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Impact of Horizontal Run-out Length on the Thermal Response of Full-Scale Energy Foundations

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ABSTRACT: This paper includes the results of a combined thermal response test performed simultaneously on four full-scale energy foundations beneath a new building at the U.S. Air Force Academy. The temperatures of the fluid circulating in and out of each of the closed loop heat exchangers in the drilled shaft foundations were monitored over the course of 21 days during application of a constant input energy. The temperatures of the foundations at different depths were also monitored. The horizontal length of pipe connecting each energy foundation to the manifold through the grade beam of the building was different. The results of the tests indicate that a longer horizontal run-out length leads to a lower apparent thermal conductivity, potentially due to the greater mass of concrete being heated, or lower heat transfer in the grade beam due to the higher temperatures of the ground surface during testing.

INTRODUCTION

Energy foundations are structural elements that incorporate a series of geothermal heat exchanger loops embedded in reinforced concrete, and are used for the purpose of exchanging heat between the subsurface and a building. Heat is transferred from the subsurface, which has a relatively steady temperature compared to the ground surface, to a fluid circulating through the heat exchanger loops, to a refrigerant circulating within a heat pump in the building. The heat exchange capacity of an energy foundation can be characterized using a thermal response test (TRT). These tests consist of injecting heat at a constant rate into the fluid circulating through the loops. TRTs are often performed on a foundation soon after installation, in which case heat is only transferred into the reinforced concrete and surrounding subsurface. However, these tests neglect the horizontal portion of the heat exchange loop within the building slab or grade beam that connects the foundation to the manifold and heat pump. In most cases, this horizontal run-out length is not insulated because of economical and time constraints and may be affected by surficial temperature fluctuations. Accordingly, the run-out length may affect the heat exchange capacity of the system. This paper presents an evaluation of the impact of horizontal run-out length through evaluation of the results of a thermal response test performed on four identical energy foundations installed beneath a building.

BACKGROUND

Thermal response testing of geothermal borehole heat exchangers has been in use for several years (Sanner et al. 2005), including development of testing standards and analysis approaches (Loveridge and Powrie 2012). Energy foundations differ from borehole heat exchangers in that the reinforced concrete can store heat during a thermal response test, and the geometry of the foundations and embedded heat exchangers do not satisfy the assumptions of most simple thermal response test analyses. Several investigations have been conducted to characterize the thermal performance of energy foundations, in terms of either the heat pump efficiency (Wood et al. 2009) or the system thermal conductivity (Brettmann and Amis 2011; Ozudogru et al. 2012; Loveridge and Powrie 2012). The heat exchange characteristics of energy foundations depend on the thermal properties of the different structural materials and geologic strata, groundwater flow, foundation dimensions, thermal response test procedures, and the analysis method. The heat exchange response during operation of a building depends on the heating or cooling load applied to the foundation (Sanner 2001). Loveridge and Powrie (2012) and Bourne-Webb (2013) collected data from a number of studies and observed that foundations with a low length to diameter ratio have a greater heat flux per unit meter (Q/L). Further, they found that transient heating tests lead to a greater Q/L than steady-state heating tests. This was attributed to the thermal mass of the concrete, which has a higher specific heat capacity than the surrounding soil.

ENERGY FOUNDATION SYSTEM

Building and Project Description

A new building at the US Air Force Academy (USAFA) was constructed to evaluate the long-term performance of energy efficiency technologies to aid in the development of “net zero” energy consuming structures for the U.S. Department of Defense (DoD). These technologies include energy foundations with different heat exchanger configurations, a radiant in-floor heating system, solar photovoltaic panels, and a solar water heating system. The building contains a conventional gas-powered heating system which will be used to provide back-up heating to the ground-source heat pump coupled with the energy foundations, and will also permit comparison of the energy efficiencies of the two systems under similar environmental conditions.

Subsurface Conditions

Relevant data from a site investigation within the building footprint is shown in Table 1. 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. No groundwater was encountered during the site investigation or foundation installation, so it is assumed to be at a depth greater than 16 m. Field classification tests indicate that all materials are non-plastic and non-expansive. Thermal conductivity of each layer was measured on site in disturbed samples recovered from a split-spoon sampler using a thermal needle (KD2Pro from Decagon Devices of Pullman, WA).

Table 1. Summary of stratigraphy encountered during subsurface exploration

Layer	Depth to bottom of stratum (m)	Material encountered	Gravimetric water content (%)	Dry unit weight (kN/m ³)	Thermal Conductivity (W/mK)
1	1	Sandy fill w/ silt, gravel	5	18.4	1.118
2	2	Dense sands, silt, gravel	7	19.2	0.785
3	12+	Sandstone	N/A	N/A	1.233

Energy Foundations and Heat Exchanger Configurations

Eight drilled shafts provide support for the structure, each having a depth of 15.2 m and a diameter of 0.61 m. Although the one-story building could have been constructed with a shallow foundation, the drilled shafts were incorporated to evaluate the thermal and mechanical response of the energy foundations as part of this research study. 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 perimeter of the building. The shafts were constructed using the dry hole method due to the lack of groundwater and the competency of the subsurface material.

Each foundation contains a closed-loop heat exchanger constructed from 19 mm-diameter high density polyethylene (HDPE) tubing. Each shaft has either one, two, or three heat exchanger loops configured as shown in Fig. 1. The tubing is routed from the foundation to the manifold 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 separated diametrically by at least 90° to minimize thermal short-circuiting where heat is lost by direct transmission from the inlet to outlet tubes. U-shaped couplings were used 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.

Figure 1: Heat exchanger loop configurations in the energy foundations

This study focuses on the behavior of Foundations 1 through 4, each of which has identical heat exchanger configurations with two continuous loops arranged in a W-shape. Each of the four shafts contain a total of 61 meters of heat exchanger tubing, but each has a different horizontal run-out length. The grade beam was constructed around the foundations and the heat exchangers were routed through the grade beam into a manifold in the mechanical room. A photo illustrating the run-out tubing in the grade beam prior to concrete placement is shown in Fig. 2(a). The routing of the run-out pipes and lengths are shown in plan view in Fig. 2(b).

Figure 2: (a) Run-out tubing in grade beam prior to concrete placement, (b) Plan view of run-out tubing connecting foundations 1-4 to the manifold

Instrumentation

Vibrating wire strain gages and thermistors were incorporated into Foundations 1, 3, and 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 Fig. 3. Foundations 1 and 3 contain six thermistors, while Foundation 4 contains twelve. Foundation 4 has twice the number of gauges with the intent of capturing a more discretized temperature distribution with depth. At three locations within Foundation 4, gauges were located at the same depth on opposite sides of the reinforcing gage to gain redundancy in temperature readings and to capture any differential temperature measurements across the width of the shaft. 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.

Figure 3: Locations of thermistors in each instrumented foundation

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 Fig. 1. The subsurface temperatures around Foundations 3 and 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 for the Thermal Response Test

A heating test was conducted to evaluate the thermal response of Foundations 1 through 4. As these foundations have identical heat exchanger configurations, the impact of the run-out pipe length on the apparent thermal conductivity could be assessed. A photo of the manifold system is shown in Figure 4. The manifold was insulated during the test to reduce the influence of ambient outside air temperatures on thermistor readings. An 11 kW thermal response test unit was used to circulate and heat a 20% propylene glycol-water mixture. Fluid properties of the glycol mixture are shown in Table 2. The heated fluid passed into the supply header, circulated through the foundations, and then passed out of return header back to the test unit. The fluid rate out of each foundation was measured when the fluid temperature was 30 °C using a differential pressure meter inserted into a pressure and temperature port (P/T ports). The P/T port includes a Venturi balancing valve for calculation of the flow rate from the differential pressure. The ball valves were adjusted with the goal of maintaining the same flow rate through each foundation, but the accuracy of the meter only permitted the flow rates to be within 30 ml/s of each other. During testing, the inlet and outlet fluid temperatures for each foundation were monitored using pipe plug thermistors installed in the P/T ports.

Figure 4: Energy foundation manifold configuration prior to insulation

Table 2: 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

RESULTS

Seasonal temperatures vs. depth were recorded at various times over the course of a year, as shown in Figure 5. Ground temperature fluctuates between 5 °C and 16°C near the surface then becomes relatively stable at a temperature of 9 °C at depths below 4 m. The depths in this figure (and other figures) are measured from the bottom of the grade beam, which is 0.91 m below the ground surface.

Figure 5: Seasonal temperature profile of Foundation 4

Figure 6 shows the inlet and outlet fluid temperatures for the four foundations. In all cases, a relatively rapid rise in temperature was observed in the first 25 hours before reaching more steady conditions. The differences in fluid temperatures, ΔT , are also plotted on the right vertical axis for each foundation. A constant value of ΔT reflects a uniform heat input energy into the system. Although the data acquisition system malfunctioned over a weekend causing a gap in the data, the trends are clear.

Figure 6: Temperature rise curves and differential temperature during testing: (a) Foundation 1; (b) Foundation 2; (c) Foundation 3; (d) Foundation 4

The temperatures of Foundations 1, 3 and 4 as well as the thermistor borehole strings were monitored during the test. The time series and temperature profiles for Foundation 4 and Borehole 5 (located 1.2 m from the center of Foundation 4) are shown in Figure 7. The temperature rise in Foundation 4 is relatively uniform with depth during heating. An increase in temperature does not occur in Borehole 5 until 50 hours after the test is started, after which the temperature rises steadily indicating uniform heat flux. The sensor at 0.61 m is warmer due to its proximity to the surface.

Figure 7: Temperatures: (a) Foundation 4 time series; (b) Foundation 4 profiles; (c) Borehole 5 time series; (d) Borehole 5 profiles

ANALYSIS

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

$$Q = \Delta T \dot{V} \rho_{\text{fluid}} C_{\text{fluid}} \quad (1)$$

where 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, ρ_{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 value of ΔT was defined using the average of the time series shown in Fig. 6 after reaching steady state.

The most rigorous approach to estimate the thermal conductivity of the energy foundation-soil system would be to solve Fick's second law inversely considering the boundary conditions and optimizing the layer thermal properties to match the data in Figure 6. However, it may be impossible to find a unique solution for such a complex system. Several analytical solutions to Fick's second law are available for simplified heat exchanger geometries, including the infinite or finite line or cylinder sources. Analytical solutions have the shortcoming that the thermal heat capacity of the

different materials cannot be considered, an issue that is relevant in transient heating and cooling of energy foundations (Bourne-Webb 2013). However, these solutions provide a simple approach to assess the role of horizontal run-out length. The infinite line source equation was used in this study for simplicity, acknowledging the fact that the heat exchanger is not a linear element. The line source method involves prediction of the change in temperature of a medium surrounding a line heat source with constant heat input energy. The change in temperature of medium at a radial distance of r away from the line source can be calculated as follows:

$$T(t, r) = -\frac{Q/L}{4\pi\lambda} \text{Ei}\left(-\frac{r^2}{4\alpha t}\right) \quad (2)$$

where r is the distance from the source in m, Q/L is the heat input energy per unit length (W/m), λ is the thermal conductivity in W/mK, α is the thermal diffusivity, and t is the time from the start of heating. Ei is the solution to the following integral, which can also be presented in a linearized form for small values of r , as follows:

$$-\text{Ei}(-x) = \int_x^\infty \frac{e^{-t}}{t} dt \cong -0.58 - \ln(x) \quad (3)$$

where x is the term in parentheses in Eq. (2). After inserting Eq. (3) into Eq. (2), the differential form of Eq. (2) can be rearranged to define the system thermal conductivity, as follows:

$$\lambda_a = \frac{Q}{4\pi L} \left[\frac{dT}{d(\ln t)} \right]^{-1} \quad (4)$$

where λ_a is the apparent thermal conductivity of each foundation in W/mK, L is the effective length of each foundation system in meters (representing the distance from the manifold to the tip of the foundation), and the term in brackets represents the slope of the change in mean fluid temperature versus the logarithm of time. The mean fluid temperature vs. logarithmic time is plotted in Fig. 8 and a constant slope is observed for each of the four foundations. The slope is calculated at large times after which it is assumed that the heat capacity of the concrete has been reached and heat is being transferred by conduction into the surrounding subsurface.

Figure 8: Mean fluid temperature rise vs. logarithm of elapsed time

Details of each foundation and TRT results are summarized in Table 3. As each of the four foundations has the same length and heat exchanger tubing, the only difference is the horizontal run-out length. Foundation 1 has the longest horizontal

run-out length (and largest L), and has the highest heat input energy consumption, Q, and the highest average value of ΔT . However, the heat transfer per unit length, Q/L, is the lowest. Foundation 3 has the shortest run-out length and the lowest heat energy consumption but the highest heat transfer per unit effective length.

Table 3: Details of loop lengths and summary of results

Foundation #	1	2	3	4
Run-out length, H_{ro} (m)	27.4	18.3	6.1	8.4
Effective length, L (m)	42.6	33.5	21.3	23.6
Flow rate (ml/s)	109	119	137	106
Q (W)	3133	2696	2180	2081
Q/L (W/m)	73.5	80.5	102.3	88.2
dT/d(ln t)	4.01	3.96	4.10	4.05
λ_a (W/mK)	1.5	1.6	2.0	1.7
$\lambda_{a, corrected}$ (W/mK)	2.0	2.0	2.1	1.9

Note: Each foundation is 15.2 m long and contains a length of 61.0 m of tubing.

The apparent thermal conductivity and heat transfer versus effective length for each of the four foundations are shown in Fig. 9. For greater effective lengths, the thermal conductivity and heat input energy per unit length decreases by nearly 0.6 W/mK. The response is similar to the decrease in heat transfer for increasing length to diameter ratios observed by Bourne-Webb (2013). This is potentially due to the greater mass of concrete being heated, or lower heat transfer in the grade beam due to the higher temperatures of the ground surface during testing. This indicates that in the design phase of an energy foundation system, consideration for energy loss through the horizontal portion of the geothermal loop needs to be considered. In practice, energy foundations may be connected in series to reduce this effect. The system described in this study was plumbed in parallel in order to characterize and operate each energy foundation individually.

Fig. 9: Trends in apparent thermal conductivity and heat flux per unit length

A linear relationship was used to estimate the value of apparent thermal conductivity representing the case of a foundation without the effect of horizontal run-out length, as follows:

$$\lambda_{a, corrected} = \lambda_a - m_{HR} \times H_{RO} \quad (5)$$

where $\lambda_{a, \text{corrected}}$ is the thermal conductivity of the foundation-soil system without the impact of the horizontal run-out length in W/mK, λ_a is the apparent system conductivity calculated from Eq. (4) in W/mK, m_{HR} is the run-out length correction factor in (W/mK)/m, and H_{RO} is the horizontal run-out length in meters. Use of this equation assumes that the thermal conductivity of each of the foundations is the same, which is reasonable as there is no significant change in stratigraphy between the foundation locations. After the correction is applied, values of apparent thermal conductivity range from 1.9 to 2.1 W/mK. This approach can be used for the other foundations at the site to eliminate the impact of horizontal run-out length on system conductivity to evaluate the thermal properties of the foundation-soil system alone.

CONCLUSIONS

The impact of the length of horizontal tubing connecting an energy foundation to the manifold and heat pump on the heat exchange characteristics of the energy foundation system was investigated in by measuring the temperatures of four foundations and surrounding soil boreholes during a 21 day-long thermal response test. The thermal conductivity and heat transfer per unit length results indicate that foundations with lower effective lengths (lower horizontal run-out lengths) may have greater normalized heat transfer performance. An empirical relationship was developed to account for the effects of horizontal run-out length, and corrected values of the apparent thermal conductivity ranged from 1.9 to 2.1 W/mK.

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