A REVIEW ON PERFORMANCE OF ENERGY PILES AND EFFECTS ON SURROUNDING GROUND

PREGLED NAČINA RADA ENERGETSKIH PILOTA I UTJECAJA NA OKOLNO TLO

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Abstract: *Thermo-active ground structures represent low-energy and sustainable technology which is a clear priority for many countries. Heat transfer between such structures and the surrounding soil is understood to play an important role both in the overall thermal performance of buildings and in the evolution of stresses in structural elements and the surrounding soil. This paper presents an overview of recent research efforts and developments in relation to energy piles. General aspects on the performance of energy piles and their impact on the surrounding ground are presented based on previous field, laboratory and numerical investigations as well as existing case studies. Based on the current knowledge, further research opportunities are identified and highlighted.*

Keywords: *Energy piles, temperature effects, renewable energy, ground source heat pump*

Sažetak: *Termički aktivne podzemne konstrukcije predstavljaju nisko-energetsku i održivu tehnologiju čija je primjena prioritet za mnoge države. Izmjena topline između podzemnih konstrukcija i okolnog tla ima važnu ulogu u ukupnoj energetskoj učinkovitosti zgrada te doprinosi naprezanjima u konstruktivnim elementima i okolnom tlu. U ovom je radu prikazan pregled nedavnih terenskih, laboratorijskih i numeričkih znanstvenih istraživanja te izvedenih projekata i dobivenih saznanja na području energetskih pilota gdje su prikazani glavni aspekti energetskih pilota i utjecaji njihova rada na okolno tlo. Na temelju navedenih spoznaja, u ovom se radu navode smjernice za buduća istraživanja u ovom području.*

Ključne riječi: *Energetski piloti, temperaturni efekti, obnovljiva energija, dizalica toplina*

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1. INTRODUCTION

Climate change is one of the greatest issues the world has been exposed to with a huge environmental, economic and social impact. There are currently more than 160 million buildings across the Europe accounting for over 40% of the total energy usage which is predominantly used for heating, ventilation and air conditioning (Thomas & Rees 2009). Burning fossil fuels is the most common method of generating energy. Due to the fact that fossil fuels are non-renewable and contribute to the greenhouse effect, alternative technologies which promise renewable and sustainable ways of producing energy are required. Moreover, energy-efficient design of buildings is essential for achieving the EU Action Plan for Energy Efficiency which targets 20% energy saving by 2020 (Thomas and Rees 2009).

In the recent years, utilisation of the shallow geothermal energy for heating of buildings is spreading rapidly in Europe and around the world. The emerging technology that is known for using such energy is ground source heat pump (GSHP) system. Two conventional systems can be used for extracting the heat from the ground, i.e. open loop and closed loop systems. The former one uses the groundwater and pumps it directly into the heat pump while the latter uses fluid carrying pipes laid either horizontally or vertically (Kovačević et al. 2012). Due to the high cost of vertical drilling and the need of large land area for placing horizontal loops, fluid carrying pipes are recently being installed within structural foundation elements known as energy piles (Suryatriyastuti et al. 2012).

Energy piles represent a sustainable geo-energy solution with significant environmental and economic advantages. They combine structural components of the buildings with ground source heat technologies which can be used for heating and cooling applications. In most regions of Europe, seasonal ground temperature is relatively constant below a depth of 10-15 m with values between 10°C and 15°C, representing good conditions for heat extraction and injection (Brandl 2006).

During the past decades, there were many energy pile systems installed all over the world, particularly in Austria, Germany, Switzerland and United Kingdom as well as in Japan and China (Laloui & Di Donna 2011). One of the largest projects in the UK was a building at the Keble College, Oxford which was also the first energy pile structure in the UK, built in 2001 (Suckling & Smith 2002). Since then, a number of installed energy piles in the UK has rapidly been increasing, with almost 4600 piles (cumulative) in 2010 (Laloui & Di Donna 2011). For comparison, by the end of 2004 there were already around 23 000 energy piles installed in Austria and since 2005 more than 6000 energy piles per year (Brandl 2013).

It is obvious that energy piles represent a good solution for heating and cooling of residential, office and commercial buildings since they are a combination of ground structures needed for stability and energy source which results in an additional low costs. Therefore, many universities and research centres have focused both their experimental and numerical work to enhance the understanding of the behaviour of thermal piles under significant temperature changes. Extensive overview of such efforts has been presented in Laloui & Di Donna (2013). Although a lot of information has been gained by researchers and many buildings have been built all over the world up to date, there are still some uncertainties regarding the long term behaviour of energy piles in groups and their influence on the surrounding soil in terms of thermal, hydraulic and mechanical behaviour (THM). Furthermore, due to the fact that implementation of underground geo-structures is currently in its beginnings in some European countries, further research in that area is crucial to have a clear understanding on the performance of such structures and their impact on the overlaying building and the surrounding soil.

The current paper presents a review on the usage of energy piles and recent research efforts. A focus is put on recent case studies and research efforts in Europe, however with several examples throughout the world. In the first section, a conceptual understanding of general aspects of energy piles and the surrounding soil as well as common recommendations for their implementation and usage are presented. The second part presents and discusses recent results and findings obtained by in situ analyses, small-scale experiments and numerical simulations performed by researchers and engineers in the field. This section is then followed by real case studies conducted around the world. Finally, based on recent research findings, knowledge gaps and further research opportunities are identified and proposed.

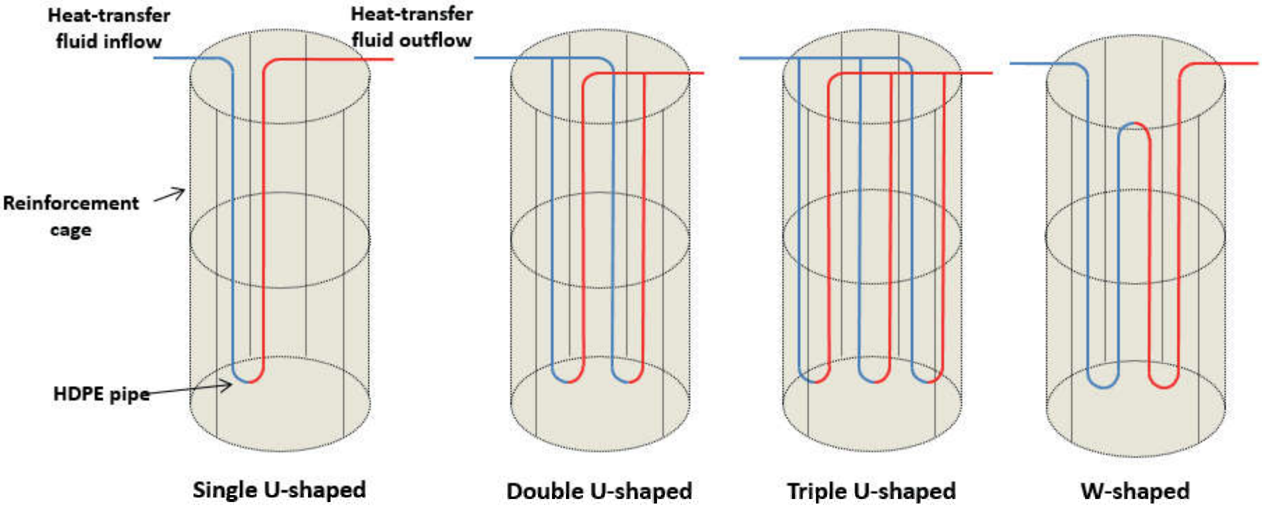

Figure 1. Typical energy pile arrangement with different pipe shapes (modified after Gao et al. 2008a)

2. TECHNOLOGICAL BACKGROUND

Energy piles are a type of closed-loop ground source heat pump system; hence they have higher initial cost but long-term economic benefits. Piles represent a primary unit of the overall heat pump system with the purpose of extracting and injecting heat into the ground through the heat carrying fluid flowing through the pipe system (**Fig. 1**). System can operate in two different modes, i.e. a single mode with heating/cooling only or both heating and cooling operation (De Moel et al. 2010). Heat pump works similar to the principle of a reverse refrigerator (Brandl 2006). It contains a fluid with low boiling point which turns into vapour in contact with the fluid circulated within energy piles (Brandl 2006). Temperature of the vapour is then increased via compressor. Obtained heat is subsequently used to heat the fluid within the secondary unit, i.e. pipework for heating within the building (De Moel et al. 2010). In the cooling mode, secondary unit is used as the heat source and energy piles transfer heat into the surrounding ground which represents a heat sink. Hence, primary and secondary units have a reverse role depending on the season (De Moel et al. 2010). A device parameter that reflects the performance of the GSHP system is COP, i.e. Coefficient of Performance (Brandl 2006). This parameter indicates how much heat can be gained for a unit input of electrical energy and its value often varies between 3 and 5 (De Moel et al. 2010).

Precast or cast in situ reinforced concrete is the most common material used for energy piles because of its high thermal storage capacity and heat transfer capabilities (Brandl 2006). Steel foundation pile, because of its low thermal resistance and high thermal conductivity, can also be used (Nagano 2007). Absorber pipes used in energy piles are made of high-density polyethylene (HDPE) and their diameter ranges from 20 mm to 25 mm. Pipes are commonly delivered to working sites on reels and then fixed to the reinforced cage of the energy foundation (Brandl 2006). The most common shapes used in piles are single, double or triple U-shaped pipes and W-shaped pipes (**Fig. 1**). Due to the increased heat exchange rate resulting from higher fluid flow rates, turbulent flow conditions should be achieved in pipes (Brandl 2006). Moreover, the effectiveness of the heat transfer might reduce as the temperature difference between the fluid and the pile-soil interface reduces around the pipe circuit (Loveridge 2012). Hence, it is recommended to keep the circuit length between 300 m and 400 m, depending on flow conditions. In case where there are several piles connected into a single pile circuit, a temperature difference between each successive pile will occur, but its magnitude will decrease at higher fluid flow rate (Loveridge 2012).

Pile diameters range from <300 mm up to 1500 mm (Loveridge 2012). Regarding the pile length, it should be larger than the soil upper heterothermal zone which is influenced by seasonal fluctuations (Suryatriyastuti et al. 2012). According to Brandl (2006, 2013), the economical minimum is 6 m because for getting 1 kW of energy, required contact area between the pile-saturated soil and pile-dry sand is 20 m^2 and 50 m^2, respectively. Investigations have also proved that spherically shaped heat-exchanging elements can extract more heat energy per unit area than squared ones, hence are more effective (Brandl 2006). Long term behaviour of energy piles is best to represent by the aspect ratio (length divided by the diameter) where piles with shorter length to diameter ratios will reach thermal equilibrium with their surroundings more quickly (Loveridge 2012). However, Nagano (2007) showed that steel piles with effective length of only 4.7 m and diameters from 600 mm to 800 mm, screwed at 4.0 m deep from the ground level proved efficient.

Because of the possibility that negative fluid temperatures might affect the pile behaviour as well as the soil-pile interface and cause freezing, a mixture of glycol and water is commonly used as a heat transfer fluid (Brandl 2006). Both experimental and numerical work suggest that extreme fluid temperatures last for a limited period of time and that would not cause freezing in the pile-soil interface. Moreover, Loveridge (2012) suggested that if concrete's significant role in storing energy rather than just transferring it to the ground is considered, it is possible that fluid temperatures fall below 0°C. Hence, guidance suggested by Brandl (2006) that the fluid temperature should not fall below 2°C is considered conservative for the UK ground conditions (Loveridge et al. 2013). Nevertheless, it is advisable in the absence of calculations that fluid temperatures for large diameter piles (≥600 mm) and small diameter piles are kept above -1°C and 0°C, respectively (Amis et al. 2008; Bourne Webb et al. 2009; Loveridge et al. 2012; Di Donna et al. 2013).

In case where the temperature at the soil-pile interface is negative, thermal conductivity and thermal storage capacity of soil with high water content change, reducing the efficiency of the energy system. Furthermore, significant heave and reduction in the shaft capacity of the pile might occur (Brandl 2006). Hence, it is important to keep the temperatures at the interface above the freezing point. However, temperature gradient that exists across the pile, which can be up to 10°C, depends on the position of the pipes, applied heat flux and properties of the pile (Loveridge et al. 2012). Thermal deformation brings out increasing of mobilised shaft friction at soil-concrete interface (Suryatriyastuti et al. 2012). Furthermore, adhesion and the friction angle on the interface are affected by moisture transfer in the partially saturated soil caused by temperature changes.

Behaviour of the pile is affected by heat extraction during winter and heat storage during summer because in reality a pile will be able to expand slightly during heating and contract during cooling due to the restraints at the top by the building and at the toe by the underlying soil (Amatya et al. 2012). Hence, there will be a certain amount of additional axial forces developed in the pile (Bourne-Webb et al. 2013). It was observed in several examples that responses are quite complex, but the variation also depends on the type and properties of the soil surrounding the pile (Laloui et al. 2006). Brandl (2006) suggested that the hydration of the fresh pile concrete may also cause thermal strain-induced cracking since temperatures up to 70°C can develop. Hence, pile should have sufficient reinforcement.

Heat transfer mechanism in soil is very complex due to its multiple phase system and involves conduction, convection, vaporisation and condensation processes while radiation, ion exchange and freezing-thawing processes can be neglected (Brandl 2006). Hence, knowledge on ground thermal properties is required for a proper design of energy piles (Loveridge et al. 2013). One of the most important parameters, soil thermal conductivity, is commonly measured using a thermal response test (TRT) or alternatively using laboratory testing (Loveridge et al. 2013).

High-permeability ground and groundwater with high hydraulic gradient are of an advantage if only heating or only cooling is to be performed because if a flow of water is present and sufficiently large, a natural regeneration of soil is achieved. For seasonal operation where heat is being stored in the ground during the cooling mode, reversed conditions are favourable (Brandl 2006; Suryatriyastuti et al. 2012). Moreover, saturated soils conduct heat at a much faster rate while loose dry soils trap air and are less effective for heat transfer (De Moel et al. 2010). Work of Thomas and Rees (2009) has showed the importance of the groundwater table on the energy efficiency of the overlaying buildings where with deeper groundwater table heat losses from the building are decreasing. Consequently, this indicated the importance of considering soil moisture content above the groundwater table when estimating soil thermal properties.

It should be noted that the Thermal Pile Standard published by the GSHP Association (GSHPA 2012) provides more detailed information for materials and general specifications of a closed-loop energy pile system which can be used as guidance when considering ground source installation.

3. RESEARCH EFFORTS

Many authors focused their work in both numerical and experimental investigation of energy piles' behaviour. Majority of this work was carried out in terms of thermo-mechanical behaviour of piles and temperature changes in the surrounding soil. Work of Bourne-Webb et al. (2009), Amis et al. (2008) and Amatya et al. (2012) have provided information about an in-situ test performed at the Lambeth College in South London where a pile loading test incorporating temperature cycles was performed.

Thermal-mechanical behaviour of a pile 600 mm in diameter and 23 m in length was observed for 7 weeks, as well as the temperature profiling in the adjacent borehole and anchor piles located 0.5 m and 2.15 m from the pile, respectively. The site investigation showed 4 m of sand and gravel overlying the London clay formation with groundwater table about 3 m below ground level.

Working load of 1200 kN was applied which resulted in an initial pile settlement of 2.4 mm. The temperature range applied was from -6°C to 56°C which represents an extreme case because in the operational range, temperature changes are more likely to vary between -1°C and 30°C. In situ ground temperatures varied from 18°C to 20°C because of the heat energy radiating from the nearby London underground tunnels. A maximum cooling was provided to the test pile throughout the period of 4 weeks with the inlet fluid temperature of -6°C. In the first week, pile cooled by 14°C – 16°C and after 2 weeks reached a state of near equilibrium showing that low injection temperature did not lead to freezing at the pile-soil interface (**Fig. 2**). During the daily cooling and heating cycle, pile head movement was increased to 4.4 mm and decreased to 2.8 mm, respectively proving the thermally-elastic behaviour of the pile. Total mobilised shaft resistance developed during the thermo-mechanical loading was within the permissible range of ultimate shaft resistance, with some margin of safety. Hence, it was considered unlikely that the geotechnical capacity of the pile was affected significantly. During the cooling stage, negative shaft friction developed over the lower section while during the heating stage, negative shaft friction developed over the top section as the pile expanded upwards. The lowest temperature recorded was 0.3°C near the toe of the pile, while the maximum temperature change in the adjacent borehole was 9°C, but the temperature reduction appeared in a much slower rate. After the heat pump was switched off and the recovery period begun, temperatures in the pile and the borehole recovered and appeared to be stabilising towards an initial value from the start of the test. Anchor piles located 2.15 m from the test pile showed 4°C reduction during the cooling phase and returned to near ambient conditions during heating. As a result of observations, a descriptive framework for explaining the contribution of pile material and end-restraints to the overall response of thermo-mechanically stressed piles has been presented in Bourne-Webb et al. (2013).

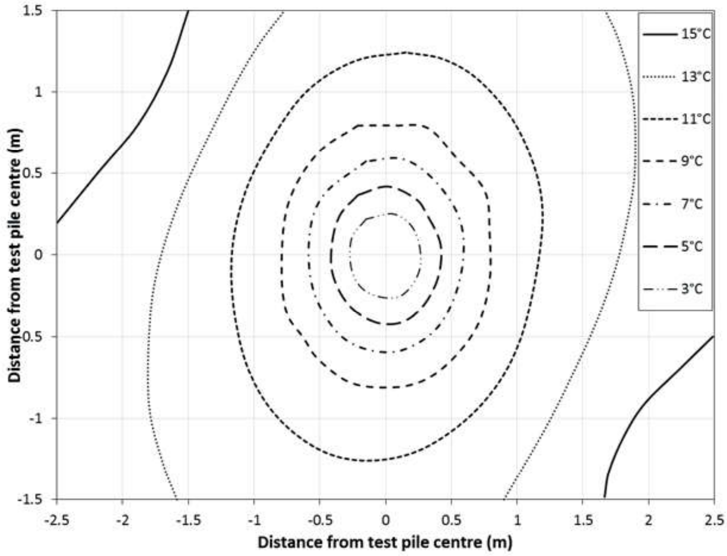

Figure 2. Contours of temperature variation at 12 m depth at the end of cooling (modified after Bourne-Webb et al. 2009)

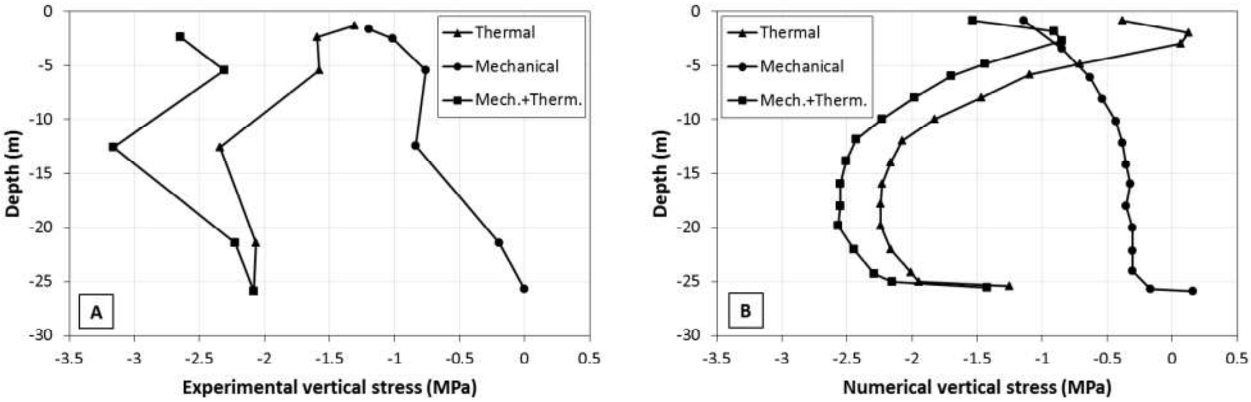

Figure 3. Thermo-mechanical vertical stresses in the pile: (a) experimental results; (b) numerical simulations (modified after Laloui et al. 2006)

In situ test and numerical simulations have been reported by Laloui et al. (2006) for a new four storey building at the Swiss Federal Institute of Technology of Lausanne, Switzerland. Tested pile was 0.88 m in diameter and 25.8 m in length with a slight increase in pile section with depth. Hence, a radius of 0.5 m was adopted for further numerical analysis. The first 12 m of ground consisted of alluvial soil overlaying sandy gravelly moraine layer with groundwater table very close to the ground surface. Pile was subjected to two types of loading, mechanical and thermal, which were applied separately. Maximum thermal increment applied to the pile was on the order of 21°C. It was shown that the thermal load is larger and rather uniform than the mechanical one and that temperature increment of 1°C resulted in an additional temperature induced vertical force on the order of 100 kN. In addition, a numerical modelling (THM) of soil behaviour was performed through which it was shown that even if the thermal effect propagates more in the soil than does the mechanical load, the induced strains are limited and do not affect the pore water pressure evolution. It was also shown that the developed numerical model was able to reproduce the increase in thermally-induced vertical stresses with depth as well as the decrease in mechanical vertical stresses with depth (**Fig. 3**).

An experimental observation of the ground temperature change and its impact on the pump efficiency over time in relation to heat extraction has been presented in the work of Wood et al. (2009). System consisted of 21 energy piles 300 mm in diameter and 10 m in length installed within 2 distinct layers, where the first 3 m consisted of an inhomogeneous material made of gravel, cobbles, sand and fine coal overlaying a very soft, red-brown clay with a slight gravel content, for a two-storey residential dwelling. The moisture content varied from 23% at 3.5 m depth to 16% below 5.5 m. The heat load and the inlet water temperature were adjusted throughout the season as would be typical for an actual heat pump installation. It was observed that the overall change in COP was not significant during the period of a case study, i.e. one heating season, proving the efficiency of the overall system (**Fig. 4**).

Furthermore, temperature data showed that the effect of heat extraction dominates at a distance of up to 1 m from the pile edge at a depth of 10 m while the seasonal influence is a dominant process at a depth of 2.5 m For comparison, at a distance of 5 m from the pile edge at a depth of 10 m, no temperature change has been observed. Recorded temperatures before the start of the heating season made at abovementioned depths, i.e. 2.5 m and 10 m were taken as reference temperatures for calculating the change in ground temperature across the heating season.

A full scale experiment with two concrete energy piles 1.5 m in diameter and 20 m long has been reported by Sekine et al. (2007) for the experimental institution built on-site at the University of Tokyo where both heating and cooling were required. Thick layer of fine sand was overlaid by 8 m of clay with groundwater level at 11 m below the ground. Underground temperatures were observed for a whole season at two different measuring points, i.e. point A 0.5 m and point B 2 m from the pile edge. During the heating period, temperatures at 1 m below the ground surface were influenced by the ambient air temperature while temperatures at 10 m and 19 m fell gradually after the start of the heat extraction and stabilized at about 15°C 0.5 m from the pile edge (**Fig. 5a**). Initial ground temperatures at depths of 10 m and 19 m were 19°C and 17°C, respectively. At the distance of 2 m from the pile edge, temperature reduction appeared at a much slower rate at depths of 10 m and 19 m suggesting that the effect of heat extraction on ground temperature approximately halved in comparison to the measure point located 0.5 m from the pile edge (**Fig. 5b**).

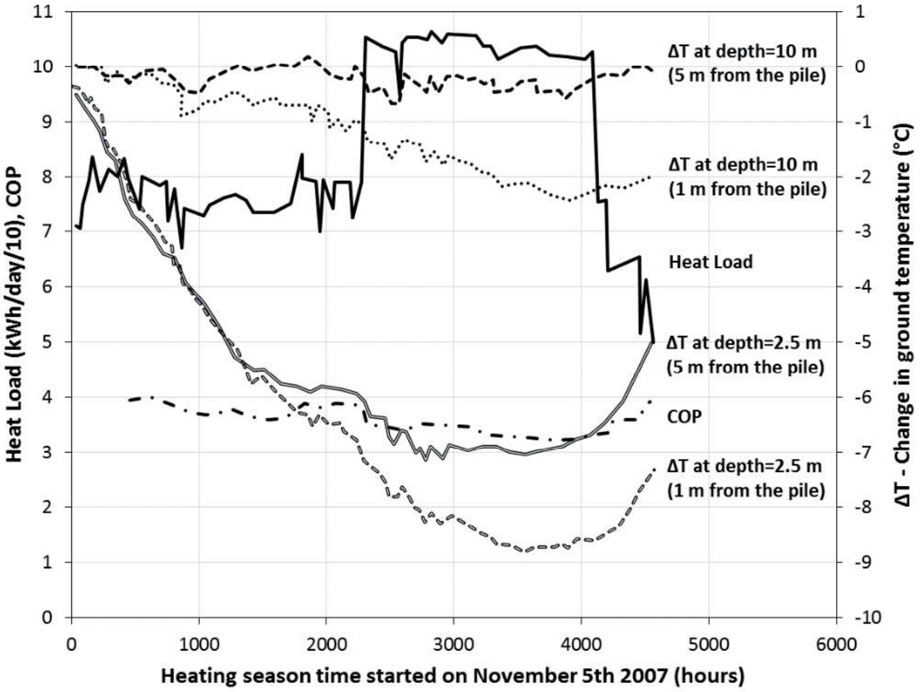

Figure 4. Heat pump monitored parameters and ground temperature 1 m and 5 m from the pile edge at different depths across the heating season (modified after Wood et al. 2009)

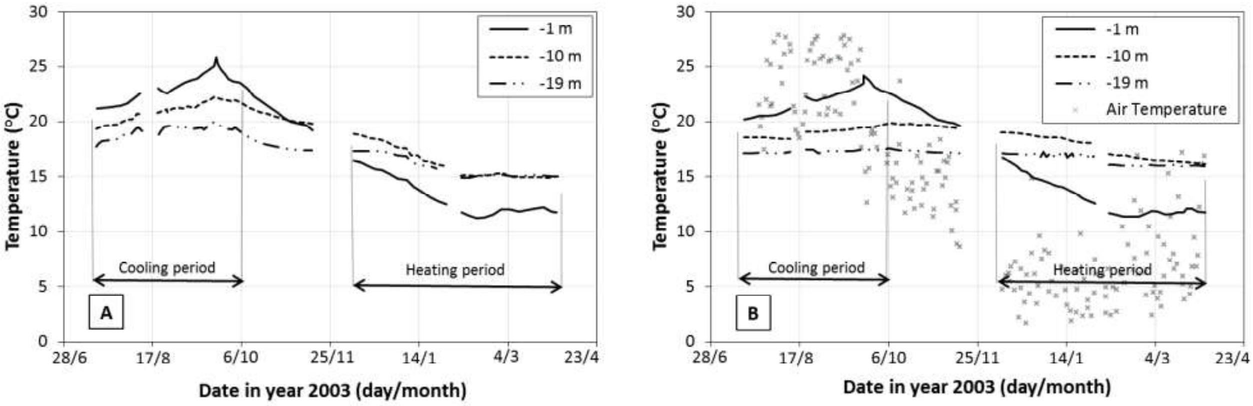

Figure 5. Underground and air temperature variations at different locations from the pile edge, A: 0.5 m; B: 2 m (modified after Sekine et al. 2007)

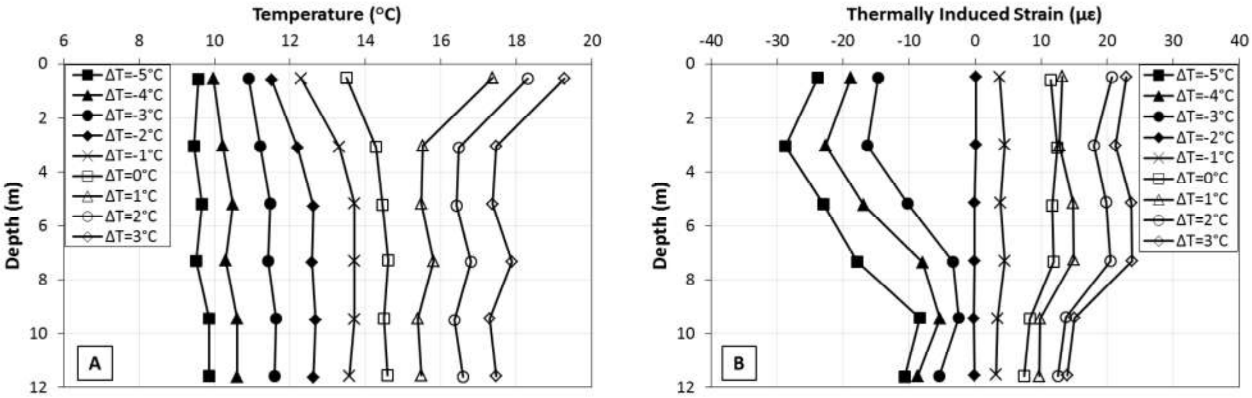

Figure 6. (A) Temperature profiles and (B) thermal axial strain profiles within the energy foundation for different average changes in foundation temperature (modified after Murphy & McCartney 2012)

Due to the high cost of boring in Japan, an examination of construction costs was performed by comparing the conventional borehole system and the energy pile system. It was concluded that the cost of construction per heat extraction and rejection unit of the proposed energy pile system was 75% cheaper than that of a borehole system and was expected to pay for itself within ten years. Furthermore, based on the average COP of 4.89 for this system, authors concluded that it is about 1.7 times more efficient than the more commonly used air-source heat pump (ASHP) system which makes it commercially viable.

Two of 60 drilled shaft foundations for an eight storey building built in Denver, Colorado were converted into energy piles and their behaviour has been discussed in the work of Murphy & McCartney (2012). Both foundations were 1.1 m in diameter but with different lengths, 14.8 m and 13.4 m. Hard sandy claystone bedrock found at 7.6 m of depth was overlaid by a 4.6 m thick layer of sand and gravel and 3 m of fill consisted mostly of clayey sand. Since temperature difference between the inlet and the outlet fluid of 2°C is sufficient for normal operation of heat pump, maximum difference in this case of 10°C had potential for good heat exchange. During the heating operation, temperature of the energy foundation tended to stabilize at 10°C (initial ground temperature was 15°C), indicating steady flow of heat from the ground into the energy pile while for the cooling operation maximum increase of pile temperature was 3°C from the initial ground temperature. Although shorter foundation had one additional heat exchange loop comparing to the longer one, temperatures of both foundations were similar which indicated that the number of loops may lead to a more uniform temperature distribution within a pile but may not improve heat exchange (**Fig. 6a**). The shapes of thermal strain profiles indicated that foundations are expanding upwards from the relatively rigid bedrock (**Fig. 6b**). Hence, conclusion was made that strains and stresses as a result of temperature changes are not expected to lead to structural issues.

A case study has been performed for a district cooling and heating system in Shanghai, China by Gao et al. (2008a, 2008b). A group of 5500 concrete pile foundations, 600 mm in diameter and 25 m in length, was planned to be installed in a land parcel of 100 m x 1000 m which would take about 30% thermal load of district cooling and heating. Besides 5 year numerical simulation of ground temperatures, both numerical and in situ tests were performed to investigate the effect of pile type. Thermal efficiency between single, double, triple U-shaped and W-shaped types was compared under different flow rates. It was concluded that under the same flow rate within the pipes, W-shaped type is the most thermally efficient if the cost is not the definitive index.

Wang et al. (2012) have conducted a laboratory investigation of a coupled thermo-mechanical loading of a steel heat exchanger pile with an outside diameter of 25.4 mm and 250 mm in length. Silica sand around the pile at initial moisture contents of 0%, 2% and 4% was heated to 40°C and 60°C. The influence of temperature on the moisture content adjacent to the pile was observed. Additionally, mechanical loading/unloading was performed before and after the heating to assess the change in the shaft resistance. It was concluded that the shaft resistance reduction is proportional to thermal loading, i.e. higher shaft resistance reduction resulted from higher thermal loading in a soil sample with the initial moisture content of 2%. Moreover, higher drop in moisture content immediately next to the pile was observed with higher thermal load (**Fig. 7**). However, pile shaft resistance recovered when thermal load was removed and the soil sample was cooled to room temperature at 20°C for 24 hours due to moisture migrating back towards the pile. Furthermore, in the soil sample with the initial moisture content of 4%, drop in the moisture content adjacent to the model pile and the shaft resistance reduction were less significant comparing to the soil with the initial moisture content of 2%, while the change in the shaft resistance in dry sand was negligible after applying the thermal load.

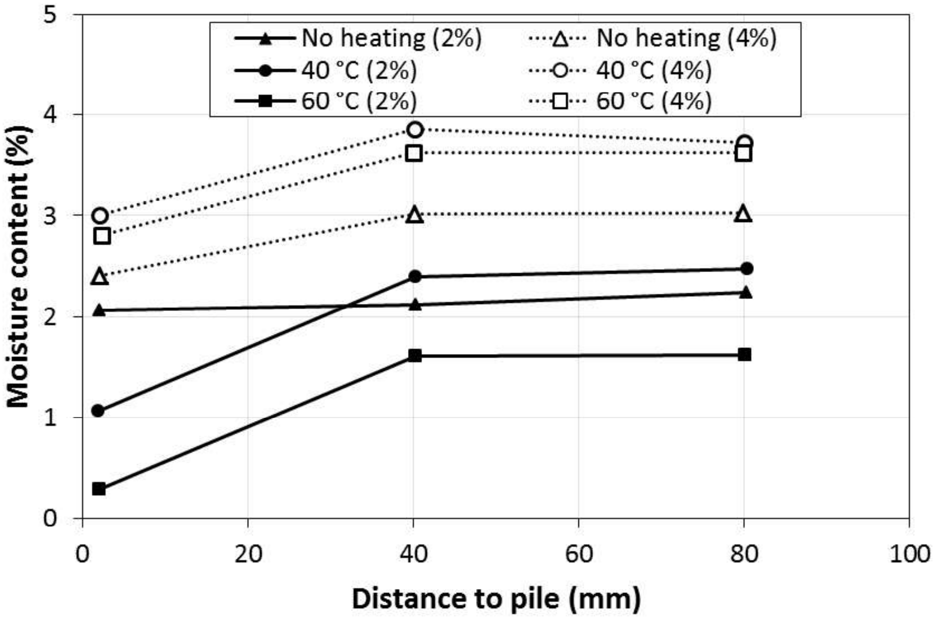

Figure 7. Soil moisture content after 24 hours for soil with initial soil content of 2% and 4% (modified after Wang et al. 2012)

Numerical investigation of the energy pile foundation behaviour, focusing on its long-term response to a seasonally cyclic thermal loading has been performed by Di Donna et al. (2013). The assumption was made that both concrete and soil were porous materials and the whole medium was fully saturated with initial temperature of 11°C. Numerical model consisted of a slab with 7 rows of 15 energy piles each (0.8 m in diameter and 20 m in length) with 7 m spacing between each pile. After the first 5 years, temperature in the most thermally solicited zone (10 m depth) between two piles oscillated among a maximum value of 17°C during summer and 10°C during winter. According to soil's proposed behaviour, its thermal deformation resulted in additional displacements of the foundation which made the foundation moving downward during the cooling period and upward during the heating period. In such case, irreversible displacements were also registered, completely developed during the first 5 years. Since piles were heated and cooled equally together, an additional differential settlement was not induced. Thermally induced pore water pressure was negligible, hence conclusion was that the heating phase occurred in almost drained condition which is likely the case in all energy pile foundations. However, authors used relatively high value of hydraulic conductivity (10^{-8} m/s) which allowed quick pore water pressure dissipation. In this study, piles had a structural capability to carry both the mechanical and the thermal load applied. It was concluded that soil plastic contraction developed during the first thermal cycles induced a reduction of the confinement cycle after cycle. Consequently, the portion of external load which was initially transmitted through the pile-soil interface reduced during the first 5 years from 70% to 66% and the difference was transmitted through the base of the pile.

A new user-friendly numerical tool, called "Thermo-pile" has been developed on the basis of previous experimental and numerical analyses (Knellwolf et al. 2011). Receiving conventional soil parameters such as cohesion, internal friction angle of the soil and lateral earth pressure coefficient as an input, it is able to couple the thermal evolution in the soil to the thermo-mechanical behaviour of the soil-heat exchanger pile system. Since it is based on the discretisation of the pile into segments, it allows for the consideration of different soil layers with different properties. Numerical model was validated through the existing data from in situ tests, i.e. Lambeth College and Lausanne Test Pile.

Work of Mimouni & Laloui (2014) gave insight on the impact of temperature variation on the mobilised bearing capacities of energy piles that has been obtained by numerical modelling using the “Thermopile” software. Change of soil and soil-pile interaction properties with temperature was not taken into account. The mechanics involved in variations of the bearing forces mobilised by piles under the temperature variation was not found to induce failure. Hence, conclusion was made that increasing the factor of safety of geothermal piles does not provide better serviceability, while it can significantly increase costs.

Suryatriyastuti et al. (2012, 2014) have suggested that there is a lack of knowledge concerning the impact of thermal cyclic behaviour of energy piles on the geotechnical performance and that no design code is available yet that takes into account the thermal interactions on the geotechnical capacity. Numerical simulation to analyse the cyclic behaviour of energy piles on the pile-soil interface was performed and conclusion was made that according to the axial fixity at the pile head, degradation of the soil-pile resistance during heating-cooling cycles generates an increase in pile head settlement for the free pile head or decrease in pile head capacity for the restrained head pile. Furthermore, it was found that the groundwater flow has an important role in the heat diffusion process controlling both the ground temperature equilibrium and the soil-pile stress equilibrium.

In order to investigate the impact of an energy pile on ground temperatures, a simple two dimensional heat transfer model of a pile heat exchanger has been set up by Loveridge et al. (2012). Pile was 600 mm in diameter with 4 heat transfer pipes of 25 mm outer diameter symmetrically placed 75 mm from the outside edge of the pile. A sensitivity analysis was performed with different combinations of thermal properties of the concrete and the surrounding ground. Results of the analysis showed that if the thermal conductivity of the concrete is higher than the conductivity of the surrounding ground, temperature difference between the pipes and the pile edge is small. Hence in such case, negative fluid temperatures could lead to the pile-soil interface freezing.

In the work of Ghasemi-Fare and Basu (2013), numerical modelling of the heat transfer through a concrete geothermal pile with an embedded U-shaped circulation tube has been performed. Pile with radius of 300 mm and length of 30 m was considered. It was noticed that the thermal influence zone around the pile extends approximately up to a radius of 3.2 m after 60 days of heat injection from the pile to the ground which can be considered as an extreme scenario. Beyond a depth of 6 pile radii below the pile base, the change in ground temperature was less than 1°C which was considered negligible. Since with the decrease in soil water content, value of the soil thermal conductivity reduces, heat transfer performance was investigated in the presence of a 5 m desiccated zone from the ground surface. It was noticed that the thermal influence zone is smaller within this layer, but increase of the ground temperature adjacent to the pile is greater due to lower thermal conductivity of unsaturated soil.

Moritz and Gabrielsson (2001) have performed a field experiment for heat storage in clay for two stores with groundwater 2 m below the ground surface. Maximum temperatures of 70°C and 90°C were applied to the first and the second store, respectively. It was observed after 7.5 years that the settlement in the first store was 70 mm while in the second store a settlement of 140 mm was recorded. Furthermore, an excess pore water pressure developed during the heating phase and negative pore water pressure developed during the subsequent cooling.

Thermally induced volume changes of saturated fine-grained soils have been experimentally investigated by numerous researchers and an extensive review has been presented in Abuel-Naga et al. (2015). Excess pore pressure during heating is induced by 7-10 times higher thermal expansion coefficient of water with respect to the solid particles (Laloui and Di Donna 2013). Volume variations caused by heating clayey soils in drained conditions depend on the consolidation state of the soil. For normally or lightly over-consolidated clayey soils, heating usually results in contraction while for highly over-consolidated clays elastic expansion is typical (Abuel-Naga et al. 2007). Furthermore, with an increase in temperature, yield limit shrinks and the reduction of the pre-consolidation pressure occurs (Laloui & Di Donna 2011). In case where the soil is highly permeable and the temperature is increased slowly enough, pore pressures have time to dissipate because the heating phase approaches drained conditions (Di Donna et al. 2013). Conversely, an increase in the pore water pressure in low permeable soils causes a decrease in effective stress of the soil (Brandl 2006). In saturated low permeable and chemically active porous media, osmosis phenomena are among key processes identified to control the water flow and deformation behaviour. In particular, flow of water driven by a temperature gradient, i.e. thermo-osmosis was found to contribute to pressure distribution and flow in such media (e.g. Trémosa et al. 2010). Zagorščak et al. (forthcoming 2016) have conducted an investigation on the effects of thermo-osmosis on hydraulic behaviour of saturated soils. Sensitivity analysis was performed using different values of thermo-osmotic conductivity and it was concluded that the effect of thermo-osmosis is considerable for chemically active soils with thermo-osmotic conductivity values larger than 10^{-12} $m^2K^{-1}s^{-1}$.

It was showed that temperature changes in the partially saturated soil cause moisture movement towards the colder region which changes the stress-strain-strength behaviour of the soil and the soil-pile interface (e.g. Wang et al 2012). Consequently, soil thermal properties are affected (De Moel et al. 2010; Ghasemi-Fare and Basu 2013). Such processes gradually cause shrinkage in the warm zone and expansion in the cold one in unsaturated fine-grained sensitive soils (Brandl 2006). From geotechnical point of view, heating of foundations may also have an important advantage in improvement of soil characteristics which might result in a reduction of foundation costs (Laloui et al. 2006). Positive effect on resilience of clayey soils under cyclic loading can be achieved by thermal pre-treatment which can result in a higher resistance of the buildings against earthquakes (Laloui et al. 2006).

4. EXAMPLES OF ENERGY PILE INSTALLATIONS

Many examples of successful energy pile installations exist around the world. By the end of 2006 in Austria, there were nearly 300 buildings fitted with energy piles or energy diaphragm walls (Brandl 2006). In Switzerland, more than 40 projects have been built on energy pile foundations and probably the most famous one is the Dock Midfield terminal at Zürich airport (Laloui & Di Donna 2011). Germany and UK are countries in which several buildings have been equipped with energy piles (Laloui & Di Donna 2011). In the UK, energy pile systems are mainly constructed in London, but the first one ever built in the UK was at the Keble College, Oxford. According to Laloui & Di Donna (2011) some installations have been made in Japan, Canada, Scotland, Liechtenstein, Italy and Netherlands.

4.1. Keble College, Oxford, UK

In the work of Suckling & Smith (2002), an example of the first energy pile installation in the UK built in 2001 has been presented. A six storey structure included a basement up to 7 m below the existing ground level. Soil consisted of 4 different layers with a groundwater table at about 5 m below the surface. Mean ground temperature below 10 m depth was around 13°C. Very stiff to hard Oxford clay at a depth of 7.5 m was overlaid by a 3.5 m thick Thames river deposits above which mixed layers of firm alluvial clay and made ground were found. It was planned that the heat pump increases the temperature of the fluid from 13°C to between 25°C and 35°C. The retaining wall was executed as a hard/soft secant wall comprising in total of 223 piles of different type. Length and diameter of the piles ranged from 9-15 m and 600-750 mm, respectively. Furthermore, 61 bearing piles with 450 mm diameter and 12 m in length were added to accommodate structural loads. Plastic pipes for fluid flow were attached to the reinforcement of the foundation elements prior to concreting. No pile diameter or length was increased to accommodate geothermal requirements above that designed for the required structural or geotechnical applied loads.

4.2. Sapporo City University, Japan

The world's first energy pile system which utilized steel foundation piles as heat exchangers for the new building at Sapporo City University built in 2005 has been presented in the work of Nagano (2007). System consisted of 51 energy piles screwed into the ground predominantly consisted of gravel and sand at 4 m depth from the ground level. Diameter of the piles varied from 600 mm to 800 mm, while their average length was 6.2 m. Due to the usage of indirect closed circulating system (using U-tubes soused in water) with 2 sets of U-tubes inserted into each pile, effective length of each pile resulted in 4.7 m. According to calculations based on the condition that the pipe temperature did not fall below –2°C, system could supply daily base heating load of 40 kW. However, heating output of 50 kW was required so three additional boreholes were planned to be drilled at a reasonable length of 75 m to satisfy the heat output.

A novel GSHP designing and performance prediction tool has been also developed based on the work of author's group, able to treat the random layout of ground heat exchangers with high speed calculation algorithm. Tool includes database of heat pump performance curves according to both outlet temperature of the primary side, i.e. energy piles and inlet temperature of the secondary side, energy prices and specific CO_2 emissions. As a result, hourly energy consumption and energy cost can be obtained. Moreover, life cycle energy and life cycle CO_2 emissions can be evaluated.

Prediction of performance showed that when the system adopted a constant-speed pump in order to satisfy maximum heat output, Seasonal Coefficient of Performance (SCOP) was 2.7. However, during winter and summer the maximum SCOP can reach 4.4 and 5.7, respectively suggesting that a variable speed pump depending on the heat loads can be effective to improve SCOP. Annual operating cost and annual CO_2 emissions of the GSHP system were compared with those of gas systems; a gas boiler providing heating only and a system providing both heating and cooling. Operating cost for the GSHP system represented half the cost of a gas boiler providing heating only and 42% of the one with cooling and heating system. Annual CO_2 emission of GSHP was 12 tons which is 3.8 tons and 7.4 tons less compared with a gas boiler providing heating only and system providing both heating and cooling, respectively.

4.3. Dock midfield of Zürich airport, Switzerland

System design and construction of the New Terminal E at Zürich Airport has been presented in Laloui & Di Donna (2013). New terminal was built on 440 foundation piles, of which 300 were equipped with five U-pipes fixed on the reinforcement. Piles were approximately 30 m in length with a diameter ranging from 0.9-1.5 m fully passing through soft lake deposits and standing on a moraine layer. It was expected that energy piles meet around 65% and 70% of heating and cooling demands, respectively. Terminal has been in use since 2004 and the overall ratio of thermal energy obtained by the system and the total electric energy used to run was set as 5.1. Hence, it has proven to be economically more profitable than a conventional pile system.

4.4. Projects in Austria

Few research projects performed in Austria have been presented in the work of Brandl (2006). A rehabilitation centre comprising of seven floors, two of them beneath the ground surface, was constructed on a system of 175 piles, of which 143 were fitted with heat exchangers. Diameter of the piles was 1.2 m while the pile length varied between 9-18 m depending on the static requirements and ground properties. Ground consisted mostly of silty sand and clayey to sandy silt with groundwater at 4-5 m below the surface. In the first winter period, minimum pile temperature was close to 2°C. It was shown that operational fluid temperatures between –2°C to –3°C (temporarily – 5°C) caused the formation of ice lenses in the ground and a heave of 15 cm of the surface behind the piles. However, this was partly attributed to low air temperatures. The system has been in use since the autumn 1997 without any problem. Significant influence of the groundwater flow as well as the influence of air temperature on the system was clearly visible where strong groundwater flow enhanced pile temperature recovery (**Fig. 8**).

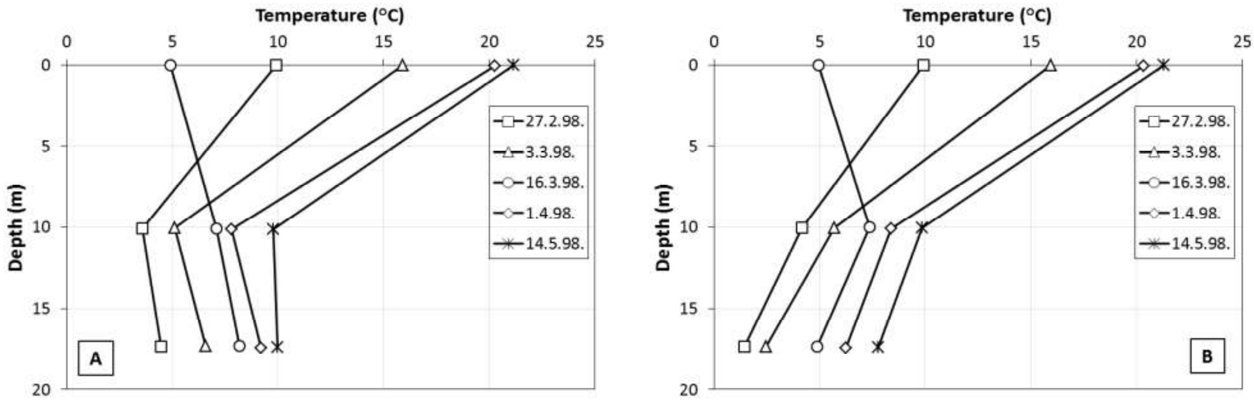

Figure 8. Temperature evolution (measured in the centre of the pile) along two different piles A) Strong groundwater flow (6 l/s), B) Poor groundwater flow (0.6 l/s) (modified after Brandl 2006)

A deep foundation comprised of 320 cast in situ concrete piles was built for a multipurpose hall with a capacity of 8000 people. Piles were 18 m long and 0.5 m in diameter totally containing about 65 km of absorber pipes. An annual saving of 85 000 m^3 of natural gas, equivalent to 73 tons of CO_2 was achieved by this cooling and heating system. Nearby, a spa hotel with geothermal cooling and heating was also built. In a foundation of 357 piles, 30 m long around 69 km of plastic pipes were installed. Energy extracted from the ground during the winter corresponds to the energy demand of about 160 modern one-family houses.

Arts Centre with a foundation comprised of energy piles and diaphragm walls was built. The diaphragm wall thickness varied between 0.5 m and 1.2 m while the diameter of the piles was 1.2 m. Depth of a diaphragm wall was 28 m while the pile length varied between 17 m and 25 m. Soil was mostly consisted from loose sand and weak clay with a groundwater level about 1 m below the surface. Building was heated during the winter and cooled during the summer through the energy pile system which resulted in both environmental and economic benefits. Calculations showed that the saving in investment costs was €1.32 million while the annual savings in energy and operation costs were €22,700 in comparison with a conventional air-conditioning system.

Paper-processing plant was built on a piled raft foundation consisting of 570 driven reinforced concrete piles (0.4 m x 0.4 m). Length of each pile was 24 m with only the top 14 m used to accommodate absorber pipes. Building heating demand was achieved through combined usage of the waste heat from machines and energy piles while the cooling demand was predominantly achieved through the usage of energy piles. System has been running since autumn 1995 without problems.

The first thermo-active traffic tunnel (“energy tunnel”) was also built in Austria using two different methods. The first section was performed using the cut and cover method, consisting of 59 energy piles 1.2 m in diameter and 17.1 m in length, while the other one was the NATM section. The cut and cover section was connected with the adjacent school in order to provide heating to the building. Predictions were made that annual savings in operation will be €10,000, compared with the old natural gas system, and a decrease in annual CO_2 emissions of 30 tons will be achieved. Calculations showed that down to –5°C of the outdoor temperature, school building can be fully heated with the GSHP system.

Besides for residential and commercial heating and cooling purposes, energy geo-structures are used in various environments, e.g. cooling and heating of metro stations, bridge decks, road pavements and parking places, airport runaways, etc. Brandl (2006) and Laloui & Di Donna (2013) have given a more detailed overview on the usage of ground energy.

5. FUTURE PROSPECTS AND RESEARCH CHALLENGES

During the past 30 years, the number of installed energy pile systems has been constantly increasing. Although their geotechnical dimensioning and designing was based on experience and empirical considerations, there has not been any structural or geotechnical collapses up to date. However, common practice was to adopt increased safety factors in comparison to conventional piles which resulted in additional cost. It was proved in several examples, both numerically and experimentally, that thermal stresses in the pile within normal and expected temperature boundary conditions are significant and if this is considered in the design, potential hazards should be avoided. However, stresses and strains were measured only in the axial direction while it can be expected that the radial behaviour of the concrete and the soil mass could have an impact on the pile-soil interaction. Furthermore, large thermal stresses measured in situ for isolated thermal piles that were part of a conventional pile system may be unrepresentative of situations where a system of energy piles is heated or cooled at the same time. Most numerical analyses were based on regular arrangement of energy piles, developed from borehole heat exchangers which are commonly used in regular patterns. Since in reality this is rarely the case, numerical modelling including irregular position of piles with different lengths would provide further understanding of their influence on the overlaying structure and the surrounding soil. Furthermore, investigating the effect of such system in a dense urban environment where the surrounding soil is also being used for heat extraction by other dwellings would be beneficial. In addition to that, as recommended by the GSHPA Thermal Pile Standard (GSHPA 2012), case where energy piles are connected into a single pile circuit across different soil layers should also need to be considered in the future work because variable temperature field developed in the ground could cause differential settlements of the system and potentially endanger the structure stability.

An extensive experimental work in relation to thermally induced volume changes in cohesive soils has been conducted showing that normally consolidated and lightly over-consolidated soils exhibit significant consolidation over time. In addition, it has been shown that pore water pressure in low permeable soils increases reducing the effective stress near the heat source. Influence of such behaviour on end bearing and shaft resistance of pile groups has not yet been sufficiently understood and adopted in daily energy pile designs. Majority of numerical models consider soil as a single bulk phase ignoring the thermodynamic pore water density, viscosity and pressure variation with temperature. While it has been experimentally shown that heating of foundations cause the moisture migration away from the heat source reducing the shaft resistance even in non-cohesive soils such as sands, considering soil as fully saturated and neglecting the phase transition in unsaturated soils in the current models limits their application in different conditions and climates. Induced volume changes in soil are of high importance in cases where the soil around energy piles is being used as heat storage, as it has been experimentally shown that heat injection over several years can cause significant settlement of the soil.

Additionally, moisture migration is expected to alter heat transfer properties of the partially saturated bulk soil, i.e. thermal conductivity, heat capacity and thermal diffusivity. One of the most important thermal properties of the soil, i.e. thermal conductivity can be measured using field or laboratory test. While field tests, such as TRT are expensive and time consuming, laboratory test are simple to conduct but the interpretation of results should be performed with great care due to the soil disturbance and idealized boundary conditions used in comparison to the real ground conditions. Hence, interpreting such properties over a range of time periods taking into account cyclic thermal behaviour of energy piles in multiphase and multicomponent soil materials and comparing to the initial design values, would enhance the design of energy pile systems. In that case, more realistic linear rates of heat injection/extraction would be able to be determined.

Several in situ tests revealed the importance of groundwater flow in the natural thermal recharge of the ground, while numerical studies have not taken such phenomena into account. While convection is of less importance in low-permeable soils, i.e. clays, the significance of investigating the groundwater flow is obvious and great in semi- and highly-permeable soils. Such studies are of importance because ground temperature can gradually increase or decrease during the years if the amount of heat extracted during the winter and heat injected during the summer is imbalanced which can result in lowering the efficiency of the heat pump. In such cases, additional heating/cooling systems would have to be added increasing the cost of the overall energy system. In order to analyse the long-term performance of the entire system, predictions regarding the soil recovery process should be performed especially in cases where heating demand is predominant. Furthermore, due to unpredictable weather conditions that might arise as a result of climate change leading to modified groundwater recharge and changing the aquatic environment, taking groundwater flow and change in groundwater table into further analyses is of importance for long-term prediction of energy piles' performance.

According to several researchers and the current standard (GSHPA 2012), possible soil freezing which causes expansion of the water phase and a subsequent permanent soil deformation that may have a severe effect on the shaft resistance and end bearing capacity should be avoided. Such condition can be satisfied by keeping the fluid temperatures above 0°C, while in reality this can easily be violated simply by leaving the heating system operating beyond its design constraint. However, previous research findings showed contradictory results. While some in situ tests showed that negative fluid temperatures did not lead to freezing in the soil-pile interface, a combination of both negative air temperatures and fluid temperatures within piles caused significant heave next to piles in the other case study. Therefore, if such constraint is improved by taking into account concrete's significant role in storing the energy, it would allow the range of temperatures in piles to be extended and more heat to be derived from the energy pile system. On the other hand, in cases where freezing might occur due to the unexpected failure of the heat pump system or change in climate conditions, the influence of freezing and thawing cycles on volume change and subsequent changes in shear behaviour between the soil and the pile concrete should be further investigated. Such findings would also be highly useful in advanced geotechnical constructions conducted in areas with colder climate, i.e. permafrost areas.

In recently conducted numerical simulations, presented models have been simplified taking heat conduction as the only way of heat transfer and have been conducted focusing mostly on heat propagation around the heat source with assumption that material properties of the ground do not change with temperature. Such simplifications are introduced mostly because numerical tools for analysis of coupled processes are in general mesh-dependent, oscillatory and computationally resource demanding. Hence, such models exhibit limitations and cannot be fully used for general structural conditions and climates in daily engineering practice. Because past in situ tests were performed over a short time period, i.e. mostly one heating/cooling season, 3-dimensional numerical modelling describing transient thermo-hydro-mechanical behaviour of energy piles embedded in a soil mass is essential for providing insights into energy piles' behaviour over a long time period. Hence, further effort should be focused in developing comprehensive but numerically efficient tools that will be designed to run on desktop machines that could be utilised in engineering practice. However, full scale field experiments focusing on the long-term thermo-mechanical soil-pile interaction and laboratory experiments through which material parameters and thermo-hydro-mechanical constitutive relationships would be derived are essential for development and validation of such numerical models that would be capable of addressing potential failure mechanisms. In addition, such models could be then utilised for establishing standards and norms as well as enhancing existing guidelines.

6. CONCLUSION

In the past few decades, energy piles have proved to be innovative and environmentally friendly structural elements that function as heat exchangers providing energy to the overlaying structure. Different examples and existing research studies are presented in this paper, providing general information obtained in the previous work. Although this technology has been recently applied in various countries, there are still important knowledge gaps on the consequences of the application of such technology because of the potential risks that might arise due to unforeseen induced cyclic thermal stresses making construction companies reluctant to apply energy piles in daily practice. Potential issues and knowledge gaps related to thermal, hydraulic and mechanical behaviour of soil and the soil-pile interaction are pointed out which, if further investigated, could help to better understand the long term behaviour of such systems.

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