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RENEWABLE ENERGY APPLICATIONS USING THERMO-ACTIVE DEEP FOUNDATIONS

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Abstract: Rising energy costs and the adverse effects of carbon emissions have given rise to an increased use of geothermal energy for heating and cooling of structures. Of increasing use in geotechnical engineering practice are thermo-active foundations that contain geothermal loops integrated into structural elements in contact with the ground. Such applications have been developed for shallow and deep foundations, retaining and basement walls, tunnel linings, soil nails, and earth anchors. These structures perform the dual function of providing structural support and exchanging heat with the ground to harness geothermal energy. In particular, the use of Energy Piles, which are thermo-active deep foundation elements such as drilled shafts and driven piles, has grown exponentially in Europe over the past decade, but they have received little attention in the US. Energy Piles contain HDPE tubes filled with glycol-water mixtures which are circulated via a heat pump or cooling machine. Heat energy is injected into and withdrawn from the ground for cooling in the summer and heating in the winter, respectively. Because they are used where pile foundations must be installed anyway, these systems provide the thermal performance of deep geothermal systems without the additional drilling costs. Case studies show they can significantly lower heating/cooling costs and reduce carbon footprint. This paper discusses key geotechnical aspects of Energy Pile design and performance, along with design challenges that must be overcome to promote wider usage of this technology.

Key words: renewable energy, geothermal energy piles, thermo-active deep foundation, soil-pile interaction, ground source heat pumps (GSHPs)

1. INTRODUCTION

There is a rapidly growing trend around the world to utilize alternative energy resources. Driving forces include rising energy demands, depleting natural resources, and adverse effects of carbon emissions from fossil fuel consumption. In response, there has been a sharp increase in the use of solar and wind power, along with ground-sourced or "geothermal" energy. Although the term geothermal is often used to describe energy extracted from super-heated zones of the ground to heat water and/or generate electricity, the term used here refers to energy extracted from near-surface zones of moderate ground temperature.

The subsurface of the earth contains a tremendous potential of stored geothermal energy. The idea of exploiting this energy for heating and cooling purposes was first proposed in the late 19th century [20]. The ideal setting is a wide zone of constant temperature in the subsurface where heat energy can be exchanged with above-ground heating and cooling systems (i.e., ground coupling). Throughout much of Europe and the US for instance, the upper 100 m of the ground is well suited for supply and storage of thermal energy. Below a depth of about 10 m in these regions, seasonal ground temperatures remain stable compared to outside air temperatures. They typically lie somewhere between 10° to 18° C which is not too far from desirable room temperature. With modern ground source heat pumps (GSHPs), this heat energy can be efficiently accessed and utilized for heating and cooling. GSHPs exchange heat with subsurface soil and rock via heat exchangers consisting of buried HDPE pipes ("geothermal loops") filled with a glycol-water mixture that is circulated throughout the system. The geothermal loops are usually installed in shallow horizontal trenches or deep (~100 m) vertical boreholes, as shown in figure 1. GSHPs offer higher efficiencies than traditional air source systems, with their major drawback being higher capital costs due to installation, especially where the drilling of deep boreholes is required.

Over the past two decades, this ground coupling concept for hear exchange has been expanded into new civil engineering applications. Several variations of ground heat exchangers such as ground heat collectors, borehole heat exchangers, and thermo-active ground structures have been installed worldwide [10], [19]. Of particular interest are applications where geothermal loops have been integrated into structural elements in contact with or buried within the ground. These include shallow footings and slabs, deep foundations, retaining and basement walls, tunnel linings, sewer systems, earth anchors, and soil nails. In this application, the elements serve the dual purpose of providing structural support as well as enabling heat exchange. These systems are generally referred to as "thermo-active foundations" and their use is rapidly growing. Full-scale field tests and numerical simulations have shown that such elements can be used efficiently for heat exchange [27]. An excellent summary is provided in [10].

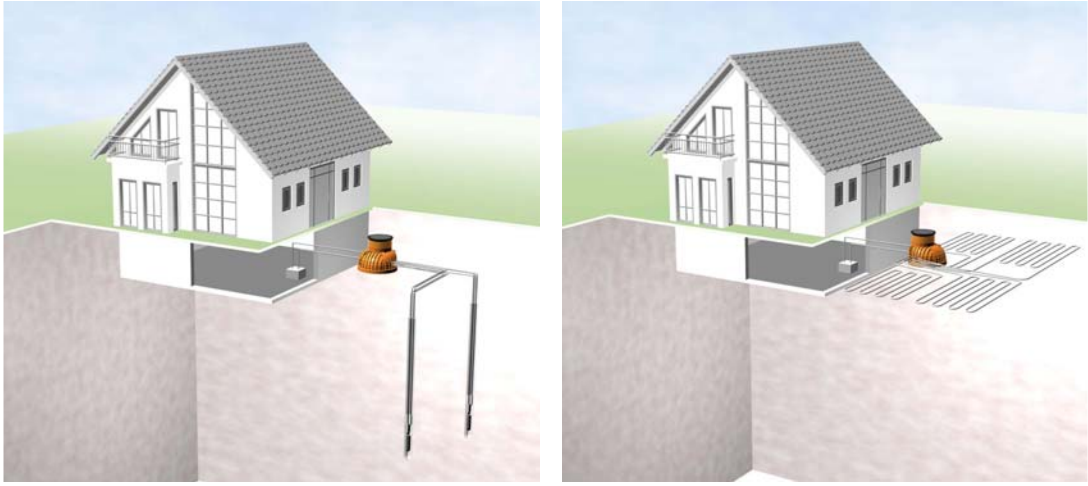

Fig. 1 Schematic showing deep vertical (left) and near-surface horizontal (right) geothermal loops.

This paper focuses on geotechnical engineering developments related to thermo-active deep foundations, such as caissons, drilled shafts, or piles used for this purpose. Commonly referred to as "Energy Piles," these systems are used in soft soil conditions where installation of deep foundations is already required for structural support. The integration of the geothermal loops comes at little

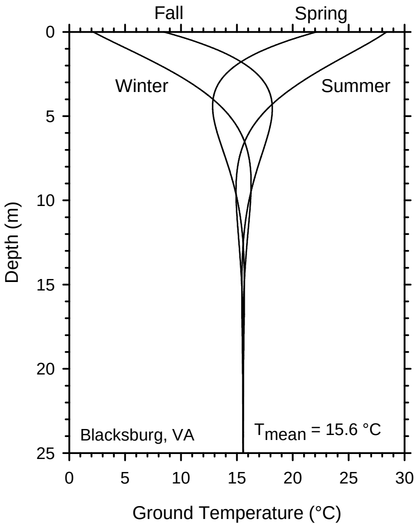

Fig. 2 Seasonal ground temperature profile for Blacksburg, VA

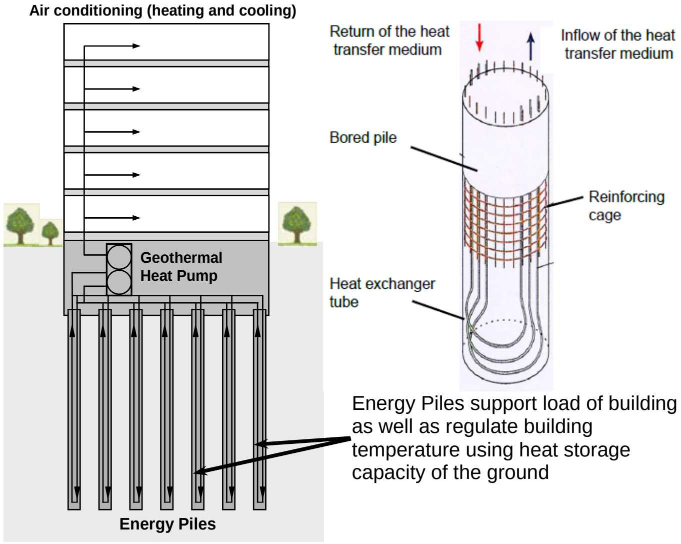

Fig. 3 Schematic of Energy Pile operation (adapted from [15])

cost. This means Energy Piles can offer the superior thermal performance of a deep geothermal system without the additional drilling costs. Case studies show that significant ecological and economical benefits can be offered by such systems.

First developed in the 1980's, Energy Piles have seen an exponential increase in the number of installations over the last decade, especially in Europe and Japan. Although much has been learned about their behavior, there are still design and technology transfer challenges that must be addressed before their benefits can be fully leveraged. This paper discusses geotechnical aspects of Energy Piles, including usage trends, key design and performance parameters, and issues that warrant further study such as long-term thermo-mechanical behavior. Recent Energy Pile case histories and research studies are discussed to provide additional insight.

2. ENERGY PILES

Energy Piles are bored, drilled, or driven deep foundation elements, such as piles, caissons, or shafts that perform the dual role of providing structural support and accessing the heat storage capacity of the ground. In most US and European climate zones, the ground temperature below a depth of about 10 m remains constant, ranging from about 10-18° C to a depth of at least 50 m depending upon the specific region [21], [10]. For example, the ground temperature profile for the campus of Virginia Tech is shown in Figure 2. It can be seen that while near-surface ground temperatures fluctuate seasonally, the temperatures below 10 m are unaltered, equal to the average yearly ambient temperature of about 15° C. Profiles with similar shapes are found in most regions. In this application, the foundation piles that are already in place for structural support of the building are used conjunctively as cooling/heating elements, as illustrated in Figure 3. As shown in this sketch, the piles contain tubes through which a glycol-water fluid mixture is circulated via a heat pump system and/or cooling machine connected between the piles (primary circuit) and the heating/cooling system of the building (secondary circuit). The fluid circulation enables absorbed heat energy to be withdrawn from the ground for heating in winter. The cycle is reversed for cooling operations in the summer.

Most Energy Piles are drilled shaft foundations made of reinforced concrete or thermally-enhanced reinforced concrete. The piles are constructed by drilling a large-diameter hole (0.4 m to 1.5 m) in the ground, lowering the steel reinforcement cage with the heat exchangers into the hole, and backfilling the hole with concrete. The piles contain geothermal heat exchange loops, usually made of High Density Polyethylene (HDPE), that are attached to the reinforcement cage for the foundations, as shown in Figure 4. New types of tube materials, such as cross-linked polyethylene and PEX, as well as new configurations, such as concentric tubes, are becoming more popular. To increase the number of geothermal loops per pile, Energy Pile diameters as large as 4 m have been used [29]. Common pile lengths are 15 to 30 m.

In addition to being a renewable energy resource that reduces carbon footprint, Energy Piles are proven to be a cost-effective heating and cooling solution (at least in terms of operational costs). Studies suggest that in ideal conditions they can reduce heating/cooling costs by up to 80% [17]. A major cost associated with any deep geothermal system is the drilling required for installation. However, since Energy Piles utilize foundation members that are already being installed for foundation support, the added capital cost of geothermal loop installation is relatively small. Another benefit over conventional geothermal borehole systems is that Energy Piles require less land availability, as the heat pump infrastructure and connections are usually within the building footprint. This can be a major advantage in densely populated urban areas. Energy Piles also have the added benefit of being applicable in any climate or region, including those where wind and/or solar power may have limited effectiveness due to energy supply variability. Low maintenance, long lifetimes, and less variation in energy supply compared to solar and wind power have also been cited as key benefits [24].

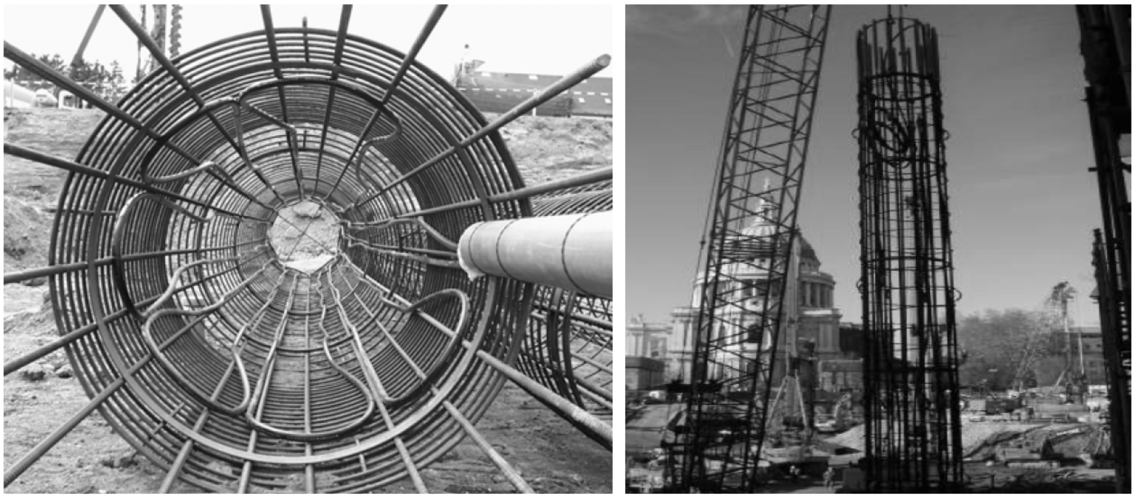

Fig. 4 Installation of geothermal tubes inside pile foundations [38]

The Energy Pile concept for heating and cooling purposes has been used for quite some time, most notably beginning in Austria in the 1980's [9], [10]. A recent summary of these systems is presented in [28]. As mentioned earlier their use has rapidly increased over the last decade, especially in Europe where more than 300 large-scale Energy Pile projects are reported. Primary usage has been in Switzerland, Germany, Austria [32], England [36], Scotland [24] and throughout the UK [4]. Representative major projects include the 56-story 200-m high Frankfurt Main Tower in Germany [15], [23], and the Dock E Terminal Extension at Zurich International Airport in Switzerland [31]. Applications have also been developed in Japan [26], [35], and China [16], among others. A major driving factor in Europe is the building codes that require the construction of zero-carbon buildings by 2019 [8]. Similar targets are being set elsewhere suggesting a continued increase in the global installation of these systems.

Although usage trends in Europe have been exponential in the past several decades, Energy Piles have received little attention in the US. In fact, as of this writing, the authors are aware of only two major US Energy Pile projects. This is partly due to a lack of awareness about their benefits, along with an absence of proven US case studies that demonstrate their cost-effectiveness and long-term performance.

2.1 Energy Pile Heat Transfer Mechanisms

The heat exchange process between the Energy Piles and the surrounding ground primarily involves conduction in dry soils, and conduction and convection in saturated soils, as shown in the schematic in figure 5. Other secondary heat exchange mechanisms such as radiation, vaporization, condensation, and ion exchange are not significant. For brevity purposes, the heat exchange process within the Energy Piles themselves, including heat transfer along the fluid-filled geothermal tubes and within reinforced concrete, is not described here. A detailed discussion can be found in [1] and [10]. A summary of the factors controlling the heat exchange process between the Energy Piles and surrounding soil is presented in Table 1. These factors influence the thermal efficiency and design parameters for the system, such as the required contact area of heat exchangers (i.e., number and length of geothermal loops) needed in the foundation.

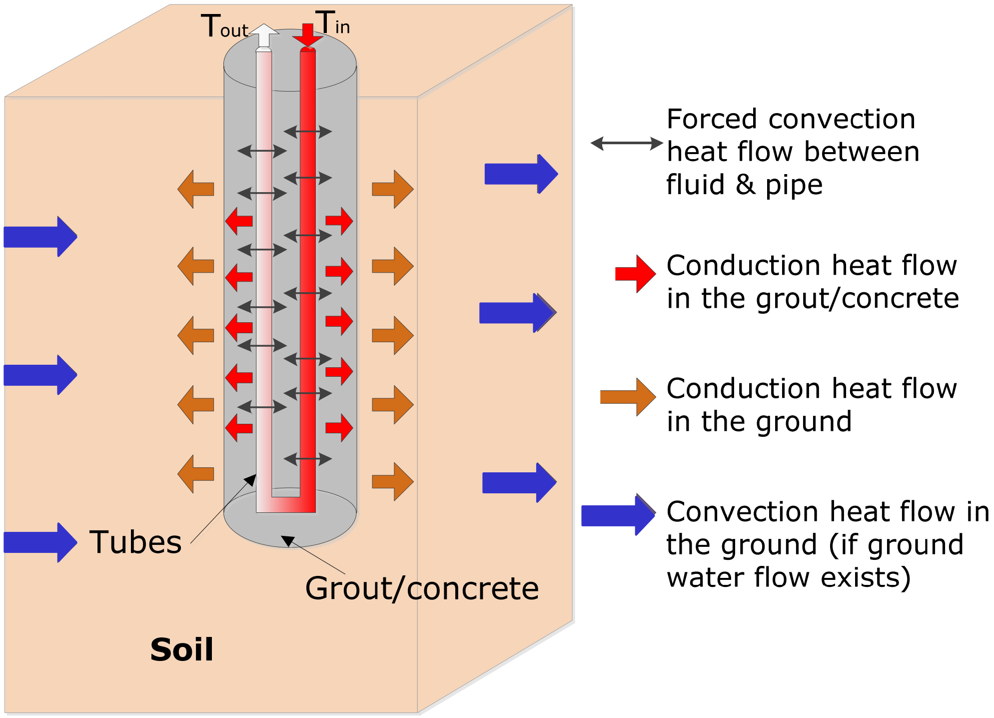

Fig. 5 General heat transfer mechanism of an Energy Pile

It is well established that the soil parameter controlling heat transfer and Energy Pile efficiency is thermal conductivity. The higher the thermal conductivity, the more heat energy can be extracted from the ground. Soil thermal conductivity depends upon several variables. The degree of saturation and depth of the water table are two key factors [2], as saturated soils have thermal conductivities about 6 to 10 times higher than dry soils [33]. Further, sites with flowing groundwater have the capacity to propagate heat energy faster than hydrostatic groundwater and thus offer greatly increased system efficiency. The specific impact of groundwater on the heat output of Energy Piles is a topic of current research [25]. In addition, [37] found that quartz content has a major effect on soil thermal conductivity, with soils containing more quartz having higher thermal conductivity values. Also, performance advantages are gained where Energy Piles can be installed with significant embedment into rock which has a thermal conductivity about 1.5 to 3 times higher than soil.

Table 1. Factors affecting the thermal design of geothermal heat exchangers and Energy Piles classified with respect to the corresponding heat transfer mode.

Heat Transfer Mode	Controlling Factor
Heat Conduction	• Thermal conductivity of the materials; circulating fluid, pipe walls, pile and in-situ soil
Heat Convection	• Fluid flow conditions (flow rate of the circulation fluid, laminar vs. turbulent flow) • Diameter of the circulation pipe • Properties of the circulation fluid (dynamic viscosity, density, heat capacity etc.) • Ground water flow

In terms of the pile materials, conventional concrete has a reasonable thermal conductivity, but special thermally-enhanced concrete, which contains a larger percentage of quartz, along with other special additives, is often used for Energy Piles. This increases pile thermal conductivity and improves thermal coupling with the surrounding soil. Typical thermal conductivities for soil and Energy Pile materials are listed in Table 2.

Table 2. Thermal Conductivity Values of Pile and Soil Materials [34]

Material	Thermal Conductivity W/(m·°K)
Dry Sand	0.77
Saturated Sand	2.50
Moist Clay	1.11
Saturated Clay	1.67
Rock	0.50 – 7.50
Conventional Concrete	0.85
Thermally Enhanced Concrete	1.50

To better understand the complex interplay of factors affecting Energy Pile heat exchange with the ground, numerical studies have been performed, such as [1]. Here parametric modeling with [13] was used to simulate conductive and convective heat transfer between the piles and the ground for a wide range of soil conditions, piles materials and configurations, and operational levels (i.e., heat-carrying fluid pumping rates). As summarized in [1], the results showed that soil thermal conductivity and pile materials were the most important variables affecting system performance and power output. This finding is consistent with other such studies.

2.2 Energy Pile Performance

The heat production of Energy Piles depends on site-specific factors, such as soil or rock type, groundwater table level, soil-foundation contact area, depth, initial ground temperature, and magnitude of temperature fluctuation. Power outputs for installed Energy Piles generally range between 20 W and 100 W per meter of pile. Table 3 provides typical power outputs in Watts/m for different ground conditions, while Table 4 presents Energy Pile power outputs for four representative projects in Europe. In common practice, the typical annual energy requirement for small and large buildings ranges from about 10 kW to 800 kW, respectively. This means Energy Piles can often supply the majority of the required heat energy for the structures they support. Design and operational limitations are placed on the maximum amount of heat energy extracted from the ground to ensure that no ground freezing occurs, and that annual heating and cooling loads are balanced to minimize the mutual thermal effect of neighboring piles and loss of long-term system efficiency.

Table 3. Typical Energy Pile Power Outputs

Ground Conditions	Power Extraction (per m of pile)
Poor ground quality	25 W/m
Average ground quality	51 W/m
Excellent ground quality	80 W/m

Table 4. Power Outputs From Recent European and UK Energy Pile Projects

Project, Location; Reference	Soil Conditions	Pile details	Power Output
Frankfurt Main Tower, Germany; [15]	Soft Clay	223 piles, 30 m long; and 3.4-m thick raft	500 kW
Zurich Terminal E Airport, Switzerland, [31]	Soft Lake Deposits	306 piles, 90-150 cm, 27 m long	1500 Mwh/a heating 620 MWh/a cooling
Keble College, Oxford, UK, [5]	Moist sand silty clay	61 drilled shafts (Energy pile wall)	45 kW
Arts Centre, Bregenz, Austria, [10]	Saturated weak clay, moraine and rock	120 cm diameter, 17m to 25m long	120 kW cooling

Recent field case studies provide data on the measured efficiencies of installed Energy Pile systems [15], [29], [3], [41], [1]. These studies have focused on measurement of Coefficient of Performance (COP), which is equal to the thermal energy output by the system divided by the electricity input to operate the system (the heat pump, etc.). Energy Pile systems, when coupled with ground-source heat pumps, have typical COPs ranging from about 2 to 3, depending upon climate, season, length of operating time, and other factors [3]. For comparison, typical COP values for air-source heat pumps are 1-3 [10]. Collectively, these studies demonstrate the feasibility of Energy Piles to provide sustainable heat energy and cost-effective heating and cooling.

3. ENERGY PILE DESIGN CHALLENGES

Although Energy Piles are being increasingly used and studied, there are questions related to their thermal and thermo-mechanical behavior that must be answered before their designs can be fully optimized and widely implemented in regions such as the US. The main challenges stem from a lack of standardized field testing procedures and a lack of long-term operational and case study data that cover a wide range of climatic and soil conditions. Some of these challenges were discussed in a recent international workshop sponsored by Virginia Tech and the Deep Foundations Institute [40], and are briefly covered below.

3.1 Thermal Design Challenges

European design specifications such as [39] provide general guidance, such as limitations on energy extraction to ensure that no soil freezing occurs, but most of the guidelines were derived mainly from experience with geothermal borehole loops. More refined geotechnical design tools are needed. Of particular need are improved standards for field measurement of Energy Pile heat capacity. As discussed in [11], current ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) procedures field measurement of thermal conductivity are not directly applicable to Energy Piles. These methods were developed for geothermal borehole systems where a relatively deep (~75 to 150 m) small-diameter (15 cm) well is drilled, installed with a geothermal circulation loop system and backfilled with a mixture of sand, bentonite and/or cement. The rate of temperature change is then used to estimate the thermal conductivity of the system using several line source models [18]cylindrical heat source method [14], and numerical methods, all based on the theory developed by [20]. The line source method developed by Kelvin assumes an infinitely-long linear heat source. As the diameter of the heat source get larger, in this case the Energy Pile with a diameter of up to 4 m, this theory becomes less applicable because it is based on a zero-diameter heat source. Another limitation of the line-source method is that it ignores end effects which may become more pronounced as the heat source becomes relatively short as in the case of Energy Piles. While the ASHRAE procedure based on line-source theory may be applicable to geothermal boreholes with typical length-to-diameter ratios over 800, their validity is questionable for Energy Piles which have length-to-diameter ratios of 30 to 60. At the time of this writing the authors have developed a field testing and numerical modeling research program to develop new field methods to be considered by ASHRAE.

A second issue relates to Energy Pile group effects and possible changes in efficiency during the operational life of the system. This relates to how long-term operations affect temperature gradients around the piles, and in turn, affect the heat exchange capacity and system efficiency as the entire soil mass is gradually heated up or cooled down. Such group effects may be a critical issue when the piles are closely-spaced. It may be found that the minimum pile spacing required to prevent thermal interference between neighboring piles, and therefore a loss in efficiency, may be more restrictive than spacings needed to support structural loads. Also the spacing and geometrical configurations of Energy Piles may be of concern in metropolitan areas where neighboring operations may interfere. This issue is being studied by several researchers, along with the authors who are performing numerical modeling to develop design tools needed for long-term sustainable design. Figure 6 schematically illustrates Energy Pile thermal performance as time evolves during heating operations.

3.2 Thermo-Mechanical Design Challenges

In addition to heat exchange design, Energy Piles also require geotechnical design to account for coupled thermo-mechanical soil-structure interaction effects that might affect foundation performance, especially over long time periods. Specifically, contraction or expansion of the piles during heating or cooling may lead to changes in pile side friction (and ultimate load-carrying capacity) or distress in the concrete.

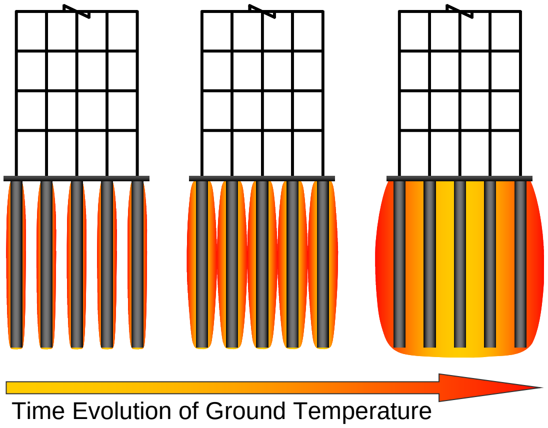

Fig. 6 Long-term temperature change around the Energy Piles and evolution of temperatures in the ground [30]

Contraction or expansion occurs in Energy Piles due to thermal elastic expansion, in which thermal strain εt occurs during a temperature change in proportion to a coefficient of thermal expansion $(\varepsilon t = \alpha T \Delta T)$. The coefficient of thermal expansion αT of concrete can be as much as 14.5 x 10-6 m/m °C, while that of the steel reinforcement is 11.9 x 10-6 m/m °C [12], indicating that reinforced concrete should be in a similar range. [8]measured a coefficient of thermal expansion of 8.5 x 10-6 m/m °C for Energy Piles. The actual amount of thermal expansion or contraction for an Energy Pile will depend upon site-specific soil-structure interaction effects, as the surrounding soil and pile head and tip restraints provide a confining effect.

These coupled thermo-mechanical loads produce a unique stress profile as illustrated in the two sets of schematics in Figure 7. When an Energy Pile is loaded under a mechanical load the highest stresses occur at the top and diminish with depth, as shown in the left schematics. If the pile is then heated (upper diagrams), it will undergo volumetric expansion. In simplistic terms, a floating pile will tend to expand about its mid-points, as shown in the central schematic. This results in an increase in compressive stresses throughout the pile, and an increase in side friction. The coupled response produces a uniform stress profile in the upper portion of the pile as shown in the upper right schematic. [8]and [23]indicate that in some cases the total stresses could be twice as high as those from the mechanical load alone especially in cases where the displacement of the pile toe is restrained such as in the case of an end-bearing pile. Although the side friction will increase uniformly with depth during heating, the direction of the side shear force will be opposite on either side of the mid-point of the pile since it is assumed to expand from the mid-point.

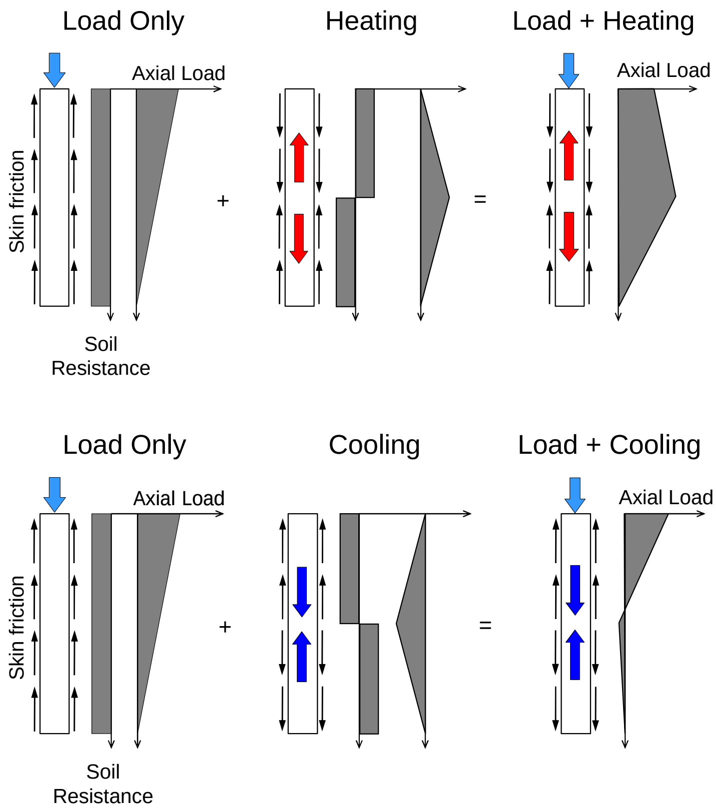

Fig. 7 Heating and cooling induced soil-pile interaction during Energy Pile operation and axial load along the pile cross section (adapted from [8])

Conversely, as the piles are cooled, they will tend to contract volumetrically. Because the mechanical load diminishes toward the bottom, negative compressive forces (tensile forces) could begin to dominate the axial stresses in the piles foundation if the cooling load is high enough [8]. This coupled response is illustrated in the lower set of diagrams. Pile contraction will lead to a reduction in radial stresses and decrease in skin friction. There is concern that repeated heating and cooling cycles over long time periods may lead to a cumulative decrease in skin friction or the formation of a gap if the soil does not fully rebound after heating. This issue is yet to be studied in detail.

Observations from recent Energy Pile field tests reported by [8] and [22] indicate measured strain profiles that are similar to the stress profiles shown in figure 7. The strain profiles are not shown here for brevity purposes.

A particular concern for Energy Pile foundations is the possibility that asymmetric thermal expansion or contraction may lead differential movements and unanticipated bending moments as illustrated in figure 8. For instance, differential expansion or contraction could occur in cases where the geothermal loops in a particular pile fail next to a fully-functioning pile [23]. [7] estimates as many as 10% of the geothermal loops will fail during their project lifetime. Differential movements may also occur near the outer boundaries of buildings where internal temperatures may be different from outer temperatures. These effects may be more severe in applications where the annual heating and cooling loads are unbalanced. As more understanding is developed, it may be possible to mitigate these effects by limiting the range of temperature changes, and possibly changing steel reinforcement and geothermal loop patterns. To counter these effects, engineers currently much higher factors of safety for thermo-active pile foundations than those used for conventional piles [7]. However, more study is needed before refined design methods can be developed.

There is also the question of whether temperature fluctuations in the ground have the potential to alter soil properties, such as water content, or induce excess pore pressures in clays under undrained conditions (during heating). If so, this may also lead to differential movements [23]. Similarly, the temperature gradients induced by Energy Piles can have unanticipated effects upon local ground water, such as inducing water flow. It has been reported in at least one case in Switzerland that this effect led to deterioration of the quality of an aquifer (B. Teknik, personal communication, September 2010).

Finally, for more widespread implementation of Energy Pile technology, such as in the US, more region-specific full-scale case studies are needed. Although much can be learned from the expertise developed in Europe, the US has wider range of climactic and soil conditions, and different energy demands, energy costs, and energy usage patterns. For instance, cooling demands, which produce a net heating of the ground via Energy Piles, are typically higher in most of the US relative to Europe.

3.3 Virginia Tech Energy Pile Research Program

Virginia Tech researchers have developed a research program to address many of the issues identified above. The aim of the program is to develop more refined design guidelines and knowledge to promote broader use Energy Piles in the US. This work involves field testing, laboratory testing, and advanced numerical modeling.

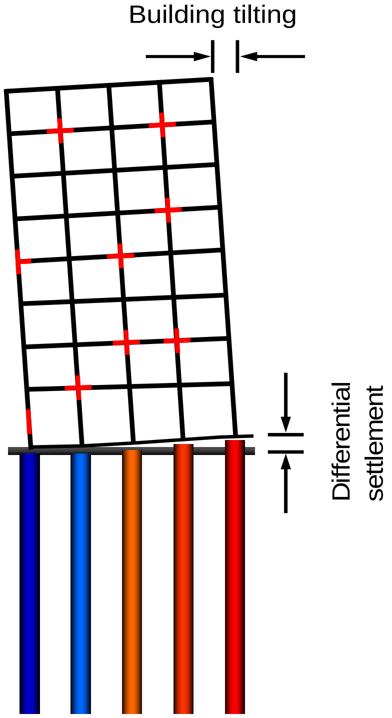

Fig. 8. Potential differential movements and distress on a structure due to uneven movements of Energy Piles (adapted from [30])

Current field work involves full-scale thermo-mechanical testing of Energy Piles installed at the campus. The layout of the test piles is shown in figure 9 along with a photograph. The test site consists of five reinforced concrete piles, four of which are Energy Piles and one is a reaction pile. The piles are 30 cm in diameter and extend to a depth of 33 m. The soil profile consists of silty clayey sand to a depth of 18 m, underlain by weak weathered rock in which the piles are embedded. The water table is 5 m deep. The piles are heavily instrumented with strain gauges and thermocouples. Observation boreholes with thermocouples were placed around the test piles to monitor ground temperatures during heat exchange operations.

Thermal and mechanical loads are simultaneously applied over long time periods to simulate in-service conditions. Thermal loads are applied using a heat pump and chiller, and mechanical loads are applied using a hydraulic jack. The mechanical load capacity of each pile is about 150 tons. These tests are being used to study soil-structure interaction effects such as the additional stresses and strains induced due to thermal loads, the potential for fatigue and stress relaxation at the soil-pile interface due to repeated cycles of radial straining from thermo-mechanical loading, possible changes in key soil parameters such as water content, and the possibility of excess pore pressure development in saturated clays. At the time of this writing the field test program is being expanded with four additional test sites across the US, including Washington, DC, McLean, Virginia, Gary, Indiana, and Houston, Texas. Together, these sites represent a diversity of soil and climatic conditions, covering regions with mostly cooling demands, mostly heating demands, and where annual heating-cooling loads are balanced.

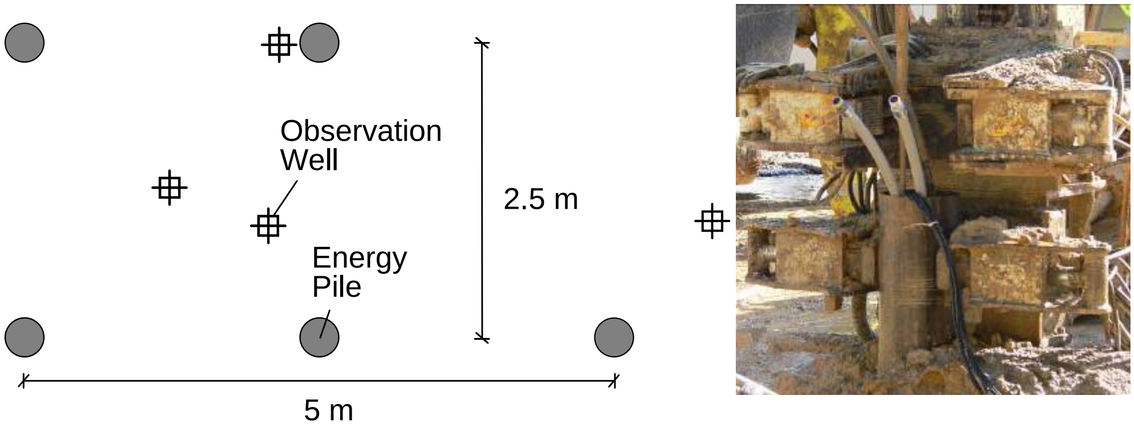

Fig. 9. Plan view of the PIs' current Virginia Tech field test layout and photograph of installed Energy Piles with the circulation loops and instrumentation cables

In addition to the field tests, numerical modeling is being used to interpret field test results, to study soil structure interaction effects, and to help develop improved ASHRAE field test methods for measuring thermal conductivity, as discussed earlier. Analyses that simulate long-term system performance, over say 20 to 30 years of continuous operation, will be conducted using System X, Virginia Tech's supercomputer. A plot from a preliminary analysis of field test results on a single Energy Pile is shown in figure 10 obtained using [13].

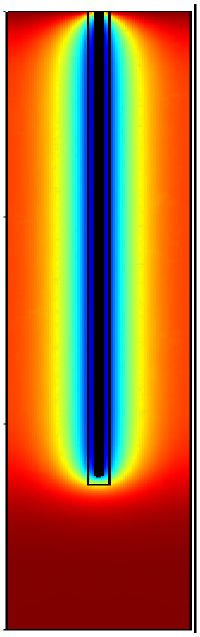

Fig. 10 Cross-section of temperature contours following simulated Energy Pile cooling operation using 3D finite element analysis

As part of this work, an international industry-academic workshop was jointly sponsored by Virginia Tech and the Deep Foundations Institute (DFI) in June 2010 [40]. Key objectives were to share results from cutting-edge research and identify strategies that will promote Energy Pile usage in the US. In addition to the technical challenges dicussed above, the participants identified hurdles such as a general lack of awareness of this technology among US owners and engineers, and widely varying regulations that impede progress. For instance, some states require all "wells", including geothermal systems, to be installed by water well drillers as opposed to geotechnical engineers. Also, the way in which most construction projects are currently bid and executed means that it is difficult to ensure that Energy Piles will be compatible with the energy demands of a structure because geotechnical engineers are not usually involved early-on in the mechanical engineering design process.

4. SUMMARY

Geothermal energy is seeing increased usage as a renewable energy resource for heating and cooling. Of great interest are thermo-active foundations which contain geothermal loops integrated into structural elements in contact with the ground such as shallow and deep foundations, retaining and basement walls, tunnel linings, and earth anchors. These structures perform the dual function of providing structural support and exchanging heat with the ground.

In particular, the use of Energy Piles, which are deep thermo-active foundation elements such as drilled shafts and driven piles that contain geothermal loops, has grown exponentially in Europe, the UK, and Japan over the past 5 to 10 years. Because they are used in soft ground where foundation piles must be installed anyway, these systems offer the superior thermal performance of deep geothermal borehole systems without the need for additional drilling, the major cost for deep systems. Energy Pile diameters range from 0.5 to 4 m, with common lengths of 15 to 50 m.

The thermal output capacities of Energy Piles are a function of soil type, ground water conditions, soil-foundation contact area, and other factors. In ideal conditions, these systems can output about 80 W/m of pile, enough to supply most of the required heat energy for typical buildings which ranges from 10 kW – 800 kW per year for small and large structures, respectively. Case studies developed in Europe and the UK support the feasibility of this approach for providing sustainable heat output and significant reductions in heating and cooling costs and carbon footprint.

Despite these successes, there are still design challenges that must be addressed before these systems can be used more broadly in markets such as the US. In addition to the need for greater awareness of Energy Pile benefits, more region-specific case studies are required. For example, findings from Europe cannot be directly transferred to the US because the soil and climatic conditions are more diverse, and energy costs and demands different (i.e., more cooling). There is also need for more refined field testing standards and better understanding of long-term Energy Pile behavior during say 20 to 30 years of continuous operation. Here, there are questions about possible differential foundation movements or reductions of ultimate pile capacity due to repeated cycles of thermal loading and other soil–structure interaction effects.

Numerous researchers are performing field and numerical studies to understand how Energy Pile performance can be optimized and their benefits fully exploited. The authors, along with industrial partners, have established a research program aimed at developing findings to promote wider Energy Pile usage, especially in the US. This technology represents an important opportunity for geotechnical engineers to contribute to global sustainable energy demands in a new way.

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