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Outcomes from the International Workshop on Thermoactive Geotechnical Systems for Near-Surface Geothermal Energy: From Research to Practice

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Abstract:
This paper summarizes the main outcomes of an NSF-sponsored workshop focused on thermoactive geotechnical systems for near-surface geothermal energy. A group of 55 researchers from around the world gathered for a 3-day workshop in Lausanne, Switzerland to discuss the current status of the linkages between geotechnical engineering and near-surface geothermal energy. This paper provides a summary of the state-of-the-art in characterization of materials in thermally active geotechnical systems, as well as our understanding of the thermal and thermo-mechanical behavior of these systems. The paper also includes a review of available thermal and thermo-mechanical design methods, along with associated lessons learned from implementation of thermally active systems. A discussion of the emerging technologies at the interface between geotechnical engineering and near-surface geothermal energy indicates that there are many opportunities to transfer knowledge between different fields. A list of current challenges and the associated research agenda for the future was identified during the workshop and indicates that many central challenges have been overcome but there are still important issues that need to be solved.

1. Introduction

Commercial and residential buildings consume 71% of the electricity generated in the U.S. and 53% of its natural gas (EIA 2008). Buildings consume approximately 39% of the primary energy in the U.S., and heating and building systems account for 20% of this fraction. Because of this significant energy use, buildings are responsible for generating 43% of the U.S. carbon emissions (EIA 2008). Development and characterization of new technologies to reduce building energy consumption are important goals in the U.S. and many other countries from both environmental and economic perspectives. Evaluation of the different ways that buildings consume energy indicates that electricity use cannot be eliminated, however there are opportunities to reduce the amount of electricity needed through energy efficiency technologies. One important energy efficiency technology that has seen widespread use since the 1970's is the ground-source heat pump (GSHP) (Brandl 2006). A heat pump is a device used to move heat from one location to another, and geothermal heat pumps specifically move heat to and from the shallow subsurface. The shallow subsurface is a naturally abundant thermal energy resource because a large fraction of the incident solar energy is absorbed by the ground. The shallow subsurface is able to retain a large amount of this absorbed thermal energy because the surface layer of the ground, which is often unsaturated (i.e., air and water are both present), is a natural insulator. Furthermore, groundwater and soil particles have a high capacity for heat storage.

Incorporation of heat exchangers into drilled shaft foundations or other civil engineering infrastructure (diaphragm walls, embankments, landfills, etc.) is a novel approach to improve the energy efficiency of building heat pump systems and provide necessary geotechnical support while using the same construction materials. However, their performance is closely tied with the characterization of material properties as well as the characterization of the system response. Design tools have been developed to consider the thermal and thermo-mechanical behavior of these systems, but further advancements are still needed to provide guidance on their implementation in emerging markets. In addition to reviewing the current state-of–the-art advances in these topics, this paper provides guidance obtained from the workshop on emerging technologies, implementation challenges, and research thrusts for the future.

2. Near-Surface Geothermal Energy

2.1 Ground-Source Heat Pump Concepts

Similar to a refrigerator, a heat pump permits heat to be moved from a source to a sink, even when the temperature of the heat source is similar to that of the sink. A schematic showing the concept of heat transfer in a geothermal heat pump system is shown in Figure 1.

An example of the ground temperature at different times of the year along with the mean monthly air temperature for a site in New York City, USA is shown in Figure 2. A relatively wide range of air temperatures is observed in this figure, which implies that both heating and cooling would be required for a building in this climatic setting. If an air-source heat pump is used to exchange heat between the building and the outside air, the efficiency of the heat pump may vary significantly throughout the year. Because the ground is a natural insulator permitting storage of solar energy, the temperature of the shallow subsurface varies much less than that of the outside air. While the temperature at the ground surface follows the air temperature, the temperatures deeper in the soil strata lag behind the surface temperature, and show less of a change in amplitude. Below a depth of 5-10 m, most of the fluctuations in temperature seen at the ground surface have damped out. In the absence of an upward geothermal gradient or strong radiative heating of the ground by the sun, the temperature of the ground at depth approaches the mean annual air temperature (Kusuda and Achenbach 1965). 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 (Brandl 2006; Omer 2008).

Because the ground has a relatively steady temperature, the efficiency of heat exchange between the ground and a building, which also has a relatively steady temperature, is more efficient than heat exchange with a more variable heat source like the outside air. By taking advantage of the relatively constant temperature of the shallow subsurface, the efficiency of heat pump operations can be improved (Lund et al. 2004). The increase in efficiency can potentially reduce energy use for space conditioning and water heating by up to 75%, depending on the type of conventional heating/cooling system used in a climatic region, as well as the need to provide heating, cooling, or both. The potential for such large reductions in energy use for space conditioning is significant for both national energy security goals as well as the ongoing battle against climate change. The Energy Information Agency has estimated potential GSHP energy savings at 2791 trillion kWh by 2030 (EIA 2008). Although GSHP systems often cost more than four times as much to install than conventional natural gas, oil, or electric heating/cooling systems, their operating costs are significantly lower (Omer 2008). To defer their high up-front cost, which has been identified as one of the main barriers to the implementation of GSHP systems (Hughes 2008), many states provide tax benefits and low-interest loans to businesses and homeowners.

There are many reasons that conventional GSHP systems and GSHP systems integrated in civil engineering infrastructure are sustainable heating and cooling options. GSHP systems are environmentally friendly, require relatively little power, help reduce fossil fuel demand, and decrease CO_2 emissions. They require minimal maintenance over their long lifetimes and encapsulation of the heat exchange tubes in concrete prevents accidental release of coolants. In addition, the installation of these systems in foundation elements (such as piles, diaphragm walls, etc.) permits the heat exchange system to be within the building footprint, making efficient use of materials and space. Heat exchanger systems incorporated into the floors of buildings offer more opportunities for radiative heating/cooling with better humidity control. Finally, because of the constant temperature of the ground, GSHP systems are less vulnerable to intermittent breaks in energy generation than hydropower (droughts), wind (or lack thereof), and solar (cloudy days and nights), and are less sensitive to energy price fluctuations. Because of these reasons, there has been an increase in the installation of GSHP systems.

2.2 Role of Geotechnical Engineers

There are many options for installing the ground-source heat exchangers used in a GSHP system. The two most-common closed-loop heat exchangers are U-loops in vertical, small-diameter boreholes and slinky-loops in horizontal trenches, as shown in Figure 3. These systems are typically installed outside of the building footprint. The additional drilling costs of these boreholes can be prohibitive, so heat exchange elements can be incorporated into geotechnical engineering systems which are already being installed to avoid this additional installation cost. One example of a thermoactive geotechnical system are energy piles, which are drilled shafts that incorporate ground-source heat exchange elements to transfer heat to or from the ground to the building (Brandl 2006; Laloui et al. 2006; Bourne-Webb et al. 2009; McCartney 2011; Olgun et al. 2012). An energy pile configuration is shown in Figure 4. A comparison of the relative heat transfer potential for conventional ground-source heat exchangers and energy piles is also shown in Figure 3. Although energy piles may not provide the full amount of energy required to heat and cool residential and commercial buildings, they may provide sufficient heat exchange to cover the base heating and cooling load for the building, which is typically 10 to 20% of the peak heating or cooling load. In this case, a conventional heating or cooling system would not be required except during peak heating or cooling events.

There are many other ways that heat exchangers can be incorporated into civil engineering systems. These include shallow foundations, diaphragm walls, tunnel or sewer lining systems, roadways, and bridges (Brandl 2006; Adam and Markiewicz 2009; Coccia and McCartney 2013; McCartney 2013; Stewart et al. 2014). Heat exchange loops installed in boreholes or energy foundations can be placed in roadways or bridges to keep the driving surface free of snow and ice. These strategies may lead to improved traffic safety, environmentally sustainable maintenance (no salts or sands needed), decreased need for snow chains, prevention of temperature-dependent rutting of asphalt, and minimization of freeze-thaw damage to base and subgrade soils among other applications. Despite their benefits and growing implementation, it is critical to evaluate the impact of temperature changes on the performance of civil engineering systems incorporating heat exchangers.

3. Material Characterization

3.1 Overview

The workshop involved a discussion on the role of characterizing the materials used in thermoactive geotechnical systems. These materials include the subsurface soil and rock, concrete, the plastic tubing used in heat exchangers, and the heat exchange fluid, which is usually mixture of water and antifreeze. These materials should be characterized from a thermal perspective to evaluate their role in the heat exchange aspect, as well as a thermo-mechanical perspective to ensure that thermally induced displacements and stresses are within acceptable limits. The characterization of these materials on an element-scale basis often requires the development of advanced testing techniques to consider the combined roles of stress state and temperature control. Advanced testing permits careful calibration of constitutive models that can be used to evaluate the behavior of each component of a thermoactive geotechnical system during heating and cooling operations. However, because thermoactive geotechnical systems involve a complex geometry and combination of different materials, it is often important to perform system-level physical modeling tests to characterize the overall response of the system. This is particularly important when considering the behavior in complex soil or rock strata (i.e., partially saturated soils, soft clays), where coupled heat transfer and water flow may be encountered or where complex thermo-hydro-mechanical processes may lead to changes in heat transfer, volume change, or stiffness.

3.2 Thermal Response

The thermal conductivity of soils and rocks on an elemental basis is often measured using a thermal needle probe, which uses the line source approach (Brandon and Mitchell 1989). A thermal needle consists of a resistance coil heater contained within a thin metal needle. A thermocouple is also placed within the needle to measure changes in temperature. A constant current is applied to the resistance coil, which will cause the needle to heat up depending on the thermal conductivity of the surrounding material. The thermal needle approach has been used to characterize the thermal properties of soils (Farouki 1981; Brandon and Mitchell 1989; Smits et al. 2012), and has been standardized in ASTM D5334. Examples of representative thermal conductivity values for minerals, rocks, and fluids are shown in Table 1. There are several variables which affect the thermal conductivity of soils and rock, including density, water content and Quartz mineral content (Farouki 1981; Brandon and Mitchell 1989; Tang and Cui 2006; Abuel-Naga et al. 2008; Tarnawski et al. 2009; Smits et al. 2012). Quartz crystal has one of the highest thermal conductivity values among minerals, while water and air (other important constituents of soils) have relatively low thermal conductivity values. The role of water content should be characterized using a single specimen to develop the thermal conductivity dryout curve (Woodward and Tinjum 2012), and it is important to consider the role of nonisothermal conditions (Smits et al. 2012). As sand bentonite is used as a thermal grout in GSHP applications (Tien et al. 2005), there are several variables that affect the thermal conductivity of this mixture, including density, water content, and the percentage of sand. In the case that concrete is used as the thermal grout, as with energy piles, the percentage of aggregate and to a lesser extent the water-cement ratio are important variables (Kim et al. 2003). However, high aggregate contents may lead to a low concrete slump, which will limit constructability of energy piles.

The heat exchange fluid is another very important component of a GSHP system (NRECA 1997; Kavanaugh et al. 1997). The properties of different heat exchange fluids are presented in

Table 2. In general, these liquids are typically mixed to some proportion with water to create an anti-freeze solution. The thermal conductivity of these liquids is often particularly low compared to that of soil and rock. The addition of anti-freeze. Although the addition of antifreeze to water drastically reduces the freezing temperature, it also leads to an increase in the viscosity of the solution. It should be noted that the viscosity decreases with temperature and the fluid may actually behave more like a viscous glass than a fluid at low temperatures. The different heat exchange fluids listed in Table 2 have acceptable environmental and toxicity risks.

The thermal response of a GSHP *system* should be regarded as equally important as the properties of the individual system components. This is because of inherent uncertainties about the geometry and layering of the soil strata in a geothermal application. In determining the thermal response of a GSHP system, a mobile heater is attached to the top of a heat exchanger loop and thermocouples are attached to the inlet and outlet fluid lines to monitor the temperature change of the fluid circulating in the borehole. Next, a constant heat source is applied to the fluid entering the borehole and the change in temperature of the outflow fluid is monitored (Shonder and Beck 1997). Shonder and Beck (1997) present an advanced equation to analyze the thermal conductivity of the temperature data, although the line source equation can also be used. Similar field thermal conductivity tests have been performed on networks of heat exchangers. A more in-depth analysis of the thermal resistance of different energy foundations has been developed by Loveridge and Powrie (2014) using the concepts of thermal resistance and shape factors.

To optimize the design of GSHPs, the system thermal conductivity, specific heat capacity, borehole resistance, and heat exchange rate must be evaluated accurately (Sanner 2001). Thermal response tests (TRT) are the most common method of determining thermal properties of the subsurface and energy foundation systems (Brandl 2006). Thermal response testing of geothermal borehole heat exchangers has been in use for several years (Sanner et al. 2005), and involves circulating a fluid through a heat exchanger while supplying a constant amount of power to the fluid. Conduction is assumed to be the primary mode of heat transport in the soil surrounding energy foundations. Most analyses assume negligible groundwater flow (and convective heat transfer).

The heat flux away from an energy pile can be estimated by assuming that it behaves like an infinitely long cylindrical source:

$$Q=-2\pi Rl\lambda \, dT/dr \quad (1)$$

where Q is the heat flux in W being supplied to the energy foundation, R is the radius of the energy pile, l is the length of the energy foundation, λ is the thermal conductivity of the medium in contact with the cylindrical source, and dT/dr is the temperature gradient in the radial direction. As the fluid flow rate through the heat exchanger pipes is sufficient to lead to a turbulent flow pattern, convection is assumed to be the predominant mechanism of heat transfer within the fluid. Conduction is assumed to be dominant through the heat exchanger pipe walls, concrete, and into the ground. During a TRT, the temperatures of the fluid entering and exiting the foundation are monitored over a period of several days. The measured values of the fluid supply and return temperatures and the mass flow rate through each foundation can be used to calculate the input heat flux in Watts, as follows:

$$Q = \Delta T_{fluid} \dot{V} \rho_{fluid} C_{fluid} \qquad (2)$$

where ΔT_{fluid} is the difference between the supply and return fluid temperatures in K, $\dot{V}$ is the fluid flow rate in m^3/s, ρ_{fluid} is the mass density of the fluid kg/m^3, and C_{fluid} is the specific heat capacity of the fluid in J/(kgK).

The thermal behavior of energy foundations depends on many factors including the thermal properties of individual materials in the heat exchanger, site stratigraphy, groundwater and its flow, heat exchanger configuration within the foundation, dimensions of the energy foundation, and thermal demands of the building (Brandl 2006). Several studies have used simple analytical solutions to investigate the thermal behavior of full-scale energy foundations in different soil types with various heat exchanger loop configurations and foundation geometries (Hamada et al. 2007; Ooka 2007; Gao 2008; Lennon et al. 2009; Brettmann and Amis 2011). The results of these studies are summarized in Table 3. The system thermal conductivity values reported in these studies range from 2.4 to 6.0 W/m·K, which is much higher than the thermal conductivity of most geological and structural materials, suggesting that the thermal conductivity values may incorporate the effects of the heat capacity of the concrete and may not represent steady-state conditions (Loveridge and Powrie 2012). To address these issues, the GSHP Association (2012) developed a design standard for energy piles that includes information on the accurate characterization of the thermal response of energy piles.

Several full-scale studies involved the evaluation of heat exchange efficiency in energy foundations during operation of a heat pump (Ooka et al. 2007, Adam and Markiewicz 2009, Wood et al. 2009). Performance of ground source heat pumps can be characterized as the ratio of thermal energy delivered to the system by the heat pump process to the electrical energy input required to operate the heat pump (the coefficient of performance). A typical COP value for a GSHP is 3 or greater, whereas the COP for an air source heat pump system is in the range of 1-3 (Brandl 2006). Wood et al. (2009) observed a COP of 3.62 for a heat extraction test on twenty-one 10 meter-deep energy piles. Ooka et al. (2007) observed an initially high COP of 6.7 for a pair of 1.5 m-diameter by 20 m-deep energy piles, although a decreasing trend over time was observed. These cases demonstrate that energy piles have good potential to be more energy efficient than air-source heat pump systems.

3.3 Thermo-mechanical Response

As a deep foundation is loaded mechanically, the axial stress is expected to be highest at the head and decrease with depth as side shear resistance is mobilized at the soil-foundation interface. The axial stress will decrease to zero if the side shear resistance is sufficient to support the building load; if not, it will decrease to a non-zero value and there will be end bearing resistance in the material underlying the toe of the foundation. As an energy foundation is heated or cooled, the reinforced concrete will tend to expand or contract axially about a point referred to as the "null point" (Knellwolf et al. 2011). The null point is the point of zero axial displacement during heating or cooling, and its location depends on the stiffness of the end boundaries imposed by the overlying superstructure and the material beneath the toe, as well as the distribution of mobilized side shear resistance (Bourne-Webb et al. 2009; Amatya et al. 2012; Murphy et al. 2014). It is also likely that radial expansion of the foundation will occur as the foundation is heated (Laloui et al. 2006), which may result in a net increase in ultimate side shear resistance (McCartney and Rosenberg 2011; Ouyang et al. 2011).

The upper limit on the thermal axial strain, $\varepsilon_{T,}$ in an energy foundation is the free expansion (i.e., unrestrained) thermal axial strain $\varepsilon_{T,free}$, defined as follows:

$$\varepsilon_{T,free} = \alpha_c \Delta T \qquad (3)$$

where α_c is the coefficient of linear thermal expansion of reinforced concrete and ΔT is the change in temperature. For geotechnical engineering purposes, the thermal axial strain is defined as positive during compression. Accordingly, α_c is defined as negative because structural elements expand during heating (i.e., positive ΔT). For the case that an energy foundation is restrained from moving such that the actual thermal axial strain ε_T is less than that predicted by Equation 3, the thermal axial stresses σ_T can be calculated as follows:

$$\sigma_T = E(\varepsilon_T - \alpha_c \Delta T) \quad (4)$$

where E is the Young's modulus of reinforced concrete. For energy foundations, soil-structure interaction mechanisms will restrict the movement of the foundation during heating. The side shear resistance, end bearing, and building restraint will influence the distribution of thermally induced stresses and strains (Mimouni and Laloui 2013). Soil-structure interaction mechanisms of energy foundations have been studied in centrifuge-scale tests for simplified soil profiles (McCartney and Rosenberg 2011; Stewart and McCartney 2013). However, evaluation of full-scale foundations imposes a set of real boundary conditions and soil strata. Several full-scale energy foundations have been evaluated to study the thermo-mechanical stresses and strains during mechanical loading, heating, and cooling (Laloui et al. 2006; Bourne-Webb et al. 2009; Amatya et al. 2012; McCartney and Murphy 2012; Olgun et al. 2012; Stewart and McCartney 2013; Murphy et al. 2014; McCartney and Murphy 2014a). The results from several of these studies are summarized in Table 4. The thermal axial stress ranges from -1 to 5 MPa and the thermal axial displacement of the foundation head ranges from 4.2 mm upward to 4.0 downward. The axial stresses are well within the compressive strength of reinforced concrete, and the axial displacements of the foundation would not lead to significant angular distortions to cause architectural damage for most buildings.

The effect of cyclic temperature-induced changes in energy pile performance is another area of research, which was discussed in other sessions of the workshop. During its lifetime, an energy pile is exposed to daily and seasonal temperature changes which result in expansion and contraction of the pile itself. These relative deformations between the soil and the pile can induce slip at the soil-pile interface which can affect the shear stress transfer between the soil and the pile. In addition, the soil surrounding the energy pile is exposed to temperature changes which can induce excess pore pressures, volume changes and degradation of the strength of the soil at the pile interface. Moisture migration away from the energy pile can reduce the thermal conductivity and also cause desaturation of the soil at the pile interface.

There are a number of experimental studies which investigated the temperature effects on the load-displacement of energy piles. A summary of these studies is presented in Table 5. These studies utilized small-scale models tested under 1-g or at increased g-levels in the centrifuge to represent field-scale stresses with different testing conditions, materials, and model preparation techniques, which may have an effect on the observed behavior and prevent them from fully representing full-scale energy piles. However, they may provide some guidance on the role of different issues.

At the University of Colorado at Boulder load tests on semi-floating heat exchanger piles have been performed in a centrifuge where different thermal loads were applied to the test pile before the application of a structural load. Partially saturated Bonny silt compacted around the pile was used for the tests. McCartney and Rosenberg (2011) observed that temperature changes affect the load-displacement behavior of energy piles in the partially saturated Bonny silt used in these tests, resulting in an increase in pile resistance. In addition, thermo-mechanical centrifuge tests were performed on end-bearing heat exchanger piles using partially saturated compacted Bonny silt (Stewart and McCartney 2013) and observed a reduction in water content near the test pile due to thermally induced water flow. Accordingly, the increase in capacity noted by McCartney and Rosenberg (2011) may be attributed to the increase in effective stresses associated with drying as well as increased lateral pressure induced by radial expansion. The compaction of the soil around the foundations may have led to an initially high radial stress that may not be representative of energy piles in the field.

Wang et al. (2011, 2012) performed tests at various temperatures on small-scale piles. Loosely compacted dry N50 fine sand, partially saturated N50 fine sand, and partially saturated 300WQ silica flour were used around the test piles. During heating, the authors observed no change in shaft resistance with the dry sand and a decrease in shaft resistance with the partially saturated sand and with the partially saturated 300WQ silica flour. The centrifuge tests performed by Goode et al. (2014) with dry Nevada sand at different temperatures did not show a significant change in pile response. Kramer and Basu (2014) performed similar small-scale tests under 1-g using F50 Ottawa sand and observed a slight increase in pile capacity at increased temperatures.

Although 1g tests have not been performed on saturated clays, pore water pressure development and thermal consolidation in saturated clays can alter the stress state and result in deformations around a heat exchanger pile. In energy piles, the rate of heating and the rate of dissipation of excess pore water pressures have to be carefully considered. Fast heating may lead to undrained heating and pore water pressure increases that may cause a decrease in pile capacity. Slow heating may lead to drained heating and thermal consolidation that may cause an increase in pile capacity.

4. Design of Thermally Active Geotechnical Systems

4.1 Thermal Design

Although GSHP systems can function successfully in any location or ground setting, the design team must understand the building requirements, assess the site before advancing to the design stage, utilize existing site resources to enhance the system and reduce installation costs, and be aware of regional geology and contractor assets/capabilities. Different types of heat exchangers (vertical borehole, shallow trenches, ponds, energy piles, etc.) will have different economic costs and the different types may or may not be possible for a given site. Ponds are typically the most economical choice, but they may not be available at every location.

After selecting a heat exchanger option, the site should be thoroughly characterized. As mentioned in the previous section, the primary variable governing the heat transfer in the ground is the thermal conductivity. Another important variable that governs the heat storage in the ground is the specific heat capacity of the ground. Water has the highest specific heat capacity of any material in a GSHP system, thus the presence of groundwater may be equally as important to the performance of a GSHP system as the rate of heat transfer. The type of analysis used in a GSHP system design will dictate the level of detail required regarding the thermal properties of the ground. Advanced finite element or finite difference solutions to heat transfer equations may require thermal conductivity of individual soil/rock layers and component materials (heat exchanger fluid, heat exchanger pipe, sand-bentonite grout, etc.). These advanced solution methods permit modeling the various heat flow mechanisms in the different components of the GSHP system (e.g., convection-conduction-radiation in the building, convection-conduction in the heat exchange fluid circulation system, and conduction in the soil). These types of analyses can be performed in commercially available software packages such as TOUGH2, COMSOL, or Temp/W. Simplified heat transfer analyses may only require the system values of the thermal conductivity and specific heat (Eskilson 1987). Although it is possible to create spreadsheet solutions for the simplified solutions, they have been implemented into commercial software packages (GLHEPro, GEOKiss, GLD, etc.) that contain databases of heat exchanger geometries and heat pump characteristics (Spitler 2000; Xu and Spitler 2006). The challenge for energy piles is to add the heat exchanger geometries and material characteristics of the different materials to the aforementioned programs. Loveridge and Powrie (2014) have developed a thermal resistance analysis that can be incorporated into these types of programs in the future.

Although the heat transfer mechanisms in the subsurface are relatively straightforward to analyze, with the mode of heat transfer in the ground being primarily by conduction, the boundary conditions from the building can be complex. During typical building heating and cooling operations, heat pumps do not apply a constant energy input to the ground loop as is done in the field thermal conductivity tests. Many heat pumps are configured to only operate when the temperature in a heating/cooling zone falls below a threshold. Although this makes the heat pump more efficient in terms of electricity use, it renders the heat transfer analysis of the actual GSHP operation particularly complex. For design, it is common to make simplifying assumptions regarding the boundary conditions to ensure that a given heat exchanger configuration can supply the required heat.

An additional level of complexity is that many commercial and larger residential buildings will have multiple heat pumps for each zone. Although fluid may be circulating through the heat exchanger loop field, which maintains a steady temperature within the circulating fluid, each heat pump will only access the circulating fluid when it is necessary. This permits a larger commercial building to move heat not only from the ground to the building, but from one zone of the building to another. There are many situations where one part of a building may need heating (e.g., a basement), while another part of a building may need cooling (e.g., an upper room with many windows and a large solar gain). This type of design would likely need a whole-building thermal analysis coupled with a heat flow analysis in the soil. Whole-building analyses are possible in freely available software packages from the U.S. Department of Energy (EnergyPlus, DoE2, eQuest), which incorporate simplified analytical solutions to heat flow in the ground to consider the design of GSHP systems.

4.2 Thermo-Mechanical Design

Historically, the design of energy piles from a thermo-mechanical perspective relied on empirical and conservative approaches to account for additional axial stresses induced during heating and cooling. An improved quantitative approach to consider the stress, strains, and displacement in energy piles is the use of thermo-mechanical load-transfer analyses (Knellwolf et al. 2011). The software program Thermo-Pile® is available to perform this type of analysis as part of a design. Limits on the stresses and displacements are described in the design standard for energy piles developed by the GSHP Association (2012). Displacement limits can be defined by evaluating the angular distortions between columns and using criteria such as those defined by Skempton and MacDonald (1956) and Bjerrum (1963). An issue with load-transfer analysis is that the curves representing the mobilization of side shear and end bearing need to be estimated for a given soil profile, and the impact of temperature is not well understood. This topic is currently under investigation through the use of a modified borehole shear device (Murphy and McCartney 2014b). Another challenge is that the resistance to expansion imposed by the overlying building is difficult to estimate. This heat restraint stiffness can be estimated by calibrating the load-transfer analyses with measurements of thermal axial strain after the building has been constructed, but it represents a complex process. Recently, researchers have developed numerical models to account for thermal loads in the foundation in addition to mechanical loads from the overlying structure (Burlon et al. 2013; Mimouni and Laloui 2013). Numerical models have the capability of incorporating boundary conditions and temperature variations to gain a thorough understanding of the anticipated foundation displacements and stresses that will be generated during mechanical and thermal loading. Numerical modeling of specific site conditions can be used to construct design charts to anticipate the head load and displacement for an estimated foundation head stiffness and temperature change. At the moment, the only approach to obtain the head stiffness is to measure the thermal axial strain distributions using embedded instrumentation.

4.3 Implementation of Thermally Active Geotechnical Systems

In addition to providing design guidance for the thermal and thermo-mechanical behavior of energy piles, the design standard developed by the GSHP Association (2012) includes information on the required coordination between the designer and different trades involved with the construction of deep foundations. There are several construction issues that need to be carefully considered. The geometric layout of the reinforcement cage and heat exchangers in an energy foundation are critical for its constructability and performance. The smallest diameter of an energy foundation is typically 0.6 m. Because the reinforcement cage is typically undersized (75% smaller), diameters less than 0.6 m make it difficult to attach the heat exchanger tubing to the reinforcement cage. The inlet and outlet tubes of the heat exchangers should be attached to opposite sides of the foundation to minimize the risk of 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 pile. However, in large diameter piles, it is important to include a sufficient number of heat exchangers in the pile to avoid having differential temperatures across the foundation and associated stress concentrations. The lower extent of heat exchange tubing should be at least 1.5 m shorter than the design length of the reinforcement cage, which is important in the case that the hole cannot be drilled to the design depth and the reinforcement cage must be trimmed. Furthermore, it is important to avoid draping the bottom loop of heat exchange tubing across the diameter of the pile, which may prevent concrete from reaching the bottom of the hole and can lead to segregation of the gravel particles in the concrete. To evaluate leaks in the heat exchanger tubing before installation and to detect installation damage, the tubing should be filled with pressurized water. Water in the tubes also facilities dissipation of the hydration heat of concrete and can help minimize the risk of the concrete to crack or pull away from the heat exchangers.

5. Emerging Technologies

There are many approaches for using the heat obtained from geothermal energy to enhance the performance of civil engineering systems. One opportunity is ground-source de-icing of bridge decks. A potential configuration of this system is shown in Figure 5. In this figure, both shallow heat exchangers in the abutments and heat exchangers in the deep foundations are used to regulate the bridge deck temperature. Under certain operational and environmental conditions it is possible to circulate the fluid directly from the foundation to the bridge deck, without using a heat pump. These systems are also able to store thermal energy in the ground as the radiative energy from the sun is collected by the bridge deck, and then transferred to the ground. This simultaneously lowers the temperature of the bridge deck, which can potentially reduce the degradation caused by cyclic temperature induced strain. Other applications involving the direct use of shallow geothermal energy are in agriculture, where the heat from the ground can be used to dry grain or to maintain a constant temperature within a greenhouse or warehouse.

There are several new opportunities for incorporating geothermal heat exchangers in other civil engineering infrastructures besides drilled shaft foundations. An interesting opportunity is the incorporation of heat exchangers into municipal solid waste landfills (Coccia et al. 2013). The biodegradation of waste due to methanotropic bacteria activity leads to elevated temperatures as high as 50 °C, which can be collected to heat buildings on the landfill property. A challenge with this approach is proper placement of the heat exchangers, as the highest temperatures occur mid-height in the waste. Coordination is necessary with the landfill operators to place the heat exchangers after reaching a given waste height lift. Furthermore, it takes 2-5 years after placement of the waste before the temperature significantly increases. A heat pump can be incorporated into the system to extract heat from the constant temperature of the waste before the bacteria become active, but this increases the cost of the system.

There are other opportunities to use the subsurface for thermal energy storage. Sibbit et al. (2006) and McCartney et al. (2013) describe the use of boreholes to store thermal energy collected from solar thermal panels. Sibbitt et al. (2006) found that an array of thirty 30 m-deep borehole heat exchangers is sufficient to provide 90% of the heating for 52 single-family homes. McCartney et al. (2013) is considering the role of phase change of water in the vadose zone to enhance the heat transfer and heat storage in the subsurface.

It is possible that the heat exchanger tubing in energy piles can be used for pile integrity tests (sonic logger). Designers may be encouraged to use this approach as it will save on the cost of the heat exchangers by allowing them to be used for multiple purposes. This approach can also be incorporated into conventional borehole heat exchangers to assess changes in thermal grout integrity over time.

There are many opportunities to exploit interrelationships with other disciplines. The fields of nuclear waste storage, deep geothermal applications, buried power transmission cables, and oil pipelines involve consideration of thermo-hydro-mechanical behavior of soils and rocks. Most of the focus in energy piles has been on the soil-pile interface, and most of the soils under investigation are relatively stiff, over-consolidated soils. However, the above-mentioned fields consider the behavior of softer soils that may experience plastic volume changes.

Another interesting option would be to incorporate phase-change materials such as CO_2 or ammonia into energy piles to form heat pipes or thermal siphons. These systems may eliminate the need for a circulation pump, which could significantly reduce the cost of GSHP systems. An advantage of energy piles in using phase-change materials is that the heat exchanger tubes would be embedded in concrete, minimizing the risk these hazardous materials leak into the environment.

6. Current Challenges

There is currently a lack of consensus on green certification and challenges in incorporating strategies like GSHPs and energy piles into green programs (BREEAM, LEED). This will require a more in depth, quantitative analysis of environmental impacts and carbon calculations for GSHP systems. A similar challenge is the consideration of insurance and regulation issues in the incorporation of energy piles and thermoactive geotechnical systems into buildings. Solving these problems will require engineers to reach out to clients, policy makers, and regulatory agencies (utilization of professional organizations and platforms). Some engineers have expressed environmental concerns due to change of ground and groundwater temperatures, which may lead to the mobilization of some precipitated materials such as heavy metals. This will require long-term monitoring of energy pile systems.

Use of performance-based analyses for the thermo-mechanical design of energy piles will lead to more efficient use of materials and optimization of geometry. However, the existing tools for the thermo-mechanical design of energy piles require information that may be difficult to estimate for some scenarios. This challenge may be overcome by using worst-case scenarios in design. For example, thermal axial displacements can be assessed by assuming free expansion, while thermal axial stresses can be assessed by assuming fully constrained conditions. However, this may result in overdesigned energy piles which may not be economic for project owners. Other worst-case scenarios such as thermally induced dragdown of the soil surrounding the pile can also be considered. A challenge regarding the thermal response of energy piles is the integration of the thermal conductivity, heat storage characteristics, and geometry of energy piles into building system-foundation interaction models such as EnergyPlus. Many locations in the world are facing an increasing cooling demand which may have implications on the long-term performance and sustainability of heat exchange in energy piles. Monitoring may be useful to assess this problem, which is also useful in verifying and improving thermal design approaches. Some engineers have worried about serviceability issues for energy foundations, and access to heat exchangers embedded in concrete. This is an important challenge that can be considered in the development of design details, and requires collaboration with the geothermal designer, geotechnical engineer, and structural engineer.

7. Research Agenda for Near Future

Several studies have developed a mature understanding of the system thermal response of energy piles, the thermo-mechanical soil-structure interaction, and the role of end-restraint boundary conditions (Amatya et al. 2012; Stewart and McCartney 2013; Murphy et al. 2014). However, many of these studies involved soil strata that were relatively stiff and unlikely to experience significant plastic thermal strains. Each of these topics deserve to be further studied for challenging soil profiles such as layered soils, non-end bearing conditions, and normallyconsolidated clays. Although design methods have been developed to estimate the thermo-mechanical response of energy piles (Knellwolf et al. 2011), there is still a need to define the T-z, Q-z, and p-y curves for non-isothermal conditions. This is currently under investigation using a modified borehole shear device (Murphy and McCartney 2014b), but there are other experimental approaches that can be used to define this information including modified direct shear tests. The effect of temperature cycles, especially in challenging soil profiles is a subject that deserves further study. Lateral loading is another interesting issue, as it is expected that heating may lead to a significant increase in lateral capacity, but cooling may lead to a decrease in soil-structure interaction near the ground surface. With regard to thermal design of energy piles, several studies are underway to integrate the thermal response of energy piles into available GSHP design tools, however more development is necessary to better understand the transient response in addition to the long-term response.

Improvements to the durability and constructability of heat exchanger tubes is still a topic of concern, including ease of connections and installations, bend radius, and cost. Enhancement to the thermal conductivity of the heat exchange tubes is an important subject for further study. A potential approach would be to integrate graphite into the polymer mix during manufacturing of the tubing. Further research is needed to optimize energy foundation geometry to enhance heat transfer (Loveridge and Powrie 2014).

A novel field of investigation is the opportunity to use waste heat from industry or buildings to improve the behavior of soils (Coccia and McCartney 2013). There are several soils that are suitable for improvement, including unsaturated soils, as well as soft, saturated soils. Challenges that need to be addressed include a practical approach to implement temperature changes, provide drainage from the soil, and balance the rate of heating with the rate of drainage to avoid thermal failure. Issues that need to be better understood include the possible level to which soil properties can be improved for a given change of temperature. The changes in volume, undrained shear strength, and stiffness, are the main parameters of concern for the thermo-mechanical response, but there may also be coupled changes in the hydraulic conductivity and thermal conductivity due to volume changes. As thermo-mechanical behavior of soils is an elasto-plastic process, it is important to understand the temporary and permanent components of any thermally induced volume changes.

8. Conclusions

The discussion in this paper indicates that engineers and researchers currently have a mature understanding of the thermal and thermo-mechanical behavior of GSHP systems and energy piles. Methods have been developed for material characterization, and have been incorporated into design methods to consider the thermal and thermo-mechanical performance of these systems. Many emerging technologies are available integrating geotechnical engineering and near-surface geothermal energy, resulting in beneficial opportunities to transfer knowledge between different fields. Despite the mature understanding of the behavior of GSHPs and thermally active geotechnical systems, there are still important challenges that must be overcome through fundamental and applied research.

9. Acknowledgements

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LIST OF TABLES AND FIGURES

Table 1: Thermal conductivity values for different minerals, rocks, and fluids

Material	Thermal conductivity (W/m·K)
Quartz crystal	9.10
Quartz glass	1.27
Granite	1.72-3.85
Calcium carbonate	3.80
Marble	2.08-2.94
Limestone	2.22
Ice	2.22
Sandstone	2.00
Dolomite	1.72
Slate	1.49
Mica	0.59
Steel	16-43
Concrete	0.10-1.70
Water	0.61
Air	0.03

Table 2: Properties of different geothermal heat exchange fluids (Chemical engineer's handbook)

Property	Units	Water	Ethylene glycol	Propylene glycol	Methanol
Molecular weight		18.01	62.07	76.1	32.04
Specific gravity at 20°C		1	1.116	1.038	0.8
Density at 20°C	kg/m^3	10.0	11.1	10.4	7.9
Freezing point	F	0	-13	-59	-98
Normal boiling point	F	100	197	188	64
Specific heat at 20°C	J/g°C	4.19	2.19	2.50	2.47
Viscosity at 0°C	Centipoise	1.79	57.4	243	-
Viscosity at 20°C	Centipoise	1.01	20.9	60.5	0.6
Viscosity at 38°C	Centipoise	0.655	9.5	18	-
Thermal conductivity	W/mK	0.609	0.258	0.147	0.202
Corrosiveness		None	Inhibitors required for steel, cast iron, aluminum, solder	Inhibitors required for cast iron, solder, aluminum	Biocide should be used to prevent fouling
Toxicity		None	Eye and skin irritation, long-term exposure is hazardous	Non-hazardous	Highly toxic by inhalation, skin contact, and ingestion
Environmental impact		None	Biodegrades when combined with water and carbon dioxide	Biodegrades when combined with water and carbon dioxide	Biodegrades into carbon dioxide and water

Table 3. Summary of thermal response test (TRT) results on energy piles from previous studies

Case	Foundation type	Foundation length (m)	Foundation diameter (mm)	#Heat exchanger loops	TRT analysis method	Thermal conductivity (W/m·K)	Heat exchange rate (W/m)
Hamada et al. (2007)	26×D.P.	9	300 (square)	1,2, Indirect/ Direct Pipe	N/A	N/A	54-69 (ext.)
Ooka et al. (2007)	2×D.S.	20	1500	8	N/A	N/A	100-120 (rej.) 44-52 (ext.)
Gao et al. (2008)	1×D.S.	25	600	1-3	Num. Method	5.8-6.0	57-108 (rej.)
Lennon et al. (2009)	4×D.P.	12-17	244 (round), 270 (square)	1	Line Source	2.4-2.6	N/A
Brettmann and Amis (2011); Ozudogru et al. (2012)	3×A.C.I.P.	18.3	300-450	2	Line Source	2.5-2.6	73-80 (rej.)
Murphy et al. (2014)	8×D.S.	15.2	610	1-3	Line Source	2.0-2.3	90-139 (rej.)
Loveridge et al. (2014)	3×A.C.I.P.	18.3	305-457	1-2	Line Source G-Functions	2.37-3.77	73-80 (rej.)

*D.S.: Drilled shaft, D.P.: Driven Pile, A.C.I.P.: Auger cast in place pile
** Rej.: Heat rejection into foundation, Ext.: Heat extraction from foundation

Table 4. Results of previous studies on thermo-mechanical behavior of energy foundations

SEE ATTACHED FILE

Table 5. Summary of small-scale experimental studies investigating the temperature effects on behaviour of energy piles (adapted from Olgun et al. 2014b)

Study	**Model**	**Soil type**	**Pile**	**ΔT (°C)**	**Remarks**
McCartney and Rosenberg (2011)	Centrifuge (24g)	Bonny silt (compacted) w=13.2% fines=84% PI=4 ϕ'=32°	Concrete D=76.2mm (1.8m) H=381mm (9.1m)	29 / 41	40% increase in side shear resistance with heating
Wang et al. (2011)	Laboratory (1g)	N50 Fine sand (loosely compacted – 10 layers) C_u=1.47 C_c=1.21 w=0.5%	Steel tube D=25.4mm t=1.2mm *Pile surface is coated with a layer of N50 fine sand using epoxy resin*	20	50% decrease in side shear resistance with heating
		300WQ Silica flour (loosely compacted – 10 layers) C_u=4.8 C_c=2.13 w=21.5%, 24%			10% to 50% decrease in side shear resistance with heating
Wang et al. (2012)	Laboratory (1g)	N50 Fine sand (loosely compacted – 10 layers) C_u=1.47 C_c=1.21 w=0%, 2%, 4%	Steel tube D=25.4mm t=1.2mm *Pile surface is coated with a layer of N50 fine sand using epoxy resin*	20 / 40	w=0% – No change in side shear resistance w=2%, 4% – Reduction in side shear resistance
Goode	Centrifu	Dry Nevada sand	Concrete	7 /	No change in

et al. (2014)	ge (24g)	D_r=60% e=0.75 D_{10}=0.09mm D_{30}=0.11mm D_{60}=0.16mm ϕ=35° G=30MPa ν=0.3	D=63.5mm (1.5m) H=342.9mm (8.2m)	12 / 18	ultimate capacity with heating
Kramer and Basu (2014)	Laboratory (1g)	F50 Ottawa sand (fine silica sand) (Air plion) e_{max}=0.78 e_{min}=0.48 D_{50}=0.28mm C_u=1.8 G_s=2.65	Concrete D=100mm H=1.22m	20	Slight increase in pile capacity (~5%) with heating Decrease in pile head stiffness with heating

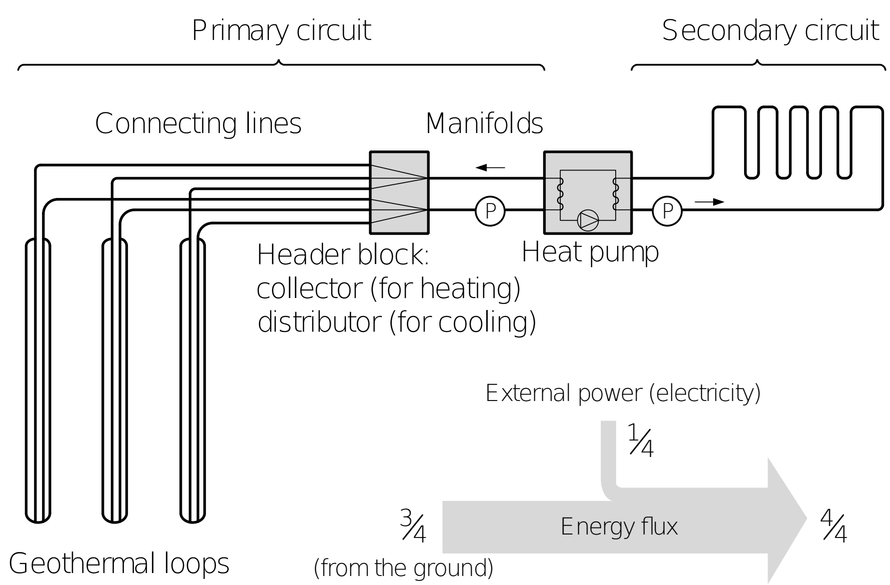


Figure 1: Schematic of a ground-source heat pump system and the method of energy delivery (after Brandl 2006)

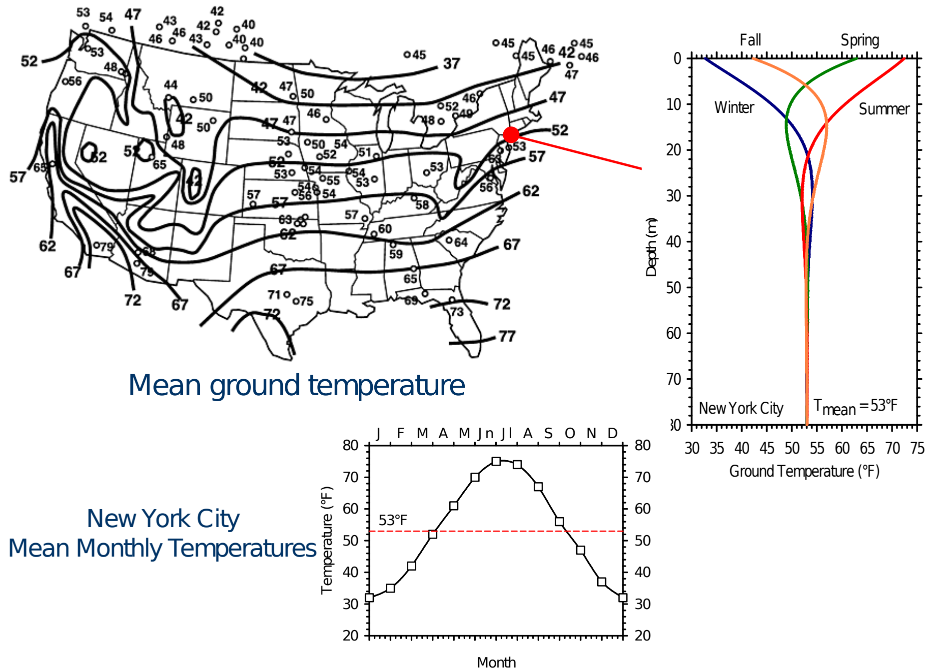
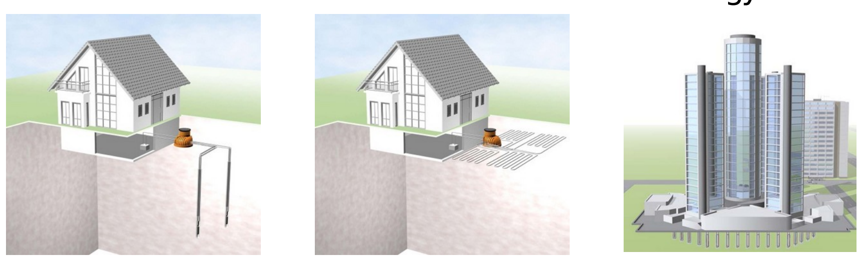


Figure 2: Example of ground temperatures and mean monthly temperatures for New York City



	Vertical	Horizontal	Energy Pile
Poor ground quality	8 W/ft	1 W/ft²	8 W/ft
Average ground quality	15 W/ft	2.5 W/ft²	15 W/ft
Excellent ground quality	25 W/ft	4 W/ft²	25 W/ft

Figure 3: Examples of thermal energy delivery for different ground-source heat exchangers

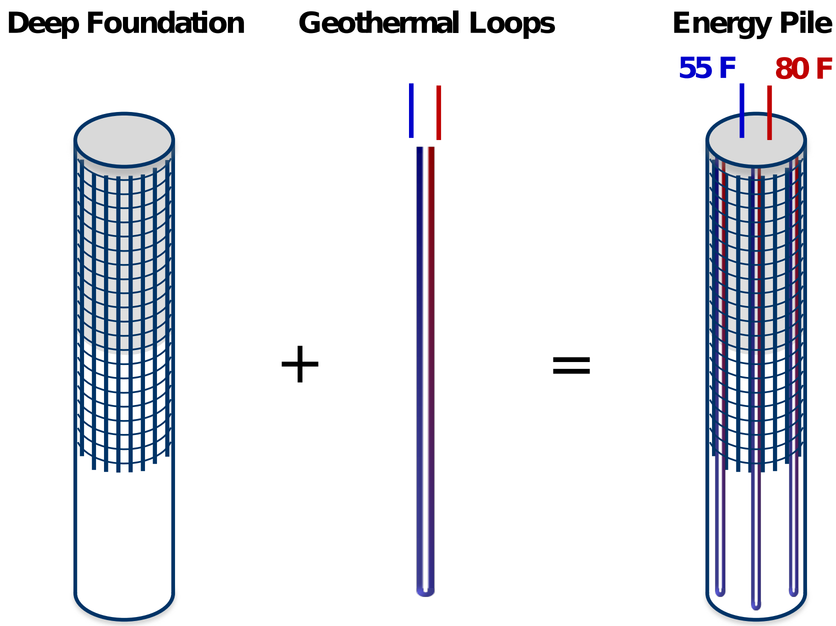


Figure 4: Energy pile configuration

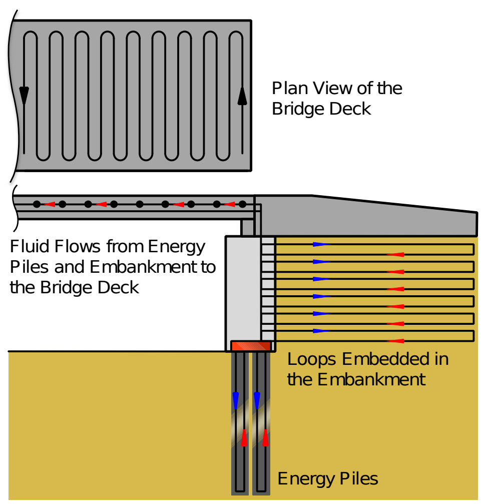


Figure 5: Example of geothermal heat exchangers used for bridge-deck deicing