisture content sensors and surface LVDTs were used to measure the deformation of the soil and foundation. A single model foundation having dimensions of 50.8 mm in diameter and 533.4 mm in length was tested in the center of the same container described in Figure 12. The test performed on these foundation were performed a g-level of 24.6, so the stresses and strains induced in the foundation are representative of a foundation which has a diameter of 1.25 m and a length of 13.12 m. Foundations having two different lengths were evaluated to assess the impact of end restraint, as shown in Figure 15.

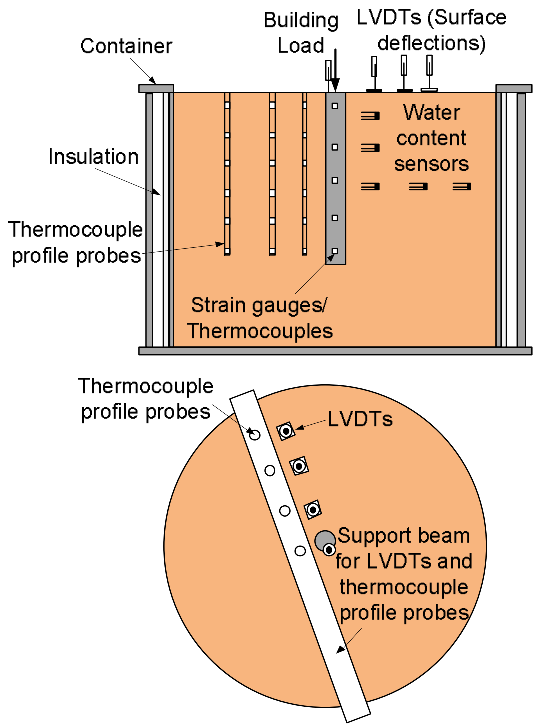


FIG. 14: Centrifuge-scale testing setup for evaluating the strain distribution in energy foundations

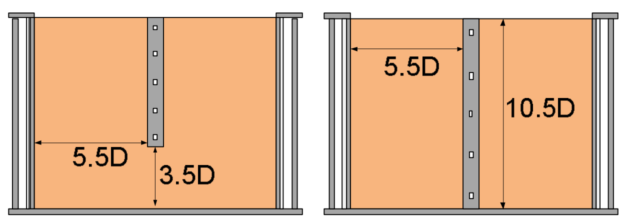


FIG. 15: Boundary condition for model energy foundations

The strain distributions measured in the foundation whose tip is resting on the bottom of the container is shown in Figure 16(a). For the mechanical loading, the strains are subtracted from the self-weight strains due to centrifugation, and the thermal strains are subtracted from those at the end of mechanical loading. The mechanical loading indicates that the surface load of 303 kN is not sufficient to mobilize the reaction from the bottom of the container, and that most of the load is absorbed by side shear. The strain distribution during heating under this loading condition up to 24.2 °C (ΔT = 8.7 °C) indicates an increase in compressive stress of more than a factor of 4. Greater thermal strains are noted in the region with lower axial stress. During cooling, it appears that a small amount of residual strains remain near the bottom of the foundation. In this case, the side shear forces may trap the compressive stresses induced by heating.

The strain distributions measured in the foundation whose tip is resting in soil are shown in Figure 16(b).

Similar to the foundation resting on the bottom of the container, a mechanical load of 263 kN was not sufficient to mobilize end bearing. During heating to two different temperatures, an interesting pattern in strains was noted. Compressive thermal strains were noted near the top of the foundation, while tensile thermal strains are noted near the bottom. This may be due stretching of the foundation deeper in the soil profile due to a lack of shear restraint from the surrounding soil. Additional tests are currently being performed to validate the trends noted in these figures.

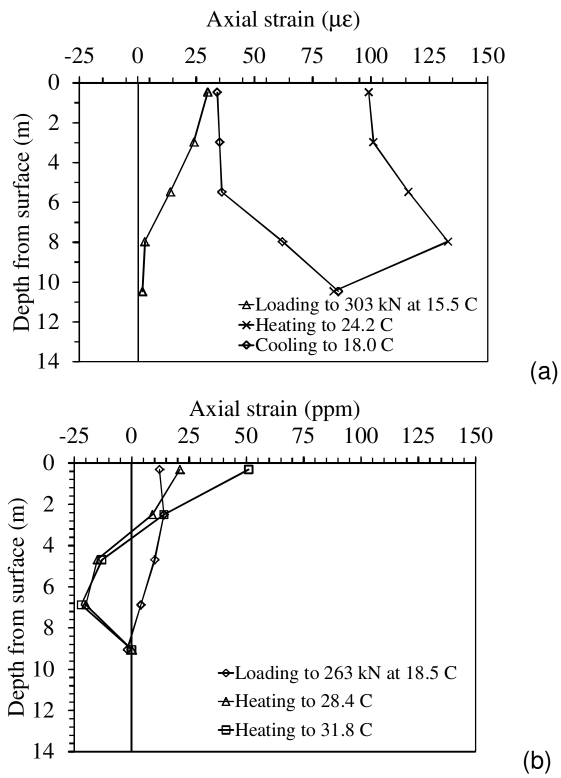


FIG. 16: Strain distributions in energy foundations

3.4 Soil-Structure Interaction (Load Transfer) Analyses

Load transfer (T-z) analysis is a simple, 1-dimensional approach to analyze the interaction between the foundation and surrounding soil during mechanical and thermal loading of the foundation. The basic principles of axial soil-structure interaction analyses during mechanical loading are well established (Coyle and Reese 1966). In this analysis, the behavior of each foundation element can be represented by a spring with elastic stiffness K_i = AE/L. A mechanical T-z analysis is performed by imposing a deformation on the toe of the foundation, and ensuring compatible foundation deformations and side shear displacements. Recently, Knellwolf et al. (2011) has developed a T-z analysis which can consider the deformation of an energy foundation during thermal loading. In this case, the shear restraint of the soil to the thermo-elastic deformation of the foundation was quantified. This simple, yet powerful analysis is capable of capturing the stress and strain distributions in full-scale energy foundations (i.e., Figure 10). Areas of thermal T-z analysis which are still being explored are the impact of thermally-induced radial stresses on the side shear resistance, different end boundary conditions, and the impact of temperature on the stress-strain curves for end bearing and side shear.

The mobilization of end bearing with tip displacement is represented using a Q-z curve. The ordinate of this plot is the normalized end bearing (ratio of mobilized end bearing to ultimate end bearing), and the abscissa is the displacement of the pile toe. Similarly, the mobilization of the side shear with displacement is represented using a T-z curve. The ordinate of this curve is the normalized side shear (ratio of actual side shear to ultimate side shear), while the abscissa is the relative displacement between the shaft element and surrounding soil. Q-z and T-z curves were defined using hyperbolic functions, with parameters selected to fit the shapes of the experimental load-settlement curves for the baseline cases, developed based on evaluation of curves for drilled shaft foundations discussed by O'Neill and Reese (1999). The Q-z and T-z curves are shown in Figure 17. Additional testing is required to evaluate the impact of temperature on these curves. The nonisothermal shear strength results from Uchaipichat and Khalili (2009) indicate that there is a thermal softening effect on the shear strength of soils, emphasizing the need for research in this area.

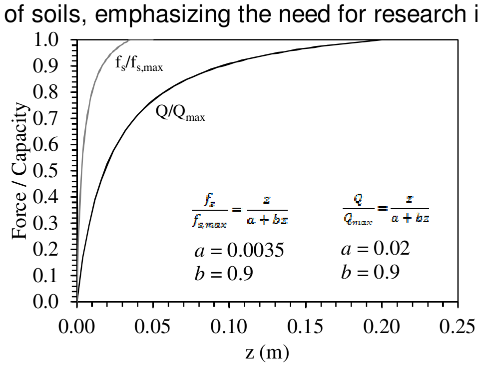


FIG. 17: Q-z and T-z curves for energy foundations

The other important inputs for a load-transfer analysis are the ultimate side shear and end bearing capacities. Although Rosenberg (2010) observed an increase in temperature at the toe, the end bearing is not expected to increase substantially with temperature unless a building load results in consolidation of the soil at the toe during foundation expansion. Some increase in end bearing likely does occur due to the downward movement of the lower half of the foundation during heating. Until this is better investigated, the ultimate end bearing can be estimated using conventional bearing capacity analyses, as follows:

(2) $Q_b = 9A_b\, c_u$

where 9 is the bearing capacity factor for deep foundations (i.e., a circular or square cross-section and a depth greater than 2 diameters), c_u is the undrained shear strength of the soil under the stress state at the tip of the foundation, and A_b is the cross sectional area of the toe. For the soil evaluated in the centrifuge tests, c_u at the depth of the capacity tests was estimated to be 42 kPa using a value of c_u/σ_v' = 0.265 and a value of σ_v' estimated using a total unit weight of 17.2 kN/m^3. The estimated value of Q_b calculated using Eq. (2) is 990 kN.

As the foundation expands laterally into the soil during heating, the soil will compress and the interface shear stress will increase in a drained fashion. The magnitude of increase in radial stress will depend on the thermal gradient as well as the contrast in linear coefficients of thermal expansion of the foundation and soil. The thermal effects from different heating situations were incorporated into an equation for the drained side shear distribution Q_s by McCartney and Rosenberg (2011), defined as:

(3) $Q_s=\beta A_s \sigma_v' (K_0 + (K_p - K_0)K_T) \tan\phi'$

where β is an empirical reduction factor representing soil-interface behavior, A_s is the side surface area, σ_v' is the overburden pressure, K_o is the coefficient of lateral earth pressure at rest (1 – sinϕ'), K_p is the coefficient of passive earth pressure (1+sinϕ')/(1-sinϕ'), and ϕ' is the drained friction angle (29° for the compacted silt used in the centrifuge tests). K_T is a factor representing mobilization of lateral earth pressure with thermal strain, defined as:

(4) $K_T=\kappa\, \alpha_T\, \Delta T[(D/2)/0.02L]$

where κ is an empirical coefficient representing the soil resistance to expansion of the foundation, α_T is the coefficient of thermal expansion of reinforced concrete (assumed to be 8.5x10^{-6} m/m °C), and [(D/2)/0.02L] is a geometric normalizing factor. κ is stress-dependent, but it was assumed to be constant in this analysis for simplicity. Eq. (3) only accounts for the impact of radial expansion of the foundation, and does not account for the upward relative movement of the upper half of the foundation during heating.

The load-settlement curve for baseline case 1 defined using the T-z analysis is shown with the measured curve in Figure 18. After modifying the T-z and Q-z curves to obtain the correct shape for the load settlement curve, a value of β of 0.55 was found to lead to the best fit for the portion of the curve at small displacements.

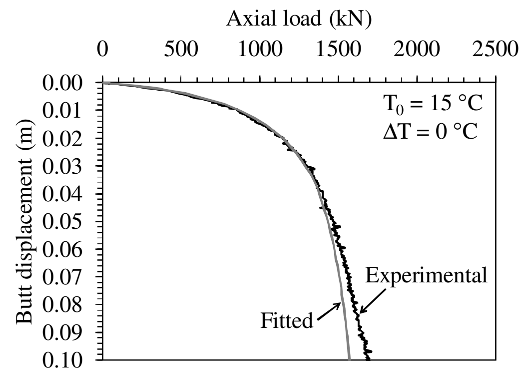


FIG. 18: Fitted T-z analysis for the isothermal baseline loading test on the centrifuge-scale foundation

The fitted load-settlement curve defined for the foundations heated to a temperature of 50 °C is shown in Figure 19(a). In this case, a value of κ equal to 65 along with the same value of β = 0.55 was observed to yield a good fit to the experimental curve. The values of β and κ were then used to predict the load settlement curve for the foundation heated to a temperature of 60 °C, shown in Figure 19(b) to have a maximum error of 16%.

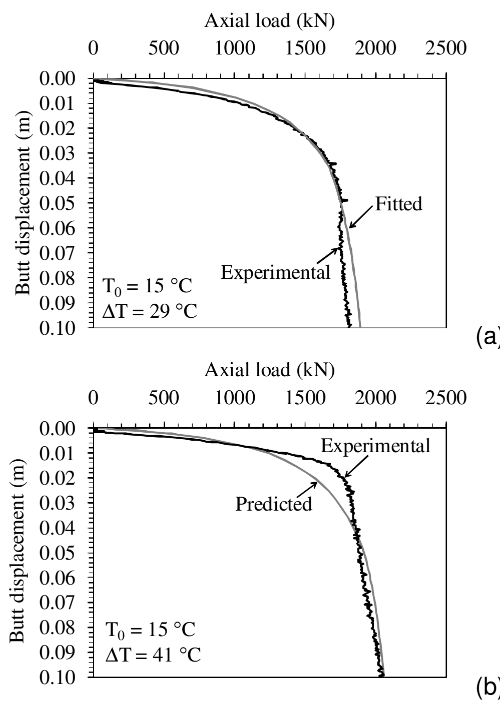


FIG. 19: Nonisothermal T-z analysis results: (a) Fitted analysis to obtain κ; (b) Prediction using fitted value of κ

3.5 Impacts of Heat Exchange on Soil Behavior

Another area in T-z analysis which is still being investigated is the impact of heating on the deformation of soils and the Heating of soil element in drained conditions may lead to both recoverable (elastic) and irrecoverable (plastic) volume changes. In the absence of clay minerals, which may be affected by temperature changes, the elastic and plastic volume changes arise due to the elastic expansion and contraction of the soil and pore water. Campanella and Mitchell (1968) and Paaswell (1967) described several mechanisms of volume change in water-saturated soils, with the primary mechanism for plastic strains being differences in the relative expansion of the water and soil particles during heating. Specifically, the coefficient of thermal expansion of pore water is approximately 7-10 times that of most soil particles (McKinstry 1965; Mitchell and Soga 2005).

In drained heating tests on normally consolidated and lightly overconsolidated soils, the differential expansions of water and soil particles leads to excess pore water pressure generation, which dissipates with time resulting in a time-dependent, irrecoverable volumetric contraction of the soil (Sultan et al. 2002; Abuel-Naga et al. 2007a, 2007b). However, this mechanism of plastic thermally induced volume change is not observed in all soils. Several studies have found that saturated soils with overconsolidation ratios (OCRs) greater than 1.5 to 3 tend to expand elastically during heating (Paaswell 1967; Plum and Esrig 1969; Demars and Charles 1982; Baldi et al. 1988; Hueckel and Baldi 1990; Hueckel and Pellegrini 1992; Towhata et al. 1993; Delage et al. 2000; Cekeravac and Laloui 2004). Additionally, soils with a greater plasticity index show more volume change during heating (Sultan et al. 2002). The impact of OCR on the thermally induced volume change of saturated Kaolin clay is shown in Figure 20. The results shown in this figure emphasize that it is not only important to understand the stress-state of the soil at the location of energy foundation installation. Models have been developed to consider the elasto-plastic deformation of soils (Cui et al. 2000).

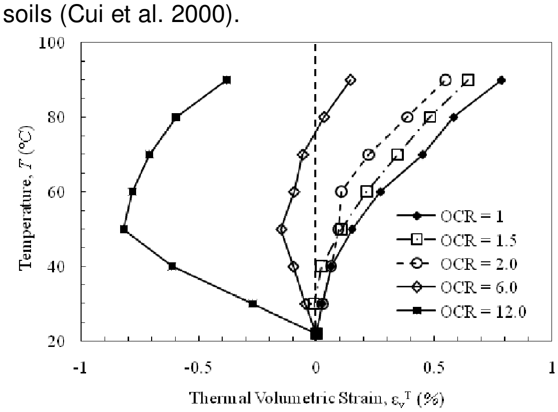


FIG. 20: Thermal volumetric strain versus temperature during heating of Kaolin clay having different values of OCR (Cekerevac and Laloui 2004)

3.6 Impacts of Heat Exchange on Foundation Design

To consider the implications of thermal-induced movements in the foundation, engineers in Switzerland double the design factor of safety for ultimate capacity for energy foundations from that used for conventional foundation design (Boënnec 2009). Bourne-Webb et al. (2009) reported that a design safety factor of 3.5 for ultimate capacity was used in the design of the energy foundation system for Lambeth College in the UK. The justification for such conservatism in safety factors is being investigated in recent research studies throughout the world, as it may effectively require twice as many foundations to support the same building load.

The most significant risk of energy foundations is in the possibility for differential movements as asymmetric thermal expansion or contraction could lead to the generation of bending moments and differential movement. Should heat exchange loops fail or clog in a given foundation, the foundation will cease to change in temperature. Significant differential expansion or contraction could occur should the heat exchange loops in a particular foundation fail next to a fully-functional foundation (Laloui et al. 2006). Boennec (2009) indicates that the current design practice in Europe is to assume that 10% of the heat exchange tubes can be expected to fail during the lifetime of a foundation. Differential displacements may also occur near the outer boundary of the building, where internal temperatures may be different from outer temperatures. These effects can be considered by limiting the range of temperature fluctuations, and possibly changing reinforcement patterns.

4 CONSTRUCTION OF ENERGY FOUNDATIONS

4.1 Geometry Issues

The geometric layout of the reinforcement cage and heat exchangers in an energy foundation are critical to its constructability and performance. The smallest diameter of an energy foundation is typically 0.6 m. This is because the reinforcement cage is typically undersized (75% smaller), so the access for attachment of heat exchanger tubing becomes complicated for smaller diameters. The inlet and outlet tubes of the heat exchangers should be attached to opposite sides of the foundation to minimize the chances for thermal short-circuiting, in which case heat will flow from the inlet tube to the outlet tube before the fluid has circulated through the length of the foundation. However, in large foundations, if there are not sufficient heat exchangers, this will lead to large differential temperatures across the foundation.

The lower extent of heat exchange tubing should be at least 1.5 m from the bottom of the design length of the reinforcement cage. This is important in the case that the hole cannot be drilled to the design depth and the reinforcement cage must be trimmed to the desired length, as shown in Figure 21(a). Further, it is important to avoid draping the heat exchange tubing over the bottom of the foundation. An approach to attach the bottom of the tubes is shown in Figure 21(b). This may prevent concrete from reaching the bottom of the foundation, or will lead to segregation of the gravel particle in the concrete.

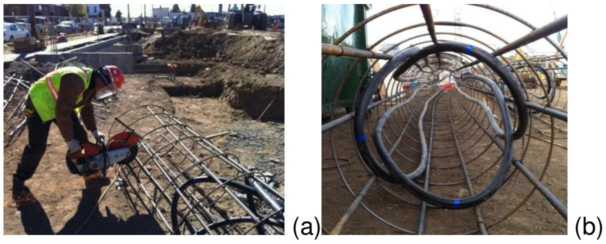


FIG. 21: Placement of heat exchangers in foundation

During installation, the heat exchanger tubing should be filled with water and pressurized. This will help to evaluate leaks in the heat exchanger tubing before installation, and will help to detect installation damage. Further, if the tubes are filled with water, the heat generated due to hydration of the concrete will dissipate quickly, and will help minimize the chance for the concrete to crack or pull away from the heat exchanger tubing.

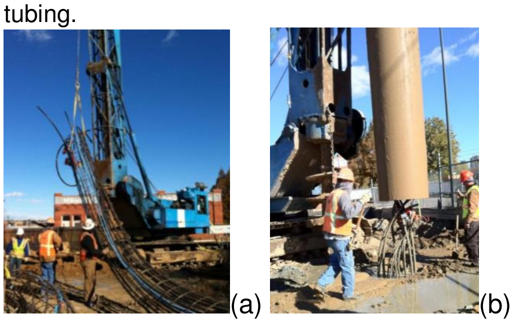


FIG. 22: Installation of energy foundations: (a) Lifting cage; (b) Retracting casing

The reinforcement cage should either be welded to avoid distortion of the cage during lifting [Figure 22(a)], or the vertical reinforcement bar should extend through the full length of the cage. In the case that a casing is used, the top of the tubing should be protected to avoid damage during withdrawal of the casing [Figure 22(b)].

4.2 Concrete Mix Design

The concrete mix design of a drilled shaft is critical to the performance of drilled shaft foundations. The impact of concrete mix variables on the thermal conductivity of concrete was performed by Kim et al. (2003). The key results of this study summarized in Figure 23 indicate that the percentage of aggregate in the concrete mix leads to the greatest impact on the thermal conductivity, as it leads to the densest mix. A lower water to cement ratio leads to slightly greater conductivity, while the ratio of quartz sand to coarse aggregate doesn't have a clear impact. Different additives may also help increase the thermal conductivity, including fly ash and blast-furnace slag.

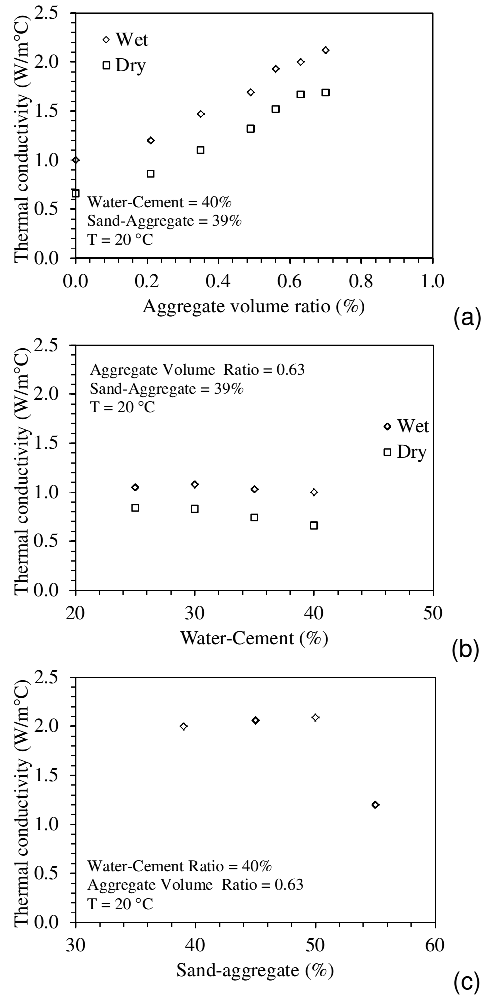


FIG. 23: Impact of different variables on concrete thermal conductivity (Kim et al. 2003): (a) Aggregate volume; (b) Water-cement ratio; (b) Sand-coarse aggregate ratio

Not only will the concrete mix determine the mechanical and thermal properties of the foundation, it will impact its constructability. The slump of concrete for drilled shafts should generally be greater than 20 cm in order to permit flow of concrete around the reinforcement cage and into the spaces around the heat exchangers (Brown and Schindler 2007). A greater percentage of coarse aggregate may lead to a higher thermal conductivity, but it will lead to lower slumps. If greater percentages of sand and super-plasticizer are added in the case of low water-cement ratios, the concrete may be self-consolidating. Although self-consolidating concrete is suitable for some locations in the country, it may not be desirable if foundations must be installed with a casing.

A comprehensive study on the impact of the concrete mix design on the thermal expansion of concrete is not yet available, but the range of coefficient of thermal expansion for different concrete mixes is listed in Table 1. Nonetheless, it is expected that concretes with a higher density will have greater thermal expansion.

5 CONCLUSIONS

A review of the literature on energy foundations indicates that they are a feasible technology to improve the energy efficiency of heating and cooling systems for buildings. Further, the thermal impacts on their mechanical response are not expected to lead to significant issues. Nonetheless, the importance of evaluating thermo-mechanical effects on the deformation and capacity of foundations and surrounding soils was emphasized using results from the literature and from a series of centrifuge scale-model tests. Ongoing research is leading to a refinement in analysis tools and an extension of the database of performance measurements. Further research is needed to formalize design guidelines and safety factors for the deformation and capacity of energy foundations.

6 ACKNOWLEDGEMENTS

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