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# UNIVERSIDADE DE BRASÍLIA

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# POSDOC LEAVE REPORT

## Study of Geothermal Energy Piles (GEPs) for Sustainable Climatization of Structures in Brazil

## Report on State-of-Art Knowledge and Research on GEP Systems

## Pós-Doutorado no Exterior (PDE)

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# LAYOUT

# INTRODUCTION & PRESENTATION

## Introduction

Greenhouse gas emissions produced by fossil fuels are causing a slow change of the climate´s conditions. Air conditioning systems in engineering superstructures demand a considerably amount of the existing carbon-related energy sources, which are pollutant and nonrenewable. In this regard many countries inside and outside the European continent have coupled ground source heat pumps (GSHP), firstly developed and built by Robert Webber in 1940 (Sani et al. 2019a) to superficial geothermal energy structures (SGES), so to exchange and store ground heat, aiding the reduction of harmful gas emissions. Actually, this idea is not new, and the 1st. documented suggestion for using ground as heat source in modern era[1] was in 1912 in Switzerland, but at that time heat pump efficiency was poor and energy prices were very low. Commercial use only started after the 1st. oil crisis in 1973 (Rawlings & Sykulski,1999).

Geothermal energy pile (GEP) systems are SGES that can provide a positive contribution to this goal by simultaneously regulating the environment conditions of the superstructures while acting as deep foundations. According to Brandl (2006) GEPs can harvest the thermal loads of the ground, since the natural ground temperature is used as a heat source for heating in winter and a heat sink for cooling in summer. Hence no additional elements must be installed below surface, as GEPs serve both structural and thermal functions. Two circuits are connected in GEP systems. The primary circuit relates to the geotechnical infrastructure, being connected via ground source heat pumps to a secondary circuit, this one related to the overlying superstructure. Heat exchange between the distinct circuits are used to regulate and to climatize the superstructure, rejecting excess heat or extracting necessary heat to and from the ground, respectively. Seasonal operations on balanced or unbalanced thermal load regimes, and different circuit configurations are possible, but the working principle never changes: Geothermal heat is transferred via heat exchanger piles to regulate the superstructure´s internal temperature along the year.

Global demand for energy services is expected to increase by as much as an order of magnitude by 2050, while primary-energy demands are expected to increase by 1.5 to times according to Dincer (2000), hence justifying the search of alternative ways to cut back harmful $CO_2$ and greenhouse related gas emissions. The use of alternative sustainable ways to climatize residential structures or industrial / agricultural venues has thus double advantages, as reducing environmental impacts as well as saving primary energy – that in the case of Brazil is mainly related to hydropower sources, in deforested areas.

Besides of using a renewable energy as its primary source, Brazil produces 1.3% of the world´s total amount of greenhouse gas. This value does not exempt the country from the Doha amendment to the Kyoto Protocol that demands a decrease in 18% of 1990 levels up to 2020 (https://unfccc.int/kyoto_protocol), thus enabling a huge political interest and a large demand for technical manners to do so. One solution is certainly the use of GEP systems. Nevertheless, uncertainties are still high, and time is running fast. There are large gaps in terms of the steady and accumulated deformations & thermal stresses in the piles

[1] As it will be shown during the review, buried structures have already been used in the past for thermal efficiency of ancient dwellings

and plastic strains in the soil during long-term cyclic thermal events. Environmental issues are also acknowledged, as the thermal interference on groundwater aquifers and biological/chemical contamination.

Although attractive in theory, and quite old in principle, the technology behind the use of GEPs in civil constructions remain uncertain, as design parameters, operation guidelines, simulation analyses, theoretical models, in-deep behavior and legislation are not yet clear, even in countries where it is more advanced. There is still a lack of better understanding on their thermal and geotechnical aspects, besides of reliable information on their performance at longstanding conditions. Simulation models & tools that encompass the thermal-hydro-mechanical aspects of the soil media are not fully stablished too. Recent results on GEP systems indicate that the heat flux is highly influenced by soil saturation conditions, and the thermodynamic efficiency decreases on unsaturated soils. However, tropical soils with abundance of minerals with high thermal capacity may have potential for a feasible application, justifying the research in predominantly tropical-subtropical influenced regions as Brazil. The overall knowledge on the thermo-mechanical behavior is still restricted to specific conditions, but it is already known that thermally induced stresses and strains will appear and superimpose with those from the mechanical loading of the piles, demanding a reassessment of the geotechnical and structural design. Cyclic behavior specially under long-term unbalanced thermal demands needs to be better understood, together with input thermal variables for existing yet non-practical thermo-hydro-mechanical models. The behavior of pile groups, and the influence of the building´s slab temperature coupled to distinct restraint conditions are challenging topics yet to be further explored.

On the legal front, large gaps remain in terms of guidelines, operation and control. Moreover, there is no common framework of design, site construction and regulation jurisprudence to allow a standardized implementation of GEP systems in Western countries as Brazil. The lack of an overall understanding undoubtedly acts as a barrier for investment, since each design is unique given the array of involved interdisciplinary issues and regional-national conditions. Public awareness and political drive are also limited or non-existent in most countries. In other words, it is an old technique still uncomprehend in modern times.

Therefore, the presented *bibliographic review* of this Report objectives the discussion of the use of this (“new”) technology, focusing on its general view and layout, advantages, challenges, difficulties, on-going research and possible scenarios for application in Brazil. It tries to highlight its importance and shortfalls, whenever possible. The review is intrinsically related to the activities of a 6 months postdoctoral leave from the author at the Instituto Técnico Superior of the Univ. of Lisbon, in Lisbon, Portugal, from July to December 2019.

# Presentation

The bibliographic review is divided into 5 main topics, or technical categories, connected to the main subfields of *Geothermal Energy Piles*, or *Thermally Active Deep Foundations*, or *Heat Exchanger Piles*, all the same definitions that, for simplicity reasons, are denoted as *GEP systems* from now on.

The following main categories are summarized along this Report:

1. Review on key findings on <u>field scale studies</u> on the thermomechanical behavior and thermal performance of GEP systems;
2. Review on key findings on <u>laboratory studies</u> on the thermomechanical behavior and thermal performance of GEP systems;
3. Review on key findings on <u>numerical studies</u> on the thermomechanical behavior and thermal performance of GEP systems;
4. Key findings on <u>miscellaneous knowledge</u> related to soils and GEP systems;
5. Key findings on <u>research theses</u> in Brazil and Portugal about GEP systems;
6. <u>Conclusions</u> on the bibliographic review on GEP systems.

The review on each of the thematic categories are provided on a time-basis order, rather than on importance or any other specific category. They are presented through one main Item and two Annexes of this Report, namely Item I and Annex 1 and 2.

Item 1 summarizes in *text format* all five categories of GEP systems, through subitems I.1 to I.5, respectively related to each previously described case. A final subitem I.6 is further presented, trying to encompass all the categories simultaneously, hence providing the main points, research ideas and the generalized/localized conclusions on the gathered knowledge that may be of importance for those interested in investing time, research and funds on this technology in Brazil and elsewhere. Annex 1 is a complement of the Item I, illustrating the main information of each of previous discussed references in a *tabulated format*, for easy access and consultation. Again, it is divided into sub annexes 1.1 to 1.5, similarly related to each of the discussed categories. It is located at the end of this Report. Annex 2 introduces a sample of a comprehensive technical course on the matter, based on the knowledge, experience and research gathered throughout the postdoctoral leave. This course has been prepared during this period and will be certainly offered soon at the University of Brasília both in undergrad and graduation levels. Negotiations are on the way to offer a short version of this course on the next 2020 (COBRAMSEG) Geotechnical National event in Campinas, Brazil.

The Report provides a final section (Item II) related to short comments or remarks on the postdoctoral leave, after gathering and consolidation of all studied material. It initially addresses the possible future benefits of the short-term leave and wraps up by acknowledging all the provided support that enabled the successful elaboration of the report. It is followed by a list of all bibliographic references adopted in the elaboration of this review.

More than 100 technical papers (mostly from International Journals) and 6 full research theses have been consulted and thoroughly read to provide this Report. Nevertheless, it can be also said that the presented knowledge is a small fraction of the reviewed information, representing the *up-to-date* present expertise on the technology of GEP systems for the sustainable climatization of superstructures. It should be emphasized, though, that this holds true within the time and resource constraints that have been faced by the present author in his 6 months of leave. In this regard, the maximum possible effort was taken to fully encompass all available material of interest herein.

# I. KEY FINDINGS ON GEP SYSTEMS

## I.1 Field scale studies on the thermomechanical behavior and thermal performance

*Thermomechanical Behavior (Table of Annex I.1)*

This subitem starts with a classical paper on this subject, published by Brandl (2006). According with this author the GEP technology is viable and has already been established with success in countries as Austria and Switzerland. In energy piles with concrete the heat transfer is significantly higher than in borehole heat exchangers, but the geothermal effectiveness of thin energy piles is smaller than in large bored exchangers. Coefficients of performance of the GSHP should be higher than 3 for a better effectiveness of the system, and a proper design requires numerical simulation including the secondary superstructure system. Technical issues are emphasized as the fact that the heat developed during hydration of fresh concrete pile imposes residual stresses within the pile, the heat extraction (winter mode) results in pile contraction, thus, decreasing the base pressure at the pile toe, the excessive heat extraction could lead to ground freezing which results in heave development around the pile, thermal strain-induced cracking of the GEP could occur due to shrinkage and during hydration of fresh concrete, the heating/cooling piles as a group induces lower axial thermal stresses at the pile head, compared to heating/cooling a single pile in the group and the axial load transmitted to the pile toe remained constant during thermal load application. Thermal interference, thermal and biological pollution, excessive settlements can also occur during the operation of GEP systems. The proper geothermal energy utilization does require an interdisciplinary design, involving geotechnical engineers, architects, building design specialists, heat and mechanical engineers, installers, plumbers, and related field experts. In this comprehensive and broad work, a set of recommendations for practical usage of the technology are provided together with design examples, theoretical approaches, misconceptions and advantages. In essence, the author concludes that geothermal geotechnics offers a promising alternative to conventional heating/cooling systems, that integrates engineering and environmental fields to provide a sustainable solution to the challenges of today´s energy policies and demands. Innovative practices with renewable energy, including thermal load harvesting and storage, should be implemented and fostered via political measures as high taxes on fossil fuels, economic incentives for private investors, public grants and, last but not least, supportive legislations.

Experimental and numerical investigation on field scale thermal piles was extensively carried out by the research group of the Swiss Federal Institute of Technology (EPFL) in Lausanne, Switzerland, with large advances on this field that have been published through joint publications of this research group with international partners (Laloui & Moreni, 1999 and Laloui et al. 2006). These authors studied the behavior of a real scale pile subjected to thermomechanical loads in a building from the EPFL campus, together with field measurements couple to metaphysical FEM modelling. They found that the understanding of the thermo-hydro-mechanical behavior of GEPs is restricted, and the strains in the test pile are thermo-elastic in nature, which intensity depends on the surrounding soil. Additional thermal-induced axial loads in the pile may be rather large and greater than solely those mechanically induced, and induced soil strains by thermal effects are limited as well as pore water pressure excess surrounding the pile. They also found that an increase in temperature results in additional friction mobilization, that thermal variation affects the mechanical behavior of the GEP in two ways: (i) increase in friction mobilization due to temperature increase; and (ii) addition of thermal compressive stresses in the GEP, and that the vertical stress developed due to coupled thermo-mechanical load is twice that due to pure mechanical loading.

Another research group from the Univ. of Cambridge in partnership with Skanska Ltd. tested another large-scale fully instrumented thermal pile within the grounds of the Clapham Centre of Lambeth College on the south-east edge of Clapham Common in South London (Amis et al. 2008, Bourne-Webb et al. 2009). The pile loading test incorporated temperature cycles while keeping an extended period of maintained loading for 7 weeks. It has been shown that the pile acts as an infinitely long heat sink/source with mobilized stresses additional to those due to static loads when heat is generated. Behavior was undoubtedly influenced by end restraint conditions of the pile, and there was a large margin between the pile ultimate shaft resistance and shear stresses mobilized at the pile/soil interface during the thermal cycling. They also found that the extreme cooling phase increased the test-pile settlement by about 2 mm and that the extreme heating phase resulted in the recovery of the pile-head after it was displaced during the extreme cooling phase. About 50% and 80% temperature reduction at the borehole and anchor pile location, i.e. 0.5m and 2.15m from the test-pile, were observed relative to that in the test-pile during the heating and cooling phases. Besides thermal cyclic loading increases and decreases the shaft resistance mobilized at the pile surface. Axial load developed in a partially restrained GEP (London test-pile) increases non-uniformly with depth and tensile forces induced due to extreme cooling cycle are unlikely to cause cracking in mass/plain concrete piles.

Amatya et al. (2012) summarized the field scale tests from both previous cited EPFL and Lambeth College sites and included another test site from Bad Schallerbach, Austria (reported by Brandl, 2006). They synthesized the results in a comparative manner and illustrated the main engineering behavior of such piles during heating and cooling, with indications of axial load increase per temperature change, in a rate of around 100 to 300 kPa/°C for $\Delta$T within 15 to +20°C. They stated that a GEP subjected to a thermal load induces thermal axial stress in the pile that was between about 50–100% of the theoretical fully restrained values and the type of restraint at the pile head and the toe, i.e. load of super structure and stiff ground or rock, could alter the magnitude of the stresses developed within the GEP. A need for further investigation on residual thermal stresses and/or relative changes in available shaft resistance is needed, although the total mobilized shaft resistance during thermomechanical loading was within the permissible range of ultimate values. A radial expansion of the piles was noted during heating and may have contributed somehow to the observed increase in shaft values. They concluded that by ensuring that design concrete stresses are not exceeded, safety factors (SFs) for skin friction and end bearing are maintained, and settlements are limited (as noticed in the tests), thermal operations are unlikely to have detrimental effects on buildings.

Akrouch et al. (2014) reported another experimental result of an in-situ tension thermo-mechanical test on an energy pile performed in a very stiff high plasticity clay, at the NGES at Texas A&M University, Riverside Campus in College State, Texas. During the in-situ test, the pile was subjected to thermal loading by circulating hot water in fitted pipes, simulating a thermal load in a cooling-dominated climate, at different levels of mechanical loading. The axial strain and temperature in the pile, and the load–displacement of the pile, were monitored at different locations along the center of the pile and at the pile head, respectively. They found that an increase in soil temperature results in an increase in pile creep rate, that heat extraction in cooling-dominated climates increases the viscous mechanism of clays resulting in long-term pile displacement effect, that the displacement of an energy pile is around 2.3 times that of a non-energy pile after 50 years of continuous heat injection operation, and that long-term energy pile displacement can be minimized by limiting the initial settlement. They finally concluded that further investigation should be carried out on the time-dependent behavior of energy piles through more load tests in different soil types and in both heating, and cooling, conditions.

An Australian research group (Wang et al 2013, 2014 and Singh et al. 2015a) from the Monash University, in Melbourne, presented the results of a large-scale field test on a single energy pile founded in predominantly dense sandy material. The pile was heated for various time intervals and the heat diffused slowly in the ground with its intensity being reduced with distance from heat source. To access effects of thermal load on ultimate shaft resistance loads and unload cycles were also applied during initial conditions and after a thermal period. The study showed that radial expansion and contraction of the GEP was observed during the heating and cooling phases, that pile shaft shear capacity increased due to heating and regained back to its initial state after cooling, and that the radial thermal strains were found to be uniform and did not change with depth, being equal to free expansion indicating that the pile expanded freely in radial direction, in an elastic fashion. No losses in pile capacity were observed after the 5 thermal cycles. They also showed that after a certain no. of heating days, a recovery time of same amount is not enough to return the temperature to its initial values, with lower $\Delta T$ increases at shallow depths due to the effect of air temperatures. They concluded that the pile can provide constant heat exchange rate irrespective of the ground temperature.

Researchers from the Univ. of Colorado at Boulder have described full-scale tests on two different sites. McCartney & Murphy (2012) and Murphy et al. 2015 presented 8 full scale instrumented GEPs that were constructed for a new building at US air force academy on an unsaturated sandstone deposit, with measured conductivities from 2 to 2.3 W/mK. 3 have been instrumented demonstrating thermo-mechanical induced stress up to 25% of the total compressive strength of concrete. They showed that during heating and cooling operations, the thermal axial strains observed were within acceptable limit, that the total strains measured due to thermo-mechanical loading were well within the range acceptable in the industry so the trends and magnitude of induced axial strains and stresses, in the piles, are unlikely to cause any structural failure. Moreover the max. upward displacement was small and not caused engineering problems to superstructure. It was also noticed that cooling and heating allowed similar behavior on the GEP with no hysteresis or permanent thermo plastic locked-in deformations, that the heat exchange through the horiz. portion of loop contributes to decrease the efficiency, rates of 210-260 kPa/°C were determined, and that the deeper portions of the foundations cooled more rapidly, and temperature has changed less underneath building slab than outside. Murphy & McCartney (2015) and McCartney & Murphy (2017), presented results from 2 full scale GEPs beneath an 8-story building in Denver. Murphy & McCartney (2015) focused on the GEP response over 658 days, with estimated heat extraction loads of 91-95 W/m. Smallest magnitudes of thermal axial strains were observed at top and bottom of the foundations due to boundary restraints, with max. thermo-mechanical axial stress of around 10 MPa. They noticed that during heating the greatest increase of thermomechanical axial stress was at the pile toe, that the mobilized shear stress followed a nonlinear profile, that the displacement and load were within reasonable safer limits although the GEP in complex soil layers may not always behave thermo-elastically. The measured displacement had limits of a max. 2mm upwards in heating and 1mm downwards in cooling. McCartney & Murphy (2017) focused on the interpretation of the axial strains for a pair of full scale GEPs beneath the same 8-story building, measured over the course of a 5-year geothermal heat pump operation. The axial strains at diff. depths showed diverging trends, i.e., predominantly contractive strains being superimposed atop the thermo-elastic expansion and contraction of the piles, especially near the toe, possibly due to the effects of dragdown or uplift of the surrounding soil. These effects were caused either by thermal influence on the subsurface soil or long-term mechanical compression of this same layer under applied building load. They concluded that the analyzed piles remained thermo-elastic during heating and cooling besides of the dragdown effect, but they were loaded very close to their max. design compressive stresses.

Szymkiewicz et al. (2015) from the Univ Paris-Est summarized another large-scale experimental study as part as a national project funded to assess the impact of temperature and heating-cooling cycles on the bearing capacity of CFA piles, and the understanding of the mechanical behavior at the interface pile-soil. 3 GEPs were instrumented and thermally and mechanically loaded at the north of France, close to Dunkerque. Distinct thermal and mechanical load periods were applied with 14 days thermal cycles of 7 days heating and 7 days cooling. They observed that the influence of thermal cycles was almost negligible in terms of displacement, but thermal cycles had an impact on the bearing capacity of the piles. This impact was basically in terms of an increase of shaft friction, due to rearrangement, i.e. densification, of the soil particles at the soil-pile interface.

You et al. (2016) have carried out full scale field tests to study the thermo-mechanical behavior of “Cement Fly-ash Gravel piles”, a popular ground improvement technology in China. 3 distinct research institutions in China (Univ. Science and Tech. Beijing, the Tsinghua Univ. and the Institute of Found. Engineering) were involved to determine the structural response of energy CFG piles in Shunyi, Beijing. The diameter of the piles used was 420 mm, the length was 18 m and 24 piles were arranged in a square, with the pile interval space being 2m. The authors found that thermal axial stress distribution along the pile is non-uniform due to partial restraint at the pile head (gravel cushion) and toe (sandy-silt), and that cooling cycle induces pronounced pile settlement and a decrease in its bearing capacity. Compared with the results of each phase, they found that the cooling stage has a larger effect on pile head settlement than does the heating stage. There is an accumulated settlement of the working pile subjected to one heating and cooling cycle, possibly because of unexpected cracking and not fully recovered shaft temperature. They concluded that cement fly gravel energy piles should be carefully designed for cooling purposes since, in this case, there was also a reduction in the bearing capacity (which kept almost the same for the heating case).

Santiago et al. (2016) from the CEDEX and the Univ. Politécnica de Valencia, described a new experiment at the Rodio-Kronsa factory in Spain with a fully monitored precast driven geothermal pile. The full-scale pile suffered 2 static load tests and subsequently a thermal test at a constant maintained load of 1000 kN, simulating its use within a geothermal installation working on summer mode. They noticed that the pile strains were of the thermo-elastic nature and they were strongly influenced by the type of surrounding soil. That means, the shape of the strain profiles depended not only on the $\Delta T$ changes but also on the resistance of the ground around the pile, that imposed distinct degrees of restrain at the interface soil-pile. They concluded however that structural problems in the pile are not likely to occur in a normal geothermal operation.

Allani et al. (2017) from the Belgian Building Inst. and the Catholic Uni of Leuven carried out an extensive full-scale test campaign on several types of GEPs in Ostend, Belgium. They were instrumented over their entire length and the thermomechanical behavior was evaluated during thermal loads. 5 GEPs of the screw type with a single U-shaped pipe exchanger loop were tested. The results have shown that shaft friction partially prevented the pile to dilate during the heating phase, leading to an increase in axial compressive strains, hence thermal stresses. Compared to mechanical loads, the thermal axial load increase varied from +50% to +250%, but the displacements at the pile head were quite small, less than 3 mm with deformations around 60% of free movement value.

Bourne-Webb and Bodas Freitas (2019) from the Inst. Técnico Superior in Portugal have reviewed many published full and small-scale physical tests on GEPs, gathering studies that involved monotonic and cyclic thermal loads on isolated piles and pile groups. Focus on the reported behavior in terms of pile-soil interactions were given, so to understand general trends of pile head displacements, internal stress changes and developed thermally induced strains. They observed that there is a balancing between movement and the alteration of internal stresses within the pile, supported by large scale tests and numerical models, that cooling and heating of groups are likely to lead to larger movements and lower stress changes compared to a single pile depending on constraints and no. of piles in the group, that after occupation of structure and thermal activation some time will take to reach a new dynamic thermal equilibrium, just altering pile-soil interactions and finally that, if external loadings exceed the available shaft resistance, then cyclic ratcheting will develop, however the response of the pile appears to stabilize with time.

*Thermal Performance (Table of Annex I.1)*

Thomas & Rees (1999) presented a detailed description of a comprehensive in situ experiment designed to monitor the thermal performance of real ground floor slabs installed at the time of construction of a modern building that has been monitored for 1.5 years. The building is part of the Cardiff School of Engineering, in Cardiff, UK. They monitored the results of transient variations of heat flux, air and ground temperature, and soil´s moisture content. They noticed that the ground temperature and moisture content could significantly change at the wall of the structure, but they were relatively constant underneath the building. The magnitude of heat losses increased considerably near an external wall relative to the heat flow through the central region of the floor slab, clearly showing a thermal edge effect. The external ground temperatures were shown to vary significantly to a depth of some 3 m below the ground surface, but underneath the building there was much less variation. The moisture content was generally found to be negligible in the 2 m of soil immediately underlying the ground floor slab.

Roth et al. (2004) described the results of a cooperative work between Chile and Argentina, specifically the Tech. Univ Federico Santa Maria (UFSM) and the Univ. Nacional del Nordeste that led to the 1st. thermal response test performed in Latin America. The TRT was carried out at the solar energy lab of UFSM in Valparaíso. A 9 days test was carried out in a borehole 16.9 m and 15cm dia. with U pipe tubbing. It was grouted with 12% bentonite mixture and led to the conductivity and thermal diffusivity of the surrounding soil and borehole thermal resistance. Values of 1.8 W/mK and 0.3 mK/W were respectively found for the conductivity and borehole resistance.

Brandl (2006) from the Vienna University of Technology has presented a broad overview on existing theory, design procedures, site performance and characteristics of

GEP systems in Europe, emphasizing it advantageous use to supply a long-term sustainable energy for common structures. Execution guidelines and observed experience was related through the monitoring of large-scale structures in Europe, among them a pilot research project in Bad Schallerbach, Austria. This author has cited key recommendations for practical use of GEPs and listed the observed performance of such systems. For instance, he noticed that a temperature difference of about 2°C between inflow and return-flow temperature of the absorber fluid is enough for economical operation of the energy system. Operational fluctuation of the groundwater temperature should be kept as low as possible ($\Delta T < 5°C$). Moreover, the spacing of the piles has a strong influence on the efficiency of the energy system. Temperature changes of the soil directly bordering on thermo-active foundations have negligible influence on bearing-deformation behavior if the energy system is properly operated. Granular soil is affected less than clay or silt, but the temperature sensibility of soil increases with its organic contents. Intensive heat input into the ground for cooling a building is less critical for the foundation but possibly so for the quality of groundwater and microorganisms.

Schnurer et al (2006) from the Technical University of Braunschweig described a German-funded research & development project that assessed 10 office buildings constructed between 2002 and 2004 in terms of the performance of their foundation absorbers, energy piles and borehole heat exchangers. The analysis was made considering the geological conditions, system configurations, energy performance and operation costs. 5 buildings were fully monitored to check on operation, performance and ground temperatures. In particular, the energyForum office building in the center of Berlim is described in detail. They concluded that it is possible to fit underground thermal energy storage systems into today´s building energy concepts. They are ideal to be combined with low temperature heating or high temperature cooling systems like concrete core activation or heating/cooling ceilings. Nevertheless, for high temperature cooling systems with fluid temperatures between 17 to 22 °C it is required modern façade-systems which keep the external thermal load out of the office.

Hamada et al. (2007) from the Hokkaido University described the field performance of an air conditioning with an energy pile in an actual foundation of a building in Sapporo, Japan. 3 large-scale tests were carried out to specify the design of a heat exchanger inside the pile, comprised by a U-tube pipe system. The seasonal amount of heat supplied accounted for 90% of the predicted continuous operation mode, allowing a primary energy reduction rate compared with a typical air conditioning system of around 23%, with an avg. coeffficient of performance for space heating of 3.9.

Gao et al. (2008 a,b) from Tongji University presented a case study in Shanghai of ground heat exchangers for a ground coupled heat pump system, in which several types of vertical pile foundation exchangers have been intercompared to determine the most efficient one. The complex was designed to have 30% of the whole thermal load provided by this pump system. In situ performance tests of heat transfer were carried out to define the most efficient type of GEP and to design the system. Avg. heat resistances and injection rates of different types of GEPs have been calculated from the site tests. The heat transfer performance was also evaluated by numerical methods with the finite volume technique and 3D soil zone. These methods were further used to investigate 5-years forecast of ground temperature changes, and to assess the potential of the geothermal energy in terms of simulations of two imbalance ratios between cooling and heating loads. They found that the W-shaped pipe exchanger was the most efficient for this case, given its better performance. They also found that the potential of geothermal energy decreases during cooling seasons and decreases with increase of the imbalanced loads, being noticeable a numerical decrease of design thermal loads of 20 to 30% during 5 years of continuous operation.

Kipry et al. (2009) from the same Tech. Univ. of Braunschweig from Schnurer et al. (2006) extended aforementioned results in relation to the project funded by the German Fed. Ministry of Economy and Technology regarding the 10 office buildings with monitored geothermal systems as BHE and GEPs. Their assessment of the data has indicated that the systems worked worse than expected, given inaccuracies in design, lack of experience and operation of such systems. They concluded that an initial phase to optimize the interactions between the underground thermal energy storage medium and the building is necessary. Due to slowness and the slight temp. diff. between ground heat storage and the geothermal apparatus the overall system reacts in a very sensitive way to errors and failures. Care in design with a well-regulated seasonal energy-balance is mandatory for a lasting performance, with post-construction control strategies and building monitoring of the inlet/outlet GEP fluid temperatures and monthly heat extraction.

Javed & Fahlén (2011) from the Chalmers University in Sweden reported the development of a new ground source heat pump system developed in laboratory and its thermal response test setup. 9 deep laboratory boreholes with 80 m in length had their TRT results compared to quantify their magnitude and variations of the estimated parameters. They have been individually tested over a period of 12 weeks with durations that varied from 48 to 260 hs. Boreholes with a rectangular 4 x 4 m grid configuration filled with water have been tested, with direct and indirect methods to evaluate the ground thermal conductivities. They found that ground conductivities and borehole resistances from TRTs can have uncertainties in the order of 7 to 20% respectively and that the effects of temperature variations in TRT results are negligible.

Jalaluddin et al. (2011) presented an experimental study of several types of ground heat exchangers (GHEs) installed in a steel pile foundation, including U-tube, double tube and multi-tube GHEs. The performance of the GHEs was investigated under actual operation and cooling modes with flow rates of 2, 4 and 8 l/min. The temperatures of the inlet and outlet circulation water was measured to calculate the heat exchange rate. This research was conducted at Saga University, Saga City, Japan, where the topsoil is soft clay with 10 or 20 m in thickness. They noticed that the double-tube had the highest heat exchanged, followed by the multi-tube and the U-tube GHE. The heat exchange rate increases significantly for flow rate increases from 2 to 4 l/min, with a slight tendency of stabilization after this latter value. They also noticed that the exchange rates were high in the beginning and decreased afterwards due to the increase of the temperature of the surrounding soil around the GHEs. They concluded that for a high flow rate, the multi-tube is an attractive choice.

Researchers from the Korea Adv. Inst. for Science and Technology (Park et al. 2013 and Yoon et al. 2014) carried out experimental and numerical simulations for the evaluation of the thermal response of a precast high strength concrete GEP and borehole heat exchangers BHEs. In Park et al. (2013) TRT´s were carried out in a partially weathered and saturated granite soil deposit with two pipe configurations (W and 3-U). In Yoon et al. (2014) a large-scale experimental study on the evaluation of a thermal response test (TRT) using a precast high-strength concrete GEP (dia. 40 cm, L of 13.3 m) and a closed vertical system ground heat exchanger (GHE, dia. 15 cm, L of 50 m) both with W-type pipes. They were immersed on a predominantly weathered granite and rock material. Field thermal response tests (TRTs) were conducted on a PHC energy pile and on a general vertical GHE installed in a multiple layered soil ground in two Korean cities (respectively Suwon and Incheon). The equivalent ground thermal conductivity was determined by using the results from TRTs and by a simple analytical solution suggested in this research. They observed that the ground thermal conductivity values from the TRTs were 2.32 W/m·K and 2.15 W/m·K for the energy pile in Suwon and the vertical GHE in Incheon, respectively. The equivalent thermal conductivity was also determined to be 2.07 W/m·K and 2.24 W/m·K for the energy pile in Suwon and the vertical GHE in Incheon, respectively. The ground thermal conductivity values obtained from the TRTs were found to be in good agreement with the actual equivalent analytical value with variations of approximately 5 to 10%. Therefore, it was concluded that that the ground thermal conductivity could be obtained from a TRT, as well as via ground thermal properties using a simple equation of the equivalent ground thermal conductivity. In other words, once the ground thermal properties are known, the equivalent ground thermal conductivity can be estimated using the simple equation proposed in the study of these authors.

Complementing previous work (on single GEPs) at the Swiss Federal Institute of Technology (EPFL), Mimouni & Laloui (2015) expanded the study to GEP groups regarding their response in terms of stresses, strains and displacements. Full-scale in situ experiments were carried out to quantify the magnitude of interactions that could develop within a thermoactive foundation based on a group of four test piles below a water retention tank. 3 field campaigns were carried out, and each test involved heating one or several piles at constant heat rate for 6 days, followed by a cooling period to ground original values. The four piles were heated to quantify the group effects, and the thermo-hydraulic response of the soil was monitored with piezometers and thermistors. One TRT was carried out in one of the piles as well. They noticed that heat from piles has not induced significant pore pressure variations, but evidenced group effects when comparing the thermomechanical responses of the single pile tests. Max. stresses never exceeded 15% of the avg. concrete strength and the TRT has demonstrated that U loop in series were more efficient than in parallel. Soil-structure interaction effects were visible as base compression increased in heated pile but decreased in unheated ones. The free head test on one of the piles without any structure on top provided information on the ground constraints on the piles, and the tank construction impacted the pile response down to the stiff soil layers. They concluded that the main impact of the group test was that diff. displacements were reduced.

The Australian research group from the Monash University complemented previous work on the large-scale field test on a single energy pile founded in predominantly dense sandy material. Faizal et al. 2016 and Singh et al. 2015 a,b focused on the influence of intermittent and continuous operation modes on energy extracted, ground and pile temperatures and axial thermal strains and stresses for daily cooling operations. They operated the system for around 480 hs (20 days) with continuous heat exchange, or 8 hs and 16 hs intermittent operations with resting periods. The results indicate that heat propagation in soils occurs predominantly in a radial direction, and the soil needed about 4 times the heating test time to recover to its initial temperature. The heat exchange rate of the GEP and the surrounding soil was directly related to the difference in inlet and outlet heat carrier fluid temperatures and its flowrate. The increase in soil temperature induced by thermal load did not significant influenced on the heat exchange rate of the GEP. The energy extracted during 8 and 16 h was around 41% and 15% higher than the 24 h heating mode, so the average energy extracted or injected per meter pile length is higher in the intermittent mode than in continuous mode. The finally noticed that thermal stresses and strains for the 8h and 16h operation modes were cyclic and returned to similar values at the end of cooling and recovery periods. They concluded that further studies are required on field scale piles to determine how the pile displacement and soil properties are affected in intermittent and continuous operations, and how optimal durations of rest period could be adapted for different pile geometries, soil profile types and geothermal superficial heat pump systems and configurations.

Complementing the initial work on the full-scale field tests of “Cement Fly-ash Gravel piles” (CFG) in Shunyi, Beijing, You et al. (2016) have also evaluated the thermal performance of the 42cm diameter CFG piles in situ. They noticed that the thermal pile test indicated that circulating water at a velocity of 0.5 m/s presents the best cost-effective solution, in terms of heat exchange rate, and such rate is positively proportional to the inlet water temperature observed during thermal performance test. Besides, the avg. heat exchange rate per meter in intermittent operation is 20% higher compared to continuous operation, and the total heat energy exchanged dropped by 14% from intermittent to continuous mode. They also observed that the heat injection and extraction rate for the group of piles decreased by 5% and 20% compared to single piles, during thermal pile tests. They finally concluded that the radial temperature influence for a single pile spreads more than 4 m, based on temperature contour distributions, so spacing between piles should preferably be higher than 8 m.

Zarrella et al. (2017) from the university of Padova investigated a TRT on a 20 m long GEP equipped with double U-pipe circuit in Venice, Italy. The test was interpreted using both infinite line source model and inverse numerical analysis via the CaRM tool that considered both pile geometry and axial heat transfer. Differences in thermal conductivity from both approaches (2.8 x 1.5 W/mK) came from distinct hypotheses of such methods, as the infinite line source theory considered only transfer along the radial direction whereas the numerical tool considered both radial and axial directions. They observed that the effect of the axial heat conduction was not negligible because there is always a gradient of temperature between top and lower ends of the heat exchanger. The results emphasized the importance to take on consideration the effects of the axial heat transfer on the design of shallow heat exchangers, and the fact that standard TRTs can be carried out in practice, but interpretation based on the infinite line source model may lead to errors in thermal conductivity values.

Bourne-Webb et al. (2019) from the Instituto Superior Técnico in Lisbon extended their previous work on the examination of the results from small-scale and large-scale tests on isolated geothermal energy pile systems, giving an extensive overall review on the pile-soil interactions in terms of both experimental and numerical based research. Given the current published work they concluded on particular aspects of the performance of thermally active systems. For instance, they found that if the foundations of a building are thermally activated, the thermomechanical response seen in the foundations will be due to the superposition of the heat flow from the structure and the thermal loading within the foundation elements. Therefore, the former can result in thermal effects similar in magnitude to those generated by thermal operation of the energy foundation alone and are not currently considered in design. Regarding scale effects, they noticed that small-scale tests often have advantages over full-scale tests in terms of cost, time, and control of conditions. However, in the tests reported to-date the mobilized shaft restraint appeared to be rather low. This probably is a reflect that most of the tests were undertaken in sandy soils and future studies should focus on testing in stiffer materials to ensure that a full range of pile-soil restraint is further examined. Finally, the review on numerical studies was able to broadly reproduce the types of response observed in field tests. Hence, where conditions in field studies have been approximated, very similar behaviors in terms of internal stress changes and pile movement were predicted. However, many numerical studies have modelled conditions that resulted in rather low pile restraint and, as a result, predicted limited changes in internal pile stress with larger pile movements, relative to those seen in large-scale testing. These authors consider that such particularities should be taken on consideration for further studies on the thematic of isolated GEP systems.

## I.2 Laboratory studies on the thermomechanical behavior and thermal performance

*Thermomechanical Behavior (Table of Annex I.2)*

Laboratorial centrifuge small-scale results from physical modelling experiments have been extensively carried out by researchers from the University of Colorado, in Denver. McCartney & Rosenberg (2011), Stewart & McCartney (2012), Stewart & McCartney (2014) and Goode & McCartney (2015) carried out an large number of centrifuge tests to characterize the transient thermomechanical response of energy foundations during heating-cooling cycles, so to provide data for calibration and validation of soil-structure interaction models. Stewart & McCartney (2014) studied the response of a scale model GEP installed in an unsaturated silt layer with end bearing boundary restraint at 24g acceleration conditions. The model foundation had 3 heat exchanger pipe loops and was heated and cooled under constant maintained mechanical load. They measured the foundation head displacements, the soil surface displacement, variations in temperature and volumetric water soil content and applied successive heating-cooling cycles on the isolated energy pile. They observed downward head movements during mechanical load and upward movements during heating thermal load. Also, that the successive thermal cycles decreased the upward thermal head displacements, with little change in the thermal axial stresses. A thermally induced water flow in the unsaturated soil medium was measured, with the greatest thermal axial stresses near the base, slightly above the “null point”, a position in the pile with no expansion or contraction. They concluded that nonlinear changes in stress with depth resulted from mobilized side shear stresses during thermal loads. Although the study did not indicate that the thermo-hydro-mechanical effects in the soil affected the GEP loading, they may be important to consider in real cases. Goode & McCartney (2015) extended previous results with the same centrifuge apparatus at 24g acceleration and small-scale isolated GEP to consider experiments on dry sand and unsaturated silt at distinct end restraints, i.e., semi floating and end-bearing toe boundary conditions. 10 experiments were carried out, being 7 in semi floating and 3 end bearing. After reaching a steady temperature at each case study, each GEP was mechanically loaded and unloaded, so to access the role of the heating thermal load on the load-settlement pile curve. The distribution in thermal axial stress and displacements have also been observed for both soil cases, unsaturated silt and dry sand. Results show that semi floating foundations in compacted silt had a clear increase in ultimate bearing capacity, whereas in dry sand negligible changes were noticed during thermal loads. This was probably due to a combination of radial stress increase and thermally induced water flows in the unsaturated soil medium. The mobilized strains during heating were greater than those due to mechanical loads, and the thermal stresses were greater at the center of the foundations. The differences in the load-settlement behavior of the semi floating GEP in either sand or silt mediums could be due to comparatively low radial resistance provided by the sand compared to the compacted silt. Besides, it was possible that more drying of the soil around the foundation in the case of the silt increased the effective stresses at interface to a higher extension. End bearing restraint conditions led to higher magnitudes of thermal axial stresses than for semi floating cases. Moreover, such stresses were higher in the silt layer than in the sand one possible given greater soil-structure interactions. They finally noticed an increase of 100% in axial stress in the end bearing foundation in dry sand when the head was restrained, compared to when it could freely expand.

Researchers from the Paris-Est University at Champs-sur-Marne (Kalantidou et al. 2012, Yavari et al. 2014 and Nguyen et al. 2017) investigated the behavior of isolated geothermal energy piles under thermal and mechanical loads at 1g conditions. They inserted a 20 x 600 mm (dia. x length) small-scale closed-end aluminum pipe into a cylinder container with a diameter of 570 mm and a height of 850 mm, filled with dry Fontainebleau sand. The sand was compacted at a density of 15.1 kN/m by a wood tamper, in several 100 mm thick layers around the pile once it was fixed in place, simulating the field conditions of a bored type foundation. For the control of the pile temperature, a metallic U-tube of 2-mm internal diameter was inserted inside the pile over its total length. This tube was connected to a temperature-controlled bath and a peristaltic pump, allowing the circulation of heated/cooled water inside the U-tube that led the pile to the target temperature level at each specific thermal load. Kalantidou et al. (2012) performed 4 tests corresponding to four values of axial maintained mechanical load on the pile, with 2 subsequent thermal cycles undertaken in each test, i.e., the pile was heated from 25 to 50°C and subsequently cooled to 25°C. They noticed that heating induced heave and cooling induced settlement of the pile head. An irreversible settlement was observed after the thermal cycles, with a hysteresis phenomenon in the temperature versus settlement paths. At lower loads the expansion of the pile or contraction is closer to the aluminum thermal expansion, but at higher loads additional settlement at the pile toe happens together with the development of irreversible strains. They concluded that the pile response appeared to be thermo-elastic under thermal cycles when mechanical load was less than 40% of the ultimate bearing capacity (hence SF > 2.5), so conventional safety factors seem to ensure a stable pile response under thermal load. However, at mechanical loads above this limit (SF < 2.5) the pile response presented irreversible settlements. Yavari et al. (2014) complemented the tests from these researchers, as the previous physical model was completed by adding up strain gauges to the pile surface for the measurement of axial load at various levels along the pile. Total pressures and temperature were also monitored at various locations in the soil surrounding the pile. To perform a test, a constant axial load was first applied to the pile head, and the pile temperature was then varied from 5 to 30°C with 2 temperature cycles applied afterwards. Various tests were performed by varying the axial head load from 0 to 70 %, so to check on the behavior of an isolated GEP under coupled thermo-mechanical conditions. They observed that the irreversible settlement of the pile at high axial loads was associated with a modification of the mobilized skin friction along the pile-soil interface during thermal cycles. The curves of mobilized friction versus displacement were compatible to those from axial load, indicating a hysteresis phenomenon. Thermo-elasticity was observed with the variation of axial forces induced by cooling compensated by heating stages, and the soil pressures below the toe were significantly influenced by the mechanical and thermal loads. They finally noticed that the mobilized interface friction gradually increased due to the mechanical load and changed in a cyclic manner during thermal load variations. Nguyen et al. (2017) complemented previous studies by investigating the long-term response of an isolated small-scale energy pile under similar 1g testing conditions. They carried out 30 thermal cycles while keeping the pile head load constant at 0, 20, 40 and 60% of the pile ultimate bearing capacity. They initially noticed that the irreversible settlement that accumulated after each thermal cycle decreased as the no. of cycles increased, and that heating did not induce significant settlement, whereas cooling did. Besides, the axial force at the end of a heating phase was higher than that at the end of the subsequent cooling phase. The higher was the applied mechanical load, the more important was the observed pile settlements, and the higher was the no. of cycles to stabilize them. They observed that the increment of an irreversible settlement per cycle was higher during the first cycles, but it became negligible after 20 cycles, at least for cases of low applied loads (< 40% max.). For high maintained mechanical loads (> 60% max.) the settlement continued to increase after 20 thermal cycles. The axial force in the pile also increased with cycles, and the authors speculated that this could be explained by the degradation of the interface shear stress.

Researchers from the Hong Kong Univ. of Science and Tech. in Hong Kong also studied the thermomechanical response of GEPs via small-scale centrifuge tests. Ng et al. (2014) and Ng et al. (2015) described 4 tests on isolated energy piles under 40g. The piles were embedded in clay under distinct overconsolidation ratios and were loaded to failure under ambient temperature (2 tests) or loaded to a working load followed by 5 thermal cycles with varying temperatures (2 tests). Each pile was made from aluminum tubing with a conical pile toe to close their base. They had a diameter (D) of 22 mm and an embedded depth of 420 mm. A new heating and cooling system developed to control the cyclic temperature was also described by these authors. They noticed that the pile embedded in lightly over-consolidated clay undergoes a more pronounced ratcheting settlement pattern with a reduction in severity due to thermal cycles, compared to the pile embedded in heavily over-consolidated clay. A cumulative settlement of 3.8%D was observed in the pile installed in lightly over-consolidated clay, compared to the 2.1%D associated with piles in heavily over-consolidated clays, after the thermal cycles. However, in both OCR cases, the piles continued to settle with thermal cycles, displaying a non-linear hysteresis loop with continuing plastic deformation at a reduced rate. According to the authors, the larger settlement in lightly over-consolidated clay could be due to an accelerated creep rate at the pile-clay interface caused by the thermal cycles. In the experiments it was noticed that the neutral point located below mid-depth of the piles moved downwards due to increase in temperature. Under pure heating load, there was also an additional mobilized base resistance due to the constrained vertical expansion. They also observed that by subjecting energy piles EP1 and EP2 to 37 °C and 52 °C respectively, there was a 13% and 30% increase in their bearing capacity compared to the reference pile (i.e. with no thermal load applied). This was achieved through the increase in mobilized shaft resistance for EP1. In the case of EP2, heated to 52 °C, the applied vertical load was further resisted by the larger resistance mobilized at the pile toe. They concluded that ratcheting effects in GEPs can have serviceability implications at long performance.

Minto et al. (2016) from the University of Dundee, in Dundee, developed a new thermally enhanced plaster-based model mixture which could “realistically” reproduce both thermal and mechanical properties of a concrete pile at prototype small-scale. This material was used to create a 1:20 scaled reinforced concrete thermo active square 25 x 25 mm pile for future use in centrifuge tests. They investigated the effects of temperature on the pile´s thermomechanical behavior, including the coeff. of thermal expansion, the moment capacity and the flexural stiffness. They found that the mixture of plaster, silica sand, water and copper powder at 6% volume was ideal to obtain an optimum behavior under both thermal and mechanical load conditions. At this mixture the GEP has a close to real coeff. of thermal expansion and the effects of temperature on the mechanical properties are negligible.

Kramer & Basu (2014) and Ahmadipur & Basu (2017) from the Pennsylvania State University in University Park, investigated the thermo-mechanical behavior of a 1g small-scale model geothermal pile installed in dry pluviated sand. They carried out a series of instrumented thermomechanical load tests under laboratory-controlled conditions. A 10 cm diameter precast concrete pile with an embedment depth of 122 cm was used in the experiments. One U-shaped PVC circulation tube with an inner diameter of 12.4 mm was embedded in the pile to allow circulation of the heat carrier fluid (1:1 mixture of ethylene glycol and distilled water) during thermal loading. The pile was also instrumented with embedded strain gauges and thermocouples. In order to avoid boundary effects a large ratio (1:18) of pile diameter to square steel calibration tank width was chosen. A soil depth of 6 base diameters was kept under the pile base so that both thermal and mechanical lower boundary effects could be avoided. Mechanical load tests to geotechnical failure were performed before and after imposing different thermal loadings (heating and cooling) on the pile. The model pile was connected to a constant temperature water bath which maintained the inlet fluid temperature at 40°C. The initial average temperature across the soil tank was 19°C, and thus a temperature gradient of 21°C was applied during thermal loading of the pile. Results from these small-scale experiments showed an increase in both shaft and base resistances with increase in the average pile temperature. For instance, a 15% increase in the bearing capacity load was observed when the average pile temperature was increased by 31.6°C. They also observed that the thermal influence zone around the pile was extended up to a radial distance of 6 diameters after 7 days of heat transfer, and 2 diameters below the pile base. The authors concluded that axial load-displacement behavior of geothermal piles is likely to be affected by induced temperature cycles.

Researchers from distinct universities in China (Chongqing University, Hohai University and Hong Kong Univ. of Science and Tech.) carried out a series of joint small-scale experiments on thermally active piles embedded in sand. They used a model tank with dimensions 175 x 200 x 300 cm (length x width x height) with several concrete energy piles of 160 cm embedded length and 104 mm in diameter. The adopted scale was 1:20 to the prototype piles, with adjacent piles spaced at 9.6 diameters apart in length and 6.4 diameters in the width. The base of the piles was 35 cm distant from the bottom of the tank, or 3.3 diameters. Strain gauges and thermocouples were adopted to instrument the piles, and dry hopper pluviated Nanjing sand at medium dense 63% density was used as soil medium. The energy piles were fitted with heat transfer pipes forming U-shaped loops with inner diameter of 9 mm. Wang et al. 2016 related two GEP model piles tested under such conditions, being the first mechanically loaded to failure and the second mechanically loaded and thermally loaded in cycles afterwards. The results showed that heating and cooling induced thermal stresses in the pile and the horizontal soil pressures were also changed. They observed that the pile and soil temperature within 1 diameter of the pile axis changed considerably, that the pile tip resistance and horizontal soil pressures increased during heating and decreased on cooling, that the side shear stresses had different directions at upper and lower parts of the pile, and that residual strain and stresses were introduced after heating and cooling cycles. Wang et al. (2017) used the same testing conditions as presented before, but tested 4 GEPs with different heat exchanger configurations, including one spiral type, one W-shaped and tow U-shaped. The model tests were conducted to assess the effects of cyclic heating and cooling on the thermomechanical behavior of the semi floating piles. They noticed that the thermal strains after heating and cooling nearly recovered to initial levels, but settlements of each pile accumulated at the end of each cycle. The W-shaped heat exchanger pile had the higher settlements and the largest temperature variations in pile and the soil, followed by the spiral shape GEP. The settlement in each subsequent cycle decreased in relation to the first cycle, and K0 increased during heating and decreased during cooling. Under the same heat input, the horizontal earth pressure of the W-shaped heat exchanger pile increased by the largest amount, which was 1·18 times and 1·24 times more, respectively, than the spiral type heat exchanger pile and the U-shaped heat exchanger pile. Thermal strains were also observed and were higher at upper part of the pile due to lower restraint compared to the pile base. The strain of the W-shaped heat exchanger pile showed the largest thermal strain under the same heat input along the depth and the spiral type heat exchanger pile followed, indicating different thermomechanical behavior. The pile temperatures recovered after the thermal cycles and the soil temperatures within 1 to 2 diameters of the pile axis continued to rise at the end of each cycle, causing an effect of heat storage in the surrounding soil medium. Peng et al. (2018) extended these small-scale studies by incorporating nonthermal piles on the thermomechanical behavior of a semi floating energy pile group. They used the same apparatuses previously described, but tested 11 precast concrete model piles with diameter of 90 mm and length of 150 cm. Each model pile comprised o U-shaped PVC circulation tube with inner diameter of 8 mm. 9 piles were placed in a square 3 x 3 configuration spaced 3 diameters center to center apart. The 2 remaining piles were used to test the single behavior and placed separately at a distance of 89 cm, spaced 6 diameters apart. Same pluviation technique was adopted, reaching a density of 70% for the Nanjing sand. The distance of from the edge of the model tank to the pile group was 5.5 diameters. 5 test setups were specified, being 2 on the isolated piles, that were mechanically and thermomechanical loaded, and 3 on the pile group, that were either mechanically loaded, or thermomechanical loaded in all piles or in six of the nine piles. The authors noticed that the behavior of a group is distinct of a single pile in terms of axial stress and can be explained by higher lateral confining pressure on a single pile compared to the same pile within a group given interaction effects. These differential confining pressures also lead to distinct end restraints. They also observed that during heating no soil-pile slippage occurred, but during cooling of the pile soil-slip took place, due to the cooling-induced change in the contraction volume of the soil that reduced the lateral confining pressures on the piles. The magnitude of this effect was larger for the pile group than for the single pile. For the case where not all the piles in the group were thermally active, nonuniform displacement could occur. However, under the heating condition, this behavior is a function of the pull-out resistance of the nonthermal pile, whereas under the cooling condition, it is controlled by the reduction in the skin friction of the thermal pile due to the cooling-induced volume contraction behavior. They concluded that the thermally induced axial pile stress change is a function of the restrained boundary condition of the pile, which is determined mainly by the lateral conf. pressure, therefore as pile interaction reduces the restrained condition of the pile group, the thermally induced axial stress is larger for the isolated pile in relation to the same pile in a group.

Yazdani et al. (2019) from Universities of Wisconsin-Milwaukee and Virginia Polytechnic Institute carried out 1-g small-scale tests on an isolated energy pile with 19 mm in diameter and embedded length of 230 mm. The tests were performed inside a cylindrical container chamber with 170 mm inner diameter that housed the pile subsection and the surrounding saturated normally consolidated kaolin clay. The model energy pile was constructed using a hollow steel tube (shaft) coated with a thin layer of concrete. The ratio of the container to pile diameter (around 9) was chosen as to minimize the scale effects on the shaft resistance. The pile and the surrounding clay were subjected to non-cyclic and cyclic temperature variations by circulating temperature-controlled fluid inside the energy pile. The pile was constrained at the bottom end and free at the top so that it could expand and contract freely during thermal loading. Five identical tests were performed under different thermal loading conditions, with temperature variations between 24 and 34 °C. Only cooling mode was tested, i.e., using the soil as a heat sink. They observed that the shaft resistance was considerably influenced by the cyclic thermal loading, however increasing the no. of thermal cycles did not made appreciable differences in shaft resistance. The thermal cycles also generated a cyclic pore pressure variation. The authors concluded that the heat process can improve the axial capacity of the pile and the initial stiffness of the pile load-settlement response. Besides, cyclic and non-cyclic heating can cause differences in shaft resistance, but the values are almost independent of the no. of heating cycles. The interface shaft resistance may be explained by the increase in the friction angle and eff. lateral stress due to thermally induced negative pore water pressures in the clay medium.

*Thermal Performance (Table of Annex I.2)*

Kramer et al. (2015) extended previous studies in the same 1g small-scale GEP model in dry pluviated sand from the Pennsylvania State University. Same conditions as before were adopted, but present series of tests assessed key operational parameters such as the fluid circulation rate within U-shaped pipe and its initial temperature on the thermal behavior. The temperature data collected was used to characterize the time-dependent evolution of the temperature in the soil around the pile and to estimate the power output on energy extraction and rejection of the GEP. They noticed that the thermal influence zone extended to around 5 diameters around the model pile, besides it can be used with equal efficiency for both heat rejection or extraction. They concluded that the thermal efficiency increased as the circulation velocity increased. Moreover, the efficiency of the model pile could be increased by 30% during thermal cycling, due to the presence of high thermal gradients at onset of the thermal loading reversal.

Black & Tatari (2015) developed a new technique to study the transient thermal interaction between geothermal piles and the surrounding medium. They adopted transparent soil and the relationship between pixel intensity (in photographic images of the soil) and temperature to define the heat flow along a 1g small-scale sample of soil around a thermally active isolated pile. They tested a GEP made of aluminium with 18 mm diameter by 150 mm length founded on a cubical volume of transparent soil of 190 x 150 x 40 mm of dimensions (length x height x thickness) that was immersed on a large water bath container. The tests were carried out by taking pictures with a digital camera, a LED illumination and a post-processing image analysis. The tests were also conducted by increasing the temperature of the pile to 50°C, while maintaining the temperature of the water bath at 20°C. The authors demonstrated the presence and development of a heat flow in the soil up to 1.5 diameters radially from the GEP. They concluded that this technique is viable to contribute on the understanding of thermo-dynamic processes in the soil around GEPs, and that the extension of the influence zone reflected similar values reported in literature from large-scale field and numerical investigations.

Researchers from the Texas A&M University in College Station (Akrouch et al. 2015, 2016) explored the behavior of a 1g and 2D planar section of a GEP immersed on a square wood testing box filled with unsaturated sand at distinct degrees. The box had 1.2m x 1.2m x 0.2 m of dimensions (length, width, height) and two diameters were adopted for the circular concrete section of the energy pile (30 and 40 cm). The GEP section was fitted with two heat carrier PVC pipes, one for inlet water and the other for outlet, so to simulate the thermal load. Akrouch et al. (2015) circulated water in the pipes at a constant 37°C temperature, performing the test for 48 hs, solely with the 30 cm diam. GEP section and with the sand at 3 distinct saturation values (fully dry, fully saturated and unsaturated). At each degree of saturation, a distinct thermal conductivity of the soil medium was estimated via theoretical equation model. Although the study was essentially experimental, a coupled thermo-hydro-mechanical FEM program named CODE_BRIGHT was calibrated with laboratory results, and further used to explore the GEP thermal performance in terms of heat exchange rate and efficiency under distinct unsaturated conditions. The authors initially observed that the efficiency depended on the thermal properties of the soil´s saturation, that the heat flux was also highly influenced by the saturation conditions as well as the thermal conductivity of the sand. Akrouch et al. (2016) extended previous tests to consider other soil types (silt and sandy clay) under broader experimental conditions of 6 different saturation degrees. They also proposed a new analytical equation to be quickly used to evaluate the efficiency ratio of energy piles in unsaturated conditions, based on the cylindrical heat source theory multiplied by a analytically calibrated function related to the soil thermal conductivity (dependent on saturation degree), the thermal resistance of the pile and the classical Van Genuchten water retention curve. In this paper, the thermal efficiency ratio between unsaturated and saturated heat flux was also numerically assessed with the CODE_BRIGHT software for a simple GEP example study. The authors found that under unsaturated conditions the temperature at pile-soil interface is higher than in saturated conditions, which caused a decrease in the temperature gradient between the heat carrier fluid and the pile wall, thus resulting in a decrease of the heat exchange rate (hence efficiency) between the GEP and the surrounding medium. They concluded that the proposed analytical solution could be used for a quick estimation of the thermal efficiency factor ratio of GEPs under variable water levels or saturation degrees of the soil. Moreover, in a worst-case scenario the thermal thermodynamic efficiency of the energy pile could drop by 40% under low saturation granular soil conditions.

Yang et al. (2016) from the Yangzhou and the Southeast Universities in China investigated the effects of different factors on the thermal performance of a spiral coil energy pile type, by setting up a 1g small-scale model apparatus. The experimental system consisted of a cubical soil wooden box made of 0.8 m x 0.8 m x 1.2 m (sides and depth) filled with soil and a 20cm diameter single energy pile of distinct materials. A constant temperature water tank and a spiral tube coil type with 6 mm outside dia. were adopted, together with a water pump, temperature sensors and a data logger system. The heat was applied to the circulating water in the constant temperature water tank and released to the soil in the soil box through the spiral coil energy pile. The experimental investigation studied specifically the influence of the inlet water temperature, the intermittent operation mode, the spiral pitch and the pile material on the thermal behavior of isolated spiral coil GEP types. They concluded that by reducing the spiral pitch the total heat release rate of the coil pipe could be increased, although this also resulted in the decrease of heat release rate per unit pipe length. Besides, under intermittent operation modes, the soil temperature rose, and the temperature variation trend could be more effective, this improving the performance of the GEP. Finally, the concluded that the thermal effusivity of the pile material, i.e. its thermal characteristics, had a great influence on the heat release rate and soil temperature restoration time. The higher the thermal effusivity, the better was the heat release rate, but slower was the temperature restoration effect of the soil near pile. Fei & Dai (2016) from the same Yangzhou University but another institute (Geotechnical Engineering) improved the understanding of the effects of thermal cycles on the mechanical behavior of GEPs via another 1g laboratory-scale model test. In this case, a cubical steel box with the dimensions of 1 x 1 x 1.5 m (length x width x height) was used, being filled by pluviation technique with dry Yangzhou sand at 30% density. A single model pile of 90 cm embedded length and 10 cm diameter was made of precast cement mortar, and it was molded with a U-Shaped type polyethylene pipe of 16 mm diameter. The cyclic thermal load was imposed by heating injected water at a desired final T of 31°C, using a temperature-controlled bath system. Initially, in the first test, the GEP was mechanically loaded to failure. In the second test it was mechanical loaded up to design value of 800 N to be further thermally loaded in 3 cycles of 24 hs duration. At each thermal cycle, the pile temperature was first increased by 15°C from the initial 16°C value during 30 min of fluid circulation, allowing a natural recovery to the indoor temperature at the remaining 23.5 hs time till the next cycle. The authors also attempted to numerically simulate the thermomechanical cycling tests with 3D Abaqus FEM software, adopting two distinct constitutive models with "literature" parameters from the same Yangzhou sand, and from both loose and dense Sacramento river sands. They initially noticed that the ultimate pile resistance after thermal cycles did not decrease significantly but the accumulation of free head pile settlement was apparent on a ratcheting mechanism. A sensitive numerical analysis was also carried out, indicating that the compressive axial forces decreased with the no. of cycles for the piles in both cases of loose and dense sand, since the soil has experienced significant plastic strain. As the numerical predictions demonstrated that the soil displaced more than the GEP, downdrag forces were forecasted along the pile-soil interface. Based on both experimental evidence and numerical results, the authors concluded that GEP performance is controlled predominantly by settlement rather than bearing capacity.

## I.3 Numerical studies on the thermomechanical behavior and thermal performance

*Thermomechanical Behavior and Performance (Table of Annex I.3)*

Choi et al. (2011) numerically assessed the effect of the variation of the thermal properties of an unsaturated soil on the efficiency of intermittent operation of ground heat exchanger (GHE) systems. They employed a 3D finite element method with the software ABAQUS to simulate an isolated grouted borehole with diameter 75cm and length 40 m immersed into weathered granite. The heat carrier fluid was passed through a single U Tube element embedded into the GHE. Numerical FEM analyses with a transient heat transfer model was validated by results of an analytical infinite source model, allowing a subsequent series of parametric studies with various ground water table levels. The comparison between numerical and model results was done for 100 days of continuous cooling operation, with a final match error of 3% in wall temperatures. The authors have shown that the performance of ground coupled heat pumps depend strongly on the depth related thermal properties, which will vary according to location of the water table. In fact, the heat exchange rate at the unsaturated zone considerably affects the overall heat transfer of the GHE. They also noticed that there were negligible temperature changes in the soil for regions beyond 20 radius from the borehole wall. Hence, thermal interference between adjacent ground hole heat exchangers in unsaturated medium depend on distances between heat sources as well as depth of the ground water table. They concluded that an intermittent operation gives better performance than continuous operation in both cooling and heating modes, and differences between heat loads in intermittent and continuous operations increase as the unsaturated soil zone becomes deeper. The intermittent operation had less effect on the ground temperature than the continuous one, hence intermittent operation is more adequate for unsaturated conditions with vertical ground hole exchanger systems.

Knewllwolf et al. (2011) developed a new geotechnical method to analyze the axial stress (and force) mobilized on GEPs under simultaneous heat and mechanical loads, with basis on the load-transfer methodology currently used for settlement analysis of piles. According to them, despite of hundreds of installations, no design method is still available to consider the complex interactions between thermal storage and mechanical behavior of GEP systems. Therefore, a new method has been presented and incorporated into a software via Java programming suite. The software also allowed for the calculation of the pile displacements considering soil and pile interactions. The method assumes an 1D finite difference technique with properties that do not change with $\Delta T$. The stress-strain relationship between soil and pile (t-z curves) is known and does not change along the process. The method was validated with measurements from large-scale field tests at Lambeth College and EPFL experiments, demonstrating scenarios of GEP performance under distinct conditions.

Peron et al. (2011) carried out a parametric analysis with an isolated GEP with diameter 50 cm and length 10 m under floating, semi-floating and end-bearing conditions. It is basically an extension of the previous work of this same research group (Knellwolf et al 2011) in which a new software based on load-transfer mechanism is incorporated into Java programming to account for mechanical and thermal loads on single GEPs. It has been shown that the pile design could be adapted and optimized with respect to concrete resistance and mobilization of the pile shaft friction during the heat exchanger system operation. Besides, heating of the pile induces additional compression and increases mobilized shear stress, whereas cooling can induce a release of stress, possibly leading to a reversal of stress sign and eventually the development of tensile axial stresses in the pile. They concluded that there is an interplay between changes in friction mobilization and additional efforts within the pile, caused by variations in temperature and prevailing soil-pile-structure interaction (constraining) conditions.

Suryatriyastuti et al. (2012) studied the effect of the induced temperature on the mechanical behavior of GEPs under different soil-pile interface conditions, i.e., at perfect contact and sliding contact scenarios. The authors numerically evaluated a single square GEP with width of 0.6 m and length of 15 m inserted into loose sandy soil. They discussed the physical processes involved on a thermal transfer mechanism in energy pile foundations and carried out numerical simulations with the finite difference method using FLAC 3D software. The main objective of the paper was to evaluate the mechanical implication on the GEP performance when induced by seasonal thermal loads. The authors noticed that the stresses and displacements at the interface were lower for the sliding contact when compared to the perfect contact condition. Besides, by simulating two distinct scenarios at summer and winter operation modes, they observed that in winter the friction increased in the upper part of the GEP, and decreased in the lower bottom, whereas in summer this process was reversed. They concluded that the mechanical behavior of the GEPs are affected in seasonal time since the piles are subjected by cyclic thermal loadings during annual operation.

Arson et al. (2013) also evaluated the impact of distinct interface conditions on the thermal and geotechnical performance of isolated GEPs, by conducting numerical analyses with a perfect contact soil-pile and a de-bonding interface space of 1.6 mm between soil and pile. A single plane strain GEP of 0.45 m of diameter immersed on an expansive clay was simulated via commercially available FEM 1D software. The FEM was used to illustrate the impact of pile/soil debonding on the performance of a heat exchanger pile embedded in dry sand. Temperature distribution around a heat exchanger pile was computed over ten years, with inflow and outflow temperatures varying according to the recommendations of the ASHRAE for weather conditions typical of Southern United States. The authors noticed that the presence of an air film at the soil–pile interface acted as an insulator between pile and soil, hence decreasing the heat transfer between the pile and the ground, compared to the case of perfect adhesion. The de-bonding also caused a reduction in efficiency on the geothermal heat pump, thereby breaking the energy balance of the system. Finally, the de-bonding had a mechanical effect on the adhesion between the pile and soil, resulting in loss of friction at the interface.

Zarrella et al. (2013a) compared the performance of an isolated BHE coupled either to a helical-tube or to a double-U tube, with balanced and unbalanced thermal loads. The influence of the axial heat transfer on the overall behavior was also studied. The authors presented a new simulation tool package denominated GeoHP-Calc that calculates the energy efficiency of an entire Ground Source Heat Pump (GSHP) system. The package consisted of two detailed models of borehole heat exchangers (BHE) and heat pump equipment coupled in a single well-integrated calculation tool (CaRM model for ground/borehole and DigiThon model for pump/building). The software package was used to analyze two types of ground heat exchangers in the same operating conditions for two Italian climates. They numerically analyzed a GEP of 50 cm diameter and 15 m of length with a helical tube of 38 cm diameter and 10 cm pitch, and a GEP of 14 cm diameter and 60 m length with a double U-tube in parallel connection. They observed that the helical-tube GEP required about 50% shorter length than that of the double-U tube to yield same thermal performance. The effect of the axial heat transfer on the double-U tube heat exchanger, and the helical-tube with a balanced heating-cooling load, was negligible. However, in the case of the helical-tube GEP with the unbalanced thermal load demand, the axial heat transfer effect resulted in about 10% lower annual electrical energy consumption. They finally observed that when the axial heat transfer was neglected it was possible to obtain a seasonal coeff. of performance (COP) value of 3.7 for cooling, and 5.3 for heating, whereas when this effect was accounted for the values respectively changed to 4.3 (cooling) and 5.6 (heating). This led to the conclusion that axial heat transfer did altered and decreased the thermal performance of the BHE, consequently axial effects cannot be neglected when short helical-shaped pipes are installed.

Zarrella et al. (2013b) extended the results from previous (same) authors in regard to comparing the performance of BHEs with distinct heat carrier pipe configurations, in this case a helical-tube, a double-U tube and a triple-U tube. They adopted same numerical suite as used previously and incorporated the effect of pitch height in the helical tube, by changing it to distinct values of 75, 150 and 300 mm. The triple-U tube also had a parallel connection but was simulated with a BHE of 50 cm diameter and 12 m in length, as the helical tube BHE. They noticed that the helical-tube produced a 23% and 40% higher thermal performance compared to the triple-U and double-U tube configurations at peak load, respectively. Moreover, by decreasing the pitch from 150 mm to 75 mm there was a 14% increase in the peak load of the helical-tube, and by increasing the pitch from 150 mm to 300 mm there was a 14% decrease in the peak load. They concluded that the pitch height of helical tubes inside BHEs does influence the thermal performance of the system and should be properly accounted for.

Loveridge & Powrie (2013) stated that current design methodologies at the time for pile heat exchangers were based on methods developed for borehole exchangers which had a different geometry with a much larger aspect ratio. These methods also neglect the transient behavior of the pile concrete instead assuming a steady state resistance for design purposes. Therefore, they developed new pile temperature response functions (g-functions) which were designed to reflect typical geometries of pile heat exchangers and to include the transient response of the concrete. All presented g-functions and equations are valid for isolated GEPs and reflected upper and lower bounds for different combinations of pile/pile size and arrangements. Basically g-functions describe the change in temperature with time in the ground around heat exchangers as a result of applied thermal loads, or heat flux. The authors simulated an isolated GEP with 30, 60 and 120 cm of diameter with slenderness ratios from 15 to 50 in two particular soil thermal conductivities, and at differing time spans of operation. They also combined bi and tridimensional model outputs respectively from the axisymmetric COMSOL 2D and the 3D ABAQUS FEM software were employed. A numerical example of the method indicates that GEPs must operate across smaller temperature ranges than BHEs, and in long term scenarios there is a net imbalance of heat transfer with respect to injection and heat extraction. They concluded that the functions captured well the short-term variation in behavior depending on the internal pipe arrangements and the material thermal properties, in addition to the transient heat transfer and storage within the pile concrete.

Park et al. (2013) carried out experimental and numerical simulations for the evaluation of the thermal response of a precast high strength concrete GEP. TRT´s were carried out in a partially weathered and saturated granite soil deposit with two pipe configurations (W and 3-U). They adopted 3D FEM analyses with the ABAQUS software to obtain the thermal conductivity of the site and to check the response in terms of 3 months total continuous and

8hs intermittent operations, so to verify the efficiency of the system in regard to the short term heat resistance, exchange rate and ground ΔTs. They noticed that the heat exchanged by the 3U-shape in intermittent mode decreased by 51.7% compared to continuous operation. Similarly, the W-shape in intermittent mode decreased by 46.4% compared to the continuous mode. In intermittent operation, the 3U-shape produced a heat exchange rate that is 15% higher compared to the W-shape configuration, however, their performance for continuous operation was found to be similar. An increase in heat carrier fluid velocity resulted in increase in amount of exchanged heat, and the average exchanged heat increased linearly with higher temperature difference between the heat carrier fluid and the ground. They finally concluded that at distances of 20 radius from the pile center the ΔT rises were negligible in both operation modes. It seems that the intermittent operation was more beneficial than the continuous one, in terms of the heat exchange rate and impact on ground temperatures. Moreover, longer heat exchanger pipe affects the performance of energy piles under peak load condition positively.

Bodas Freitas et al. (2013) investigated the thermomechanical response of a single geothermal energy pile using ADINA 2D axisymmetric software to simulate a GEP with diameter of 1 m and length of 30 m, immersed in over consolidated soil. The paper dealt with the results of a preliminary numerical study of the response of an isolated foundation under steady state heating load and constant applied stress of 6 MPa. The authors assessed the thermomechanical behavior of the GEP under distinct coeff. of thermal expansion of the soil and showed that when the soil is less expansive than the pile compressive axial stresses appear, whereas when it is more expansive the reverse phenomena appears, i.e. tension stresses develop. The magnitude of such values does change in relation to restraining conditions of the GEP at its boundaries, at top or bottom. The mobilized shear stresses at the interface were similar in shape of the mobilized axial stresses and increased with the increment of the adopted Young modulus of the soil. Hence, the operational stiffness of the soil influenced the response of the thermally loaded pile. The boundary conditions were also fundamental for the numerical responses, in the sense that with zero thermal flow (perfect insulation) or a constant temperature frontier, distinct thermomechanical responses were obtained. Thus, the thermal boundary conditions also imparted their own restrain to the pile-soil interaction. The authors concluded that there is a complex interaction between the foundation and the surrounding soil that is influenced by both the thermal characteristics of the system´s materials and the restraints imposed by the mechanical/thermal boundary conditions. According to them, future research should focus on the interactive mechanisms of the interface and on the impact of both mechanical and thermal boundaries.

Suryatriyastuti et al. (2014) studied the effect of cyclic temperature changes or thermal loads on the mechanical behavior of isolated GEPs, by analyzing a square pile with 60 cm of width and 15 m of length immersed in loose sandy soil. They adopted FLAC 3D finite difference software and observed that repetitive heating and cooling cycles caused degradation of shear resistance at the pile soil interface, which decreased the pile shaft capacity for restrained and unrestrained boundary conditions. They also noticed a thermal cyclic fatigue effect, i.e. strain ratcheting and stress relaxation at the end of the analysis, that may impart thermomechanical consequences at prolonged operation times for the GEP.

Dupray et al. (2014) presented the behavior of a multi-pile seasonal storage system subjected to thermomechanical load via numerical analysis from both thermal and mechanical perspectives. They adopted Lagamine 2D FEM code to evaluate a piled group of 4 GEPs with diameter 80 cm and length 20 immersed in clayey soil. The group in 2D plane strain mode simulated a large 105 piles group on a 7 x 15 grid, spaced 7 m apart giving the raft dimension of around 52 x 117 m. They applied a mechanical load of 1500 kN on each pile, corresponding to a 3 MPa stress on an isolated pile, with heat extraction and injection rates fixed at 90 W/m. Overall, cycles of 5 months of storage (3 at constant rate) and 5 months of extraction, as well as 2 months without neither storage nor extraction, were simulated for a total time period of 5 years of operation. They initially observed with a balanced thermal loading function that the annual mean temperature of the storage decreased from one year to the next, because of thermal losses. Working at higher temperatures did not dramatically increased the thermal losses, but according to authors the extraction rates must be controlled very carefully to maintain a positive temperature in the piles. The increase in the overstress of the central pile was also not high, with a maximum 21% on top on the mechanical normal load. Heating all piles simultaneously however had a positive effect when compared to just a single GEP, as it reduced the maximum thermal overstresses by more than a half as there was a general uplift of the structure which reduced thermal stresses. They concluded that the higher temperature storage did not dramatically decrease the thermal efficiency. Such efficiency lowered at a rate of around 1.4%/°C increase, based on the difference between the annual mean storage temperature and the natural ground temperature. Besides, the use of the whole foundation as thermally active piles in a heating and cooling mode proved to be beneficial as it decreased the stresses in 60% of those found for a single pile. The axial load developed in the piles in response to the thermal load was strongly affected by their restraint at both ends. The heating phase also reduces the effective stresses on low permeability soils, as the study revealed that heating load increased the pore water pressures, which could be perhaps detrimental due to associated reduction in mobilized shaft friction. Both heating and cooling periods trigger measurable changes in soil conditions that should be considered in foundation design, i.e. a decrease in horiz. eff. stress during heating, and an increase in mean eff. stress during cooling. This fact enhances the importance of the soil permeability on the thermomechanical process of the GEP system and surrounding soil.

Olgun et al. (2014) investigated the increase in pile load capacity at transient and stationary thermal loads due to radial expansion of the pile shaft. A 2D COMSOL FEM analysis in plane strain and plane stress modes were carried out with a GEP of 60 cm diameter in undrained stiff clay. The authors numerically assessed the radial stresses and strains undergone by the pile in the surrounding deformable soil. The study indicated that radial contact pressures typically increase less than 15 kPa, which could not fully explain the increase in shaft resistance observed during heating tests. Nevertheless, an overall geotechnical increase in capacity of the pile was noted after heating modes. They noticed that the increase in pile temperature stiffened its load x settlement response, and the thermomechanical behavior depended on the adopted Young modulus of the soil. With a realistic modulus the piles should have expanded freely at the mesh interface. The transient analyses showed radial strains due to the thermal expansion of both soil and concrete, with compensating effects when the thermal expansion coeff. of the soil were 5x higher than of the concrete. The increase in contact pressure for the transient analysis is higher than in the stationary case, due to distinct thermal expansions of the soil. However the radial stresses applied by the soil in the pile surface were not significant, and in the range of 2 to 5 kPa of lateral friction gain.

Loveridge & Powrie (2014a) investigated the heat transfer in a CFA rotary bored GEP, by simulating a pile of 60 cm diameter with 2D COMSOL planar FEM software. They noticed that by installing heat deep pipe exchangers (HDPE) at the center of a CFA pile resulted in lower magnitude of temperature distribution at the pile circumference, thus leading to a small influence associated with the pile movement. Moreover, the authors noticed that CFA GEPs with loops (spiral pipe) at the center allowed a larger thermal resistance than traditional rotary bored piles where the spiral pipes are located close to the pile-soil interface.

Loveridge & Powrie (2014b) extended the previous work from the same authors in 2013 that have generated g-functions for isolated piles with distinct aspect ratios. In the present case, g-functions of the pile group reflecting the avg. response of all piles, interacting with each other, have been developed. The paper presented a method to derive such functions for use with multiple pile heat exchangers providing examples to illustrate the primary importance of pile spacing in controlling the available energy. The number and arrangement of the piles were also evaluated with the proposed functions. They carried out numerical analyses with ABAQUS 2D axisymmetric software and with MATLAB code for GEPs with diameter of 1.2 m and distinct aspect ratios (AR from 5 to 50) and relative spacing ratios (s/D from 1 to 100), with nondimensionalized values of ground conductivity and diffusivity. It was initially found that as pile spacing increases the interaction between them decreases, so if multiple adjacent piles are used as heat exchangers there will be an adverse thermal interaction between them. The interaction will increase with increase in aspect ratio and no. of piles and will decrease with enhanced pile spacing. Low aspect ratio systems tended to be more efficient, with reduced temperature changes. They observed that each interaction with its respective g-function will depend on the pile/soil thermal characteristics, thermal load, center-to-center distances and elapsed time. In a 3 x 3 GEP group configuration example they noticed that each pile provided only 16% of energy flux of an individual pile, given interaction effects, but overall the total energy obtained from multiple piles is always greater than from one. However, as the number of piles increased the produced energy per pile decreased as well, being evident that, due to interaction overlapping phenomena, it may not always be advantageous to have all piles as heat exchangers.

Jeong et al. (2014) investigated the thermomechanical response of pile groups with distinct geometric and geotechnical factors via 3D COMSOL FEM numerical analyses with groups of GEP with 50 cm diameter, 20 m of length and distinct relative spacings s/d of 3 and 5, all immersed in sand or clay material. The top raft had a width of 6.5 m and only 3 of the 9 piles of the group were thermally active. The numerical model was calibrated with field data from Lambeth College using soil properties from literature. Changes in axial load and settlement of individual piles in the group at distinct positions (center, corner, edge) were assessed in terms of pile spacing, arrangement, soil type and end bearing conditions on the final response. The authors noticed that by cooling the thermal piles there was a decrease on the axial compressive loads, especially on the center one due to raft restrictions. Cooling has also increased the shaft friction of the piles. By increasing pile spacing there was an increase on the axial loads, and similar pattern of loads have been observed for either sandy or clayey material, however given higher thermal conductivities for the sand higher thermally related axial loads on the piles were noted. End bearing constraints at the pile base has also led to higher axial loads with smaller group settlements. The authors concluded that the thermal loads caused little change in the mechanical behavior, so pile failure and excessive settlement are unlikely to occur in real conditions. It was also concluded that the raft induced significant reduction in axial load due to the restraint effect to vertical displacement in cooling energy piles, that the bearing capacity changed with temperature level, and finally that pile location affected the magnitude of the thermally induced axial loads.

Rotta Loria et al. (2015) studied the impact of different magnitudes and combinations of mechanical and thermal loads on 3 isolated GEPs in saturated Toyoura sand. Each pile had a diameter of 88 cm and a length of around 20 m. They adopted the Lagamini software with a 2D axisymmetric FEM tool. They noticed through the analyses that an increase in the thermal and mechanical load increased the magnitude of the vertical load transmitted to the pile base. Besides, plastic strains were developed at the soil-pile interface at larger magnitudes of thermal and mechanical loads, thus inducing large effective horizontal stresses, which ultimately affected the shaft resistance of the GEPs. Finally, they noted that the null point, where no induced strains are internally mobilized in the pile, moved up and down depending on the magnitude of the thermomechanical applied load, and it corresponded to changes in the stress distribution occurring in the surrounding soil.

Cecinato & Loveridge (2015) analyzed the effect of different factors on the thermal performance of GEPs, by adopting the software ABAQUS 3D to simulate GEPs with initial diameter 30 cm and length 26.8 m embedded in London Clay, all equipped with U-loop heat exchanger pipes. A finite element model was developed for the accurate analysis of the transient diffusive and convective heat phenomena, being validated by TRT full scale data and analytical values from the infinite heat source theory. Parametric analyses were conducted by varying the pile diameter, length, concrete cover, concrete thermal conductivity, number and diameter of internal pipes, and velocity of the heat carrier fluid. The simulations were done with pipes connected in series and adopting ranges of practical values for all other variables. A statistical process was used to reduce the number of sensitivity analyses to 8 to cover most of the studied possibilities. The authors noticed that the best scenario for heat conduction or efficiency was the number of pipes, followed by the pile length, i.e. all other variables being equal, the amount of pipe surface available for convective heat exchange is fundamental for an efficient thermal flux. The number of pipes is however limited to the available pile spacing (cross section, cover), and ensuring separation between pipes maximizes energy output by reducing interaction potential. The least important variable for thermal interaction was the flow velocity. They concluded that the no. of pipes was the most influential factor to maximize the pile efficiency and the fluid flow rate is not as important provided that turbulent flow happens inside the pipe.

Batini et al. (2015) assessed the effect of different pipe configurations, aspect ratios, heat carrier fluid velocities and antifreeze mixture volume on the thermal performance of GEPs. The numerical sensitivity FEM analyses were performed with the software COMSOL 3D, with an isolated pile of diameter 90 cm and length 28 m immersed in alluvial sandy-gravelly moraine material, typical of the Swiss Tech. Conv. Centre. Internal W-shaped, 1-U and 2-U pipe configurations were adopted with operation times up to 15 days for the GEP system. They noticed that such configuration strongly influenced both energy and geotechnical performance of the GEP in all time spans. Likewise, the aspect ratio was also of importance, since the lower was this ratio the lower and more homogeneous were the thermally induced axial stresses in the pile. The authors observed that the decay of thermal power extracted from the ground was high during the 5 days of continuous operation of the system, with higher extractions and decay in the first day (30% of total for 1-U pipe and 45% for 2-U and W). The W configuration pipe presented the best tradeoff for the studied cases due to higher energy extractions and lower volumetric flow rates. The heat transfer increased with the increase in pipe diameter, and the mixture of carrier fluid and antifreeze did not appreciably affect the axial temperatures, nevertheless by adopting high concentrations of antifreeze there was a considerable decrease in the heat transfer rate. The increase in fluid velocity raised the heat transfer but did not influence remarkably the derived axial stresses on the GEP. The authors concluded that the configuration of the pipes was the most important factor in the characterization of the thermomechanical behavior of the GEPs. In this regard, they stated that the choice of the most appropriate design solution for the heat exchange operation of the energy piles should be also considered based on the energy demand of the related environment with respect to the thermo-hydraulic requirements of the heat pumps.

Olgun et al. (2015) investigated the effect of long-term thermal cycles on the temperature distribution within and around pile groups using the software COMSOL 2D. This software was used to simulate a GEP with 60 cm diameter with double HDPE cross aligned pipes. Several pile arrangements in a unique group have been investigated, from a single pile to rectangular configurations of 2x2, 3x3, 4x4 and 5x5 and relative spacings s/D from 3 to 6 center to center. The analyses simulated 30 years of pile operation and resulted in significant findings for the long-term performance of heat exchanger pile systems at distinct (3) external climate conditions, where emphasis was given to energy demand and supply. The authors noticed that the nature and distribution of temperature in a GEP and its surrounding soil was dependent on the seasonal energy demand, and in a balanced system (e.g. Charlotte, North Carolina), the region influenced by temperature changes within the soil mass surrounding the GEP was minimal, hence, resulting in high efficiency over long-term. On the other hand, in an unbalanced climatic condition (e.g. Chicago, Illinois and Austin, Texas), the system lost its efficiency over time especially in larger pile grids. Basically, in a superstructure system that demands nonsymmetrical energy the ground can be progressively warmer in cooling dominated climates, or cooler in heating dominated cases. The anisotropic unbalanced thermal fields were due to distinct balances of heat extraction in winter or heat rejection during summertime, hence yielding operational implications for the efficiency of the system. For instance, in the examples provided by the authors the coef. of performance (COP) and the energy efficiency ratio (EER) of the pump system declined dramatically for larger pile grids. A standard geothermal heat pump (WFI 5 Series 500A11 ND038 with 1,050-cfm air flow capacity) was selected in this case. At the Austin city example the heat pump lost efficiency and was inoperable after 4 years in the 5x5 grid arrangement. The thermomechanical numerical analyses also showed that the displacements decreased as the heating expanded the piles in accordance to the progression of internal temperatures, but the stresses increased to a small value over the 30 years simulated operation period (in the case of Austin city, around 40 kPa). They concluded that a sustainable heat exchange is linked to a seasonal balanced energy demand, and in an unbalanced heat operation system the pumps can lose efficiency over time unless preventive measures are taken. These could include a recharging approach for the energy system to seasonally balance the ground temperatures, so to allow a sustainable usage of the ground.

Loveridge & Cecinato (2015) compared the energy performance of CFA piles and conventional rotary bored ones, using ABAQUS 3D FEM software with CFA and Bored GEPs of diameter 90 cm and length 25 m immersed in London clay. 2-U pipe loops were adopted with external diameter of 40 mm. They noticed that rotary bored piles are more efficient than CFA piles when equipped with the same number of pipes, because the pipes were situated near the pile periphery. Besides, rotary bored piles offer more room for installing a higher number of pipes in the pile cross-section, which maximizes its efficiency. A CFA can be fitted with 4 HDPE pipes rather than the conventional two pipes commonly used, however in all operation cases a turbulent fluid flow regime should be maintained in the pipes for optimal heat exchange. The current standard of installing CFA piles with steel bar for rigidity has no detrimental effect on thermal performance. However, using spacers to avoid buckling of the pipes would improve the system performance.

Gashti et al. (2015) investigated the effects of ground water flow on the GEP performance by simulating an isolated pile with diameter 60 cm and length 20 m equipped with 1-U pipe loop with 25 mm external diameter, in both cooling and heating environments. The soil thermal properties used in the model were selected from typical laboratory test data and data on groundwater flow were taken from literature. The soil was assumed to be saturated with groundwater flow velocity equal to 1.65 x $10^{-8}$ m/s. The performance of such energy pile foundation was assessed numerically by considering groundwater flow effects and short-term imbalanced seasonal thermal loadings. The structural behavior of frictional pile foundations was also analyzed using the soil elasto-plastic behavior and assuming non-linear sliding contact at the pile–soil interface. The results in winter operation mode indicated that using energy pile foundations under medium groundwater flow enhanced the productivity of system by around 20% compared with a saturated condition with no groundwater flow. In summer operation the GEP performance increased by 5% due to the groundwater flow effect. Basically, for systems with low geothermal potential in absorbing/injecting heat, differences between systems with and without groundwater flow are more highlighted. When only one tube with low energy transfer capacity is installed in the pile, there is always enough geothermal potential in the soil in the vicinity of the pile and groundwater flow will not increase the potential significantly. When higher transfer capacity is installed, the heat absorption may decrease to a higher degree the ground temperature (winter mode) in the vicinity of the pile. In such conditions, groundwater flow can transfer heat from surrounding areas and thereby increase the ground temperature and the geothermal potential near the pile. The authors concluded that systems with high heat injection into the ground during summer (using solar panels etc.) in order to increase the ground's potential as a heat source in winter are not recommended under groundwater flow conditions, due to heat energy dissemination resulting from flow effects.

Suryastriyastuti et al. (2015) compared the thermomechanical behavior of a single GEP foundation and a GEP group with distinct boundary conditions at the pile head, i.e. with and without surface cap. They adopted FLAC 3D FEM software to simulate a 60 cm diameter pile with 15 m of length in isolated and 3 x 3 group (s/D of 3) configurations, both immersed in homogeneous sandy soil. In the pile group, from the 9 piles only the 4 edge ones were thermally active. A cyclic elastoplastic constitutive model was introduced at the pile-soil interface and an applied load of 1/3 of the ultimate geotechnical resistance was applied. A thermal cyclic load of ± 10°C was also applied. The constitutive model for interface incorporated nonlinearity, cyclic degradation, post-peak softening–hardening, and contractive–dilative domains. The analyses gave insights on the long-term cyclic interaction mechanisms in GEP systems, for instance in the pile group with a cap the cooling cycles induced a loss of mobilized shaft and base resistance, whereas the heating cycles generated greater mobilized resistances. Degradation in pile capacity with cycles due to repetitive stress reversals was also noted. In such groups where not all of the piles were thermally active the presence of the cap permitted to transfer the induced displacement to the group in a more uniform manner, however the neighboring piles carried the redundant forces induced by temperature variations as to satisfy the static equilibrium of the group. The authors concluded that a balancing phenomenon between neighboring and energy piles occur regardless of head fixity conditions and it also affects the state of soil displacement contained within the group. The variation in pile response with thermal cycles depends on the initial condition at the mechanical state of loading. Therefore, the long-term effects and the interactions between energy piles and conventional piles in the group must be regarded.

Salciarini et al. (2015) carried out a fully coupled 3D thermomechanical FEM with the COMSOL software to investigate the mechanical and thermomechanical behavior of a small piled raft with energy piles, not all of them simultaneously thermally active. The study focused on the axial load redistribution among piles, and on the thermal interaction effects that could affect the heat exchange process in both heating and cooling modes. A 30 years operation period was simulated, and the finite element output assessed the effects of the geometrical layout on the structural loads and the evolution with time of the heat flow. 4 different GEP configuration groups were discretized at 2 thermal conditions of ∆T +20 and -15°C. All systems had piles with 1 m diameter, 25 m length and a 12.2 MN mechanically loaded circular raft of 16 m diameter and 2 m thickness immersed in stratified sand and clay strata. They initially noted that significant axial load changes could be experienced by both thermally active and nonactive piles on the raft, with axial load being transferred from the active piles to the nonactive ones. The load distribution reached their peak at a very early stage of the thermal process, when differences among active and nonactive piles were at largest. Peak axial load variations occurred within 2 to 4 weeks after the beginning of the thermal stage, therefore within normal operational conditions of GSHP systems. The thermal behavior was similar for the 4 systems up to 1-month operation, but efficiency decreased faster on systems with more piles due to higher thermal interference, which increased the thermal resistance of the group. They observed appreciable efficiency losses after few months of system operation. It was concluded that, regarding thermomechanical behavior, there is still a lack of simple and reliable design approaches for GEPs, which are currently dimensioned based on empirical considerations. Regarding thermal efficiency, it should be expected a significant reduction in the specific heat flux to and from the soil, given the relatively small distance at which energy piles are located compared with conventional borehole heat exchangers. Research on the interaction effects in the presence of repeated heating and cooling cycles, typical of a GSHP system live cycle, should be encouraged.

Abdelaziz et al. (2015) studied the long-term behavior of ground heat exchangers with equivalent sine wave thermal loads and the change-point statistical method. They adopted the 2D COMSOL axisymmetric software to illustrate the performance of an isolated GEP with 50 cm diameter with typical building thermal demands from 3 distinct USA locations. A simple technique that accounted for the hourly variation of thermal loads was based on the change-point statistical analysis to determine the heating and cooling superstructure demand episodes. These demand loads were later converted to ground thermal loads on sine wave format. An office building example was provided to demonstrate the new technique. In this regard, the Hvac Load Explorer software was used to solve the heat balance equations of the hypothetical design building at the three selected locations. A heat pump with capacity of 21.1 kW (6 tons) at an entering fluid temperature of 19 °C was adopted for Charlotte, NC and Chicago, IL., while, for Austin, TX a heat pump with capacity of 17.58 kW (5 tons) at an entering fluid temperature of 22 °C was used. Using typical thermal pump characteristics for the selected heat pumps and the relations between the ground and the building thermal loads provided by the Hvac software, the time histories of the ground thermal loads at the three locations were estimated. According to the authors the long-term performance of the GSHPs depends directly on ground thermal loads rather than building loads, but the ground thermal loads are based on the building loads and the characteristics of the selected pumps, hence are interconnected within the overall system´s framework. Indeed, one way to consider long-term effects is to perform a comprehensive energy balance analysis for the building and geothermal system using a commercially available computer package of FEM technique. The example demonstrated that the long-term performance of the system was independent of the initially applied sinusoidal ground thermal cyclic load. The authors concluded that this new technique that converts superstructure hourly thermal demands into ground sine-wave thermal loads enhances the numerical analysis. Therefore, it is recommended for predicting the long-term thermal performance of ground heat exchangers.

Ng et al. (2016) investigated the horizontal stress changes in floating energy piles subjected to cyclic thermal loading histories, via FEM with a hypoplastic model. A parametric study was conducted by considering the effects of thermal cycles on an isolated GEP with distinct diameters and variable slenderness L/D ratios, immersed in Toyoura sand. A 2D axisymmetric ABAQUS FEM software was employed. The piles were of the "wish-in-place" type, thus representing bored foundations. They were loaded at working conditions (SF = 2) and the study only focused the mechanical aspects of the problem with 50 full thermal cycles at heating and cooling modes. The authors observed that a reduction of horizontal stress occurred at the interface by temperature induced cyclic shearing, hence decreasing the interface shear resistance. The degree of reduction was affected by the amplitude of the thermal cycles and by the adopted pile diameters. The authors also noticed that the overall trend in reduction of shaft resistance was compensated by additional pile settlement and further mobilization of the pile base resistance. Hence the sand below the pile base was densified due to the cyclic shearing, and therefore the base resistance improved. The variation of horizontal shaft stress was shown to be almost independent of the relative density of the sand but decreased nonlinearly with pile length. This stress was also influenced by the pile diameter at least up to D = 80 cm. They concluded that for a practical design of energy piles in sand the shaft resistance reduction due to variations in horizontal confining stress should be considered, besides of being probably low for longer piles.

Saggu & Chakraborty (2016) evaluated the thermomechanical response of GEP groups in sand with active and nonactive thermal piles, by using a 3D nonlinear FEM analysis with ABAQUS software. A 3 x 3 piled raft with 15.5 x 12.9 x 1.2 m dimensions was considered and a linear elastic response was adopted for piles and raft. Piles of diameter 1 m and length of 20 m have been adopted under different combinations of thermally active piles in the group, focusing on the mobilized displacements and axial stresses. A parametric sensitivity analysis was also carried out by varying the spacing between piles. An additional effort was made to understand the response on the piles for the distinct thermal combinations in comparison to those values related solely to mechanical loading. A differential $\Delta T$ of 21°C for 12 days of heating and 16 days of cooling was simulated. The authors noticed that during heating there was redistribution of load and distinct directions of displacements on the distinct piles, either upwards or downwards depending on pile position within the group (corner, edge and middle locations). The axial stresses generated in distinct piles of the group increased at the end of heating and decreased at the end of cooling and it was always higher than due solely to mechanical load. Greater loads were noticed in the corner piles, as expected. Redistribution of load from middle to corner piles was also noticed, given the top raft displacement restrictions during thermal loading. The redistribution was also related to active and nonactive thermal piles, since for instance during heating the axial stresses in the thermally active piles increased in detriment to simultaneous decrease in the nonthermal ones. For the thermal piles closely spaced at 2.5 diameters a 47% increase in displacement was observed over that of only mechanical loading. The authors concluded that a spacing of at least 4 m should be adopted between thermally active piles in the field, corresponding to 4 diameters from adopted numerical dimensions. Differently from other studies of GEP groups with active and nonactive piles, they also concluded that geothermal energy groups should not have combinations of thermal and non-thermal piles simultaneously working together.

Di Donna & Laloui (2016) summarized the results of a 3D FEM calibration and parametric analysis with the software Lagamine. A thermo-hydro-mechanical finite element analysis was carried out with available large-scale data at the Swiss Federal Institute of Technology (EPFL) from Mimouni & Laloui (2015). These latter authors performed full-scale in situ experiments to quantify the magnitude of interactions that could develop within a GEP group of four test piles below a water retention tank. Such field experiments focused on their response in terms of stresses, strains and displacements. The present numerical analyses complemented the existing field results, by calibrating the model and extending the understanding of the group in terms of the simultaneous presence of thermally active and nonactive piles in the same system. They heated separately each of the 4 GEPs of the group while leaving the remaining 3 thermally nonactive and compared the obtained results in terms of mobilized individual axial stresses and displacements. They also heated all piles simultaneously and compared to previous results. The authors initially noticed that tilting of the raft occurred while thermally loading one pile while keeping others nonactive, nevertheless, all piles suffered internal temperature variations. This phenomenon was caused by the heat diffusion that occurred in the soil from the directly heated pile to the outer piles. By heating only the central pile the maximum increase of axial stress was 7 MPa on the heated active pile, with the least favorable stress condition at the end of the increase in temperature (in general 1 month heating and 3 months resting period). By heating only the external piles a highest axial compression stress of approximately 5 MPa was observed when their temperature reached the maximum value. And by heating all the piles the worst condition was met comparing all other simulations. Because all were thermally active piles, they were all subjected to additional thermally induced compressive stresses between 2 and 6 MPa, which decreased to 1-3 MPa at the end of the 3 months resting period. In all simulations no plastic strains were developed at the pile-soil interface, so the mechanical behavior of the foundation always remained in elastic conditions. From the results it was also possible to observe that the induced temperature variations were not negligible within the surrounding soil, with the worst condition achieved when all piles were heated, as expected. On the other hand, the induced water pressure variation in the soil was not significant. The authors concluded that the operating thermal load was not critical in terms of the displacements and stresses for the piles according to current (European Eurocode 7) standard, and thus the geotechnical stability of current GEP foundations is ensured. The thermally-induced stresses in the piles under operating conditions were generally admissible with respect to the concrete strength. On the other hand, even though these stresses and displacements are not critical under the operating conditions, they may become more significant under extreme and non-uniform thermal loading scenarios that are typical of potential future, more intensive and long-term use of energy piles.

Mehrizi et al. (2016) compared the heat transfer between 3 HDPE pipe configurations within a single GEP, and the impact of connecting 1 to 15 GEPs in series and in parallel. They used FLUENT/Gambit 3D FEM simulation software with 1-U, 6-U, 1-W, and W-all around shape pipe configuration in a GEP of 60 cm diameter and varying lengths from 20 to 30 m immersed in sandy silt. The studied cases were done in cooling mode with inlet temperature of 35°C, velocity of 0.3 m/s and turbulent conditions. They simulated the heat transfer between water, pipe, pile and soil to determine the numerical specific outlet temperature of the fluid. The W-all around or 6-U shape pipe configuration resulted in higher heat exchange efficiency by 20% and 35% compared to 1-W and 1-U shape type pipes. The inlet water temperature decreased by 4 % and 4.27 % when 10 and 15 piles were connected in parallel. Thus, connecting more than 10 piles in parallel was not economical. Moreover, connecting 6 piles in series greatly increased the amount of heat transfer by 4.54%. A moderate increase of 0.67% was obtained when 7–11 piles were connected and connecting 12–15 piles resulted in 0.13% increase. There was a 65% and 73% increase in heat energy output for piles connected in parallel and series, compared to a single pile. Therefore, the authors noticed that the rate of transferred energy via increasing number of piles was accentuated in serial connection, and the W-all around shape configuration had the highest efficiency in heat transfer rate for the declining outlet temperature of water. They concluded that the best configuration was a serial connection of 15 piles with W-all around shape pipes.

Bourne-Webb et al. (2016) investigated the impact of a limited set of thermal and thermomechanical parameters on the behavior of GEPs, via study in which the results of a set of simplified numerical analyses with the ABAQUS 2D axisymmetric software were carried out. They analyzed a single GEP with diameter 1 m and lengths of 15, 30 and 45 m with distinct surface temperatures. The parametric analyses varied the ratio of the pile length, the soil/concrete ratio of coefficient of thermal expansions (CTE ratio), and the surface temperature on the thermomechanical behavior of GEP systems. They observed that current studies do not account for the initial temperature field and boundary conditions of GEP systems, and for the response of the ground to temperature changes. According to the authors the temperature field around the pile in combination with thermal characteristics of both pile and soil play a major role in the interaction phenomenon of heat transfer. They noticed that for a given pile slenderness ratio L/D the thermally induced axial stresses varied almost linearly as the CTE ratio increased. Besides, when the soil had a coeff. of thermal expansion greater than zero (non-inert thermally materials) the thermal action effects were gradually less compressive, becoming tensile for some CTE ratios. The authors concluded that the difference between the initial temperature and the thermal prevailing conditions of the overlying structure establishes the initial thermal effect which affects the subsequent response of the system. Besides by ignoring the thermal volume response of the ground, or its CTE, the thermomechanical behavior of the GEP will be incorrect, and by assuming that the soil is thermally inert there will be conservative estimates of response.

Abdelaziz & Ozudogru (2016) evaluated the influence of non-uniform distribution of thermal strains and stresses in a GEP subjected to transient thermal loads. They analyzed an isolated GEP with diameter of 50 cm and length of 23 m immersed in silty clay with the FEM software COMSOL 3D. They showed that both thermal tensile and compressive stresses and strains were found to coexist in a GEP during either heat rejection or injection process, and this occurred because of the non-uniform temperature changes that exist within the GEP cross section.

Tsetoulids et al. (2016) investigated the effect of thermal loading on the mechanical behavior of single energy piles and pile groups with the software ABAQUS 3D and the axisymmetric FEM module. They analyzed a single pile of diameter 60 cm and length 23 m with similar soil conditions as those from the large-scale experiments at Lambeth College, and a 9-pile group in a 3 x 3 grid spaced at s/D of 3. The group had a rigid top cap connecting all piles and was simulated with all of them thermally active, and with just one central pile thermo-active. Similar pile and soil characteristics, and heating and cooling phases as those of the simulations with the isolated pile, were applied. It was observed that the derived axial forces on each pile group were significant and depended on the number of piles that were thermally active. They noted that, regarding the axial force distribution along depth, that cooling tended to increase the interface shear stress at top of the pile and decrease it at bottom. When thermally activating all piles, greater axial forces during cooling and heating phases appeared at the corner piles. When thermally activating only the central pile, the axial forces at each thermal mode were greater (tension or compression) for the central pile. Moreover, in the latter case, the axial forces at center and periphery had opposite signs to keep a stable balance of forces. The settlements during cooling and heating phases were small in magnitude but could be greater than initial (mechanical) settlement depending on the applied axial head load. Heating caused a redistribution of axial loads at the pile head for the group GEP. They concluded that, among other things, a small change of pile capacity due to thermal loading is related to a slight increase or decrease of normal stresses at the pile-soil interface.

Vieira & Maranha (2016) studied the thermomechanical behavior of a single pile in a typical Lisbon condition with the 2D FLAC Axisymmetric software. They analyzed a GEP with diameter 60 cm and length 20 m immersed in a normally consolidated saturated clay deposit of Lisbon. A critical state elastoplastic soil model with thermal hardening characteristics was formulated, implemented and calibrated with experimental results for thermal expansion tests from literature with this same soil. The GEP was considered with linear elastic thermomechanical behavior. A 5-year seasonal period was simulated, considering the influence of several factors as the prevailing atmospheric conditions in Lisbon and 3 distinct sustained mechanical load levels. The authors noticed that the thermomechanical response of the pile was reversible and elastic during distinct thermal season, but the pile has suffered an irreversible and accumulated settlement in each year of thermal cycle. Yielding of soil elements at the interface soil-pile did also happen. They concluded that the thermal actions should be considered in the structural design and monitoring is essential to assess operational conditions of thermoactivated piles as current studies do not normally consider the long-term conditions of the GEP system.

Kawuwa et al. (2016) studied the response of the soil surrounding a GEP to heating load by analyzing a single energy pile of diameter 60 cm and length 30 m immersed in London clay. They adopted the FEM axisymmetric software COMPASS, and observed that the duration of the heat injection/extraction had direct influence on the time to achieve natural thermal recovery of the soil. In general, this material required about 4 times the heating time to naturally recover towards its initial state.

Olgun et al. (2017) investigated the long-term performance of GEPs under different myriads of climatic conditions with COMSOL 2D planar FEM software. Ground thermal loads were estimated and representative equivalent half-sine waves of thermal loads from a hypothetical four floor medium size office building were created for 100+ different locations. Total required heat exchanger lengths (with a common borehole diameter of 15 cm) for each location were then estimated for the proposed building. Findings suggest that for different seasonal energy demands, amplitudes and durations of the sine waves changed significantly, consequently suggesting different loop lengths. For unbalanced climates, loop lengths found were considerably higher than balanced cases. The authors noticed that both the estimated cooling-heating amplitudes and the resulting borehole temperatures after 30 years of thermal operation were linearly proportional. As long-term performance of the ground heat exchangers was closely related to maintaining a constant ground temperature, in extreme climates, heat exchange efficiency dropped after long term usage of the system.

Wu & Gan (2017) evaluated the thermomechanical behavior of a small-scale GEP with coupling effect of thermal expansions in soil and pile. They adopted data from centrifuged tests in which a single energy pile of 20 mm diameter and 600 mm length have been tested immersed in speswhite China clay. ABAQUS 2D axisymmetric FEM software was used. Individual and multiple thermal loading cycles were applied for short and long-term performance of the GEP system, i.e. a ± 1°C pile temperature was considered for 30 cycles under mechanical applied loads of 0, 20, 40 and 60% of the pile ultimate capacity. They noticed that a relatively stationary settlement was achieved after several thermal cycles under constant underground temperature. Temperature induced settlement was stabilized in the first 3 cycles, and the first cycle in the simulation had the largest irreversible increment. Resulting settlements progressively achieved a stable state due to a densification process that occurred at each thermal cycle. Moreover, higher mechanical loads resulted in a higher irreversible thermal settlement. They concluded that since the relative settlement for thermal load was small compared with the mechanical one, that the GEP could stay safe under the current setting of thermomechanical loading conditions employed at the test.

Rotta Loria & Laloui (2017) developed design charts for displacements of GEP groups via displacement interaction factors, in a similar fashion as the charts already developed under purely mechanical loads via elasticity theory. They evaluated thermally influenced displacement interaction factors among general configurations of energy piles bearing on stiff strata and with floating conditions, under distinct relative spacings s/D, slenderness ratios L/D and a common diameter of 1 m. The solutions were obtained using stationary finite element analyses and are valid for both positive and negative temperature changes applied to the energy piles. The numerical COMSOL 3D FEM software was employed with distinct configurations of pile center to center diameter, L/D and pile-soil stiffness ratios. They observed that the interaction factors for end bearing piles or infinitely rigid soil layers were greater than for floating piles in a uniform soil deposit, and as expected the interactions decreased with the increase of relative spacing. Distinct ratios of Yong modulus base/shaft were varied, and it was observed that the displacement factors increased with such increasing ratios. The thermally induced settlements also increased with the ratio Young modulus of the pile / shear modulus of the soil. The technique was further compared, or validated, with a square group example of 3 x 3 GEPs in which some or all piles were subjected to temperature changes. Differences between both techniques, i.e. interaction factors x numerical FEM, were related to the fact that the interaction method neglected the temperature variation for the soil around the piles, whereas this effect was considered in the FEM simulation. The presence of a rigid bearing strata had also a marked effect on the vertical displacement of a pile group due to thermal loads. They concluded that the theoretical method described could predict the magnitude of vertical head displacements within the energy pile groups with a comparable accuracy to those from a more rigorous (FEM) technique. Nevertheless, more evidence is still needed for further validation.

Gawecka et al. (2017) addressed the thermal and mechanical behavior of energy piles in a clayey deposit under distinct modelling conditions by performing axisymmetric FEM simulations with a GEP of diameter 60 cm and length 23 m. Similar soil conditions as those from Lambeth College in UK have been adopted, i.e. London clay. Initially the software capabilities were assessed, followed by a detailed study that demonstrated the coupled thermo-hydro-mechanical response of the system. Several aspects that affect the design were investigated as the influence of the modelling approach, the application of the thermal load and uncertainties in the determination of the soil properties. Additional parametric analyses were performed, with the same pile and site conditions as before, and variable values for thermal conductivity and permeability. The mobilized pore pressure of the surrounding soil could dissipate between mechanical and thermal loads. Nevertheless, it has been noticed that deformations of the pile and differences in thermal expansion coefficients of soil particles have caused the generation of excess pore pressures in the soil during the distinct simulations. For instance, in the first month of cooling, the deformation of the pile, as well as the difference in the thermal expansion coefficients of soil particles and pore water, caused the generation of tensile pore pressures changes around the pile with a maximum amplitude of approximately 30 kPa. Over the following 4 months, these pore pressure changes reduced noticeably, although there was an increase in the volume of soil affected as the cooling front propagated. Conversely, heating induced compressive pore water pressure changes. The authors concluded that the thermally induced stress changes tended to reduce with time as surrounding soil reacted to changes. Besides, numerical modelling can produce distinct final results, if they are coupled or uncoupled, or if the method of thermal load application is transient or not. For the particular conditions considered in the simulations the effect of changing permeability and conductivity did not significantly alter the results, especially when compared with modelling approach related influences.

Salciarini et al. (2017) presented an extensive parametric study in which a series of fully coupled 3D thermo-hydro-mechanical FEM analyses with the ABAQUS software were conducted in a large piled raft with GEPs. The analyses were done with a group of 3 x 3 piles with diameter 60 cm and length 25 m, spaced at 2.5 m each and connected on the head by a raft of 5 x 5 m. The piled raft was fully immersed in over consolidated fully saturated stiff clay and it was considered in three distinct configurations, i.e., all 9 piles thermally active, 8 out of 9 piles active and just 1 active thermal pile. The analyses extended a previous work from same authors (Salciarini et al. 2015) with the same numerical tool but distinct objectives and group layout & thermal loads. On the present series of analyses the authors assessed some key variables on the performance of the GEP system, as the soil-pile-soil interaction effects during thermal loading, the quantification of the influence of the thermal properties of the soil (CTE, conductivity), the influence of the geometric layout on the response, and the evaluation of the active thermo pile spacing. 2 fully thermal loading cycles of 12 months each have been considered with a constant initial temperature equal to 20°C assumed for the entire domain. An initial mechanical load of 1500 kN has been applied at the center of the raft, assuming a drained initial isothermal condition in the first simulation stage. It has been shown that inactive thermal piles have same order of axial load variations than thermo active ones, and that many active piles closely spaced can significantly reduce the thermal efficiency of the system. Moreover, by adding more piles in the system there was not a proportional increase of the heat flux, or system efficiency. The authors concluded that the axial loads in thermo active GEPs depend primarily on the pile spacing and the number of active interacting thermal piles. If the spacing is relatively close, there will be a significant thermal interaction between the piles. Thermally induced settlements of the raft can be high, in the order of centimeters in the presence of a high number of active energy piles. Both the thermal conductivity of the soil and its coefficient of thermal expansion do influence the thermomechanical results of the system, hence imposing a clear necessity to better characterize the deposit either in mechanical or in thermal conditions.

Sani et al. (2018 a, b) and Sani et al. (2019b) studied in three separate publications the heat flow mechanism in a GEP system, focusing on the influence of the heat pipe configuration and location. The study has particular interest on the performance and flow characteristics for a CFA pile type, given its restricted space availability to introduce heat exchanger pipes (generally located at the pile´s center). Analyses were done with COMPASS 2D – Planar FEM tool for a pile with 60 cm diameter immersed in London clay under distinct arrays of pipe configuration. The numerical study investigated the pipe to pipe thermal interaction between inlet and outlet loop legs with 2-loops, 3-loops, 4-loops close to shaft and 1-loop and 2-loops centrally located pipe configuration. In the latter case, the central pipes were attached to a single central bar made either from steel or plastic to check on possible distinct interaction phenomena. A constant temperature of 35 °C and 30 °C was applied to the internal surface of the inlet and outlet leg of the HDPE pipes, respectively. This GSHP system mode of operation represented the process of heat injection into the soil or summer mode to provide space cooling. Radial thermal flow between pipes has been noted and numerically evaluated via analytical solutions provided by Loveridge & Powrie (2014). The authors initially noticed that such solutions were effective in estimating with good accuracy the radial flow developed through the pile´s cross section. It was found that factors such as the number of loops, pipe location, soil, concrete, pipe, steel and plastic thermal conductivities do influence the magnitude of thermal interactions between the pipes, hence affecting the flow mechanism or efficiency of the system. It was shown that the heat exchange between pipes became significant after 3 to 5 days of operation with a 5.4 W/m heat flux between inlet to outlet pipes. Besides, the higher the number of loops the greater was the temperature increase in the GEP, therefore pipe interaction. A peak of the thermal interaction happened when the thermal conductivity of the concrete was half of the soil. The specific heat of the pipe, on the other hand, did not play a fundamental role in the thermal interaction. They also observed that by locating pipes in the center there was an increase of the thermal interaction whereas with closer to edge pipes there was an increase of the magnitude of the circumferential temperatures. In this respect, the presence of a central bar increased the pipe to pipe interaction. They finally demonstrated that a GEP system with 4-loops pipe configuration, either at edge or at center position, produced a thermally active region in the soil around the pile of approximately 7 diameters.

Sani et al. (2018c) investigated the use of GEPs for heat storage in an unsaturated soil domain via COMPASS 2D axisymmetric FEM software. They analyzed an isolated GEP of 60 cm diameter and length of 30 m immersed in an unsaturated swelling clay. They observed that the heat injection process resulted in drying up of soil next to the GEP, thus resulting in a surrounding soil material with lower saturation. This soil with lower saturation resulted in lower thermal conductivity, decreasing therefore the efficiency of the system. However, this phenomenon allowed the advantage of having a higher volumetric heat storage capability. Sani & Singh (2018) extended these results with the same numerical tool. In this case they investigated the response of the same energy pile as before (60 cm dia. and 30 m length) embedded in 3 distinct unsaturated soil mediums, respectively homogeneous sand, silt and clay. Each soil had its own soil-water suction characteristic curve. The GEP was subjected to a heat injection process of 3 months followed by a recovery period of 6 months. Intermittent and continuous thermal cycles were performed, under distinct soil saturation degrees and magnitude of heat injection rates. So, degrees of saturation of 0, 20, 60 and 100% were employed, with variable thermal conductivities for all considered soil materials at each respective degree (based on laboratory results). The hydraulic conductivities also varied in accordance to the soil saturation degree, based on literature equations. The initial adopted temperature of 13.4 °C corresponded to the typical temperature value found in the UK at shallow depth, and a heat flux boundary condition of 25W/m$^2$ was applied at the GEP surface. They noticed that the temperature approached the initial state around the GEP for a duration equal to twice the heating time. Besides, by imposing excessive heat flux on the pile resulted in drying up the surrounding soil, which as noted before decreased the thermal conductivity of the material. The results have also demonstrated that the magnitude of temperature build up along the pile decreased with the degree of saturation and soil granularity. Lower hydraulic conductivities led to lower heat transfer via convection, thus resulting in a high temperature build-up and consequent decrease of efficiency of the system. The intermittent operation allowed the soil to dissipate away the heat in a faster manner when compared to the continuous operation. The authors concluded by stating that in situations where higher temperature changes are expected in the GEP due to high injection rates, or very low degree of saturations of the soil medium, it is advisable to implement an automated management unit to control the temperatures of the system.

López-Acosta et al. (2018) discussed the feasibility, limitations and challenges of using GEP systems in the Mexican content. A numerical analysis of the thermomechanical behavior of an isolated pile with diameter 60 cm and length 15m was made. They adopted 2D Plaxis Thermal FEM software to simulate an isolated GEP in a typical sandy Coatzacoalcos soil of the Veracruz state. Different combinations of thermomechanical loads were adopted, with the GEP loaded at working conditions with safety factors of 2.5 and 5.0. A constant soil temperature of 26.7°C and thermal loads at 0.5 °C/day have been applied. The results demonstrated that the magnitude of the thermally induced stresses was significant, but their effects on the thermomechanical behavior of the foundation depended on the magnitude of the applied load. They found that the thermal loads represented 6 to max. 27% of the mechanical applied load depending on prevailing designed safety factor of the pile, but their effect was limited because positions of maximum mechanical and thermal loads did not match along pile length. The results also indicated small increments of around 40 kPa/°C during loading, with relatively free pile conditions to expand during heating (11% of fully restrained conditions). The authors stated that laboratory and field investigation are required to well characterize the behavior of the Mexican national soils under thermal conditions, hence awareness and widespread promotion of this new technology is required. They concluded that the application of GEPs is economically feasible in at least nine states of Mexico, and that a long-term research program on energy geostructures is indispensable for the country.

Rotta Loria et al. (2018) complemented the previous work from this same research group (Rotta Loria & Laloui 2017) in which design charts for displacements of GEP groups were developed via displacement interaction factors and elasticity theory. In the present contribution two analytical elastic models have been applied for analyzing the vertical displacement of thermally loaded energy piles groups, based on the preliminary analysis of a single isolated GEP. The layer and the continuous model have been extensively described and directly compared with numerical 3D COMSOL FEM analyses for a single and two adjacent GEPs of 1 m diameter, slenderness L/D ratio of 50, and varying relative spacings from 1 to 5. According to authors, the layer model assumes that the soil around the shaft of piles subjected to loads that induce vertical deformation may be idealized as consisting of any number of concentric cylindrical elements, with shear stresses distributed on the surface of each element, whereas the continuous model assumes that the continuous distribution of the shear stresses at the pile shaft can be approximated as a distribution of point loads acting at the center of the elements composing the piles, as if they were linear entities generated by nodes. Both models are capable of estimating vertical displacements with depth of a single GEP and a group, and to define the interaction factors with depth between them via simplifying hypotheses of identic, isotropic, homogeneous soil, under uniform temperature changes, no head restraint and no slip at pile-soil interface, among other things. The radius of influence between piles in both models had to be numerically found with the FEM analyses, so to calibrate results. The direct comparison with the more rigorous numerical technique evidenced that the layer model was more realistic to provide interaction factors than the continuous model, although the agreement in both cases was fairly good. An extra analysis of a 5 x 5 square energy pile group with floating piles embedded in uniform soil, and with predominantly end-bearing piles in non-uniform 2-layer medium was carried out. Piles with L/D of 25, s/D of 3, 5 and 10, and variable pile-soil stiffness ratios were adopted. This example clearly demonstrated that the lower the values of relative spacing the greater were the group displacements. Moreover, greater were the values of the soil-pile thermal expansion coeff. ratio, greater were the group displacements too. As noticed by other authors in similar cases, the vertical displacement of the pile group was greater than the displacement of a single isolated pile representative of those in the corresponding group, because of the occurrence of pile–soil–pile interactions. Nevertheless, the max. thermally induced group displacement ratio (W/D), i.e. the relation between its displacement and pile diameter, varied from 0.1 to 0.4%, which is not so relevant in practice. They concluded that both models could be applied in design, allowing lower and upper level estimates of GEP group displacements.

Cui & Zhu (2018) evaluated the coefficient of performance (COP) of a 5.9 kW ground source heat pump (GSHP) system with multiple energy piles in a 2-storey building in UK, for 10 years of operation. 16 GEPs with diameter 30 cm and length of 10 m in a typical local stratified sand/clay/gravel layer were simulated with distinct 4 thermal periods per year, in accordance to climate conditions and building requirements. Thermal loading and recovery periods for the thermal loads in the piles have been specified. A numerical 3D finite volume method software was adopted, with a transient heat flow model given variable monthly heating and cooling (unbalanced) energy demands coming from the idealized superstructure. The effects of the soil thermal properties on its own temperature and on the COP of the pumps was investigated for the first and 10$^{th}$. year of operation. The numerical tool discretized the GEP component and the working fluid along the U-loop type heat exchanger pipe, to obtain heat injection and extraction estimates and soil temperatures along time in the soil, besides of daily pump COPs during heating (180 days) and cooling (90 days) seasons. Average pump COPs at each typical soil strata during the 1$^{st}$. and 10$^{th}$ years have also been presented and compared. The authors noticed that, after all the operational GSHP period, the soil has demonstrated no ability to recover by itself due to the building unbalanced heating and cooling demands. So, naturally the COP decreased after this period as the soil was not capable of thermally recovering. In this regard, a soil with high thermal conductivity and low volumetric heat capacity would have a better ability to quickly recover from thermal saturation, due to an unbalanced GEP energy operation. The authors concluded that in similar cases as those studied an auxiliary energy system, such as solar collector, would have to be additionally employed to charge the ground and balance the system. For a future research work, they suggested the investigation of the effect of groundwater advection on the soil temperature during the GSHP lifetime.

Mroueh et al. (2018) proposed design diagrams that could account for ground thermo-volumetric strains of isolated GEP systems and their relationship with the thermal loads, taking on account the rigidity of the overburden structure and cyclic aspects. Design diagrams were developed for isolated energy piles, with an analytical load transfer function model, and an estimated GEP of 52 cm and length of 12 m immersed in saturated sand. The GEP was mechanically loaded to working conditions at safety factor of 3, and thermally loaded to temperature amplitudes of -15°C to +15°C in relation to average. The thermal load was simulated in a 1-year operational period, with 3 distinct types of thermal solicitation, namely constant T with soil rest period, constant T with no rest period, and sinusoidal T variation (1 full thermal cycle, no rest) during the year. Besides of design charts, the authors also focused on the importance of considering temporal and spatial distributions of temperature for geothermal pile design. In this regard they have noticed that for a constant pile thermal load the presence of a resting phase has a small impact on the generated axial force. From the 3 thermal solicitations, the sinusoidal one yielded the lowest mobilized axial force on the simulated GEP. They observed that the temperature amplitude was a key factor in the analyses, but the thermal load rate was a more important variable as sudden changes led to high values of forces and did not stabilize thermally induced pile settlements. They concluded that for fixed head geothermal energy piles, the most common ones, resting phases during thermal load should be specified, as this procedure is remarkably favorable to decrease the mobilized axial forces along pile length.

Alberdi-Pagola et al. (2018a) applied COMSOL 3D FEM software to obtain g-functions for multiple precast pile heat exchangers, commonly used in Denmark. The g-functions are dimensionless response factors that describe the change in temperature in the ground around GEPs for an applied thermal load. They were established to calculate the wall temperature of a GEP immersed into a pile grid connected in parallel arrangement, with interacting thermal phenomenon. The developed g-functions incorporated both transient concrete and constant pipe thermal resistances, as well as undisturbed ground temperatures and pile-to-pile overlapping heat flows. The study aimed to numerically obtain simple semi-empirical model variables to define g-functions valid for up to 20 years operational spans in isolated and pile group arrangements. The numerical graphical output incorporated piles with quadratic shape, distinct relative spacings to each other (s/D) varying from 1.3 to infinity, and slenderness ratios from 15 to 53. 3 thermal conductivities for the ground were assumed and the piles were equipped with single-U and W-shaped pipe loops of 55 mm diameter. The radial outer, top and base boundaries were kept at a constant temperature of 10°C. The initial temperature was set to 10 °C everywhere in the model and groundwater flow was neglected. The authors concluded that the GEP heat flux model was able to yield acceptable estimates of thermal conductivity of the soil and pile concrete thermal resistance when used to interpret TRT data. Therefore, the proposed method allowed a fast and reliable assessment of the ground-loop fluid temperatures.

Alberdi-Pagola et al. (2018b) developed an optimization procedure for the sizing and arrangement of GEP groups within a GSHP environment, with superstructure seasonal heat demand loads, ground-borehole g-functions and pump characteristics. They adopted subroutine functions from the MATLAB software for the optimization of a pattern of GEP group with a (temperature/energy related) desirability function, that minimizes the number of GEPs based on g-functions thus providing overall returns of ground loop temperatures as well as long-term avg. fluid temperatures. The g-functions have already been defined in a previous paper from these authors (Alberdi-Pagola et al. 2018a). The procedure maximizes GEP spacing with the required (demand) thermal load of structure, enhancing the efficiency of the system for a given operation period. The thermal dimensioning of the energy piles is addressed by adopting conventional methods developed for borehole heat exchangers, implemented in commercial software packages. Once an energy pattern is calculated from a predefined grid of foundation piles then the desired temperatures are achieved to provide the seasonal thermal (demand) requirements of the building, knowing pump mechanical characteristics. A numerical procedure is taken to interactively calculate the desired temperature of the GEP grid with continuous variations of no. of piles, g-functions and (supplied) energy pattern, so that both primary and secondary GSHP energy systems are balanced. The authors applied the technique to estimate the operational average fluid temperature in an actual energy pile foundation project in Denmark. This project, at Rosborg Gymnasium high school, was carried out with precast driven energy piles of square section of 30 cm and 15 m of length. The algorithm was able to yield the minimum no. of energy piles required by maximizing pile spacing, taking on account the seasonal thermal load of the structure. With estimated ground characteristics from TRT and laboratory tests, pump details, and the grid pattern of the piles, the authors were able to reproduce (daily) average fluid temperatures of the GEP system during an operational 3 years of time, and to compare with experimentally measured values at site. The simulations diverged from observations as the heating need decreased in low activity or stand-by periods. In these stages, other factors, which were not considered by the model, began to play a role as possible groundwater flow, heat island effect from the building, heat gains through the building standing on top of the foundation, seasonal surface temperature variations and indoor temperature sensors measuring on standing fluid in pipes. Nevertheless, they attempted to predict for this same case history the return and avg. temperatures on a 25 years operational period, extrapolating existing heating and cooling (demand) loads. The computed return temperatures of the system were above 4°C minimum acceptable values (0°C), and steady-state avg. ground temp. conditions were established only after 15 years of operation. The optimal pile arrangement at which the desirability function was maximized counted 148 GEPs, distributed into an irregular grid, rather than the 219 originally designed and constructed ones. The results imply that Rosborg Gymnasium could be supplied to the current thermal demand with 32% less energy piles. The authors concluded that the desirability function approach and the flexibility of the proposed method allowed more, and better, conditions to be considered in future improvements of the design methodology, so to rationally optimize the no. of GEPs to supply the thermal demand of the superstructure.

Wang et al. (2019) analyzed the thermomechanical characteristics of an isolated GEP under cyclic thermal loads, with a 2D axisymmetric FEM software and a thermomechanical model. An energy pile of 1 m diameter and 40 m length was assumed with spiral-loop type heat exchanger pipes immersed in a single homogeneous soil layer. Idealized thermal and mechanical parameters from literature and design Chinese codes were adopted. Temperature induced additional displacements (from initial mechanical ones) and axial forces along the pile were analyzed with different pile head forces. The initial temperature of the model pile was regarded as 20°C. After heating, the increase in temperature was set to be 18°C. The bottom and the sides of the GEP were fixed, and the top was unconstrained. The application of cyclic temperatures for 12 h of heating and 12 h of cooling was considered with a 40 days simulation period, being 10 days of loading time and 30 days of resting period under maintained mechanical load. The authors noticed that cyclic heating and natural cooling led to additional axial pile forces and displacements along the pile depth. The additional displacements were linear with different pile loads at head, and there was a neutral point of zero displacement somewhere along the pile shaft, depending on the maintained load. The displacements on the pile had opposite directions upwards and downwards from this neutral point, as expected. The authors concluded that thermal loads at the energy pile top at which non-linear (mechanically derived) settlements begin to occur should be avoided, since thermal loads in this (plastic) range can induce irrecoverable displacements at the pile. On contrary, at the linear mechanical load-settlement curve range thermally induced displacements can be recovered during cooling stages.

Sutman et al. (2019) incorporated the soil-pile load-transfer model approach previously developed by this same research group (Knewllwolf et al. 2011) into numerical thermomechanical response of an isolated GEP. The numerical analysis incorporated the unload-reload shaft resistance of the pile during a single heating-cooling cycle into monotonic linear elastic load-transfer curves. It also assumed Masing rule to define soil-energy pile interaction during cyclic temperature changes. The load-transfer models were incorporated into a COMSOL 2D axisymmetric FEM analysis, to simulate an experimental real case of an isolated cast in place GEP with 45.7 cm diameter and length of 15.2 m, immersed in Richmond (USA) clay/sand profile. In the present analysis 3 approaches have been implemented for the load-transfer curves, namely an experimental based on field data, an analytical based on classical theory, and an empirical method based on pressuremeter test. The flow of the heat exchange fluid, or heat transfer between the circulation pipes, pole and soil were not included in the numerical analyses. The top of the pile was either free or partially restricted by a spring on top, depending on the presence of structural load during thermal cycles. The input temperature for the model pile was extracted from real measurements at the site, for each day during 1 month of readings. 37 temperature changes corresponding to five heating–cooling cycles without resting time were employed to ensure the proper link between the states of the model pile for each temperature change. The comparisons between experimentally, analytically and empirically derived load-transfer curves demonstrated that the stiffness for the analytical approach was lower than the other two, resulting in higher displacement limits on the numerical runs. Numerically derived thermally induced axial stresses, strains, and mobilized shaft resistances, during the 1$^{st}$. heating-cooling episode with the distinct idealized load-transfer mechanisms, were compared to measured field data. The axial strains from the idealized models were reasonably well compared to field points, but mobilized shaft resistances were higher than field results at the extremities of the pile, and lower towards the neutral point. The estimated displacements related to temperature variations were generally minor compared with what a structural load would yield, suggesting a good GEP response. The authors concluded that the distinct load transfer models yielded disparate results, revealing that assigning an accurate resistance limit for the load-transfer curve is essential. Nevertheless, the use of this approach seems to be suitable for the preliminary design of energy piles, if one takes on account that, with the presence of an structural load, a higher portion of the GEP may exceed axial displacements that could be represented by the idealized linear elastic load-transfer relationship. However, the methodology may eventually not properly capture the continuous displacement of GEPs subjected to unbalanced cyclic thermal changes.

## I.4 Key findings on miscellaneous knowledge related to soils and GEP systems

*Miscellaneous Knowledge (Table of Annex I.4)*

Rawlings & Sykulski (1999) presented a literature-based review on ground source heat pumps (GSHPs) with focus on applications, and concentrating on closed loop and ground couple systems, looking into benefits and costs. According to these authors the first documented suggestion for using ground as heat source was in 1912 in Switzerland, but at that time heat pump efficiency was poor and energy prices were very low. Commercial use started only after the first oil crisis in 1973, by which time there were around 1000 GSHP systems in Sweden. In the UK ground as a source of heat pump was first used for space heating in a single-story house in the mid 1940´s. The first GSHP in USA was installed in Indianapolis in 1945. The design of such systems requires detailed analysis of building load, energy consumption and cost-efficiency study. Nowadays it is best carried out by electronic computer aided software, besides they often perform narrowly focused tasks. Residential and commercial systems with GSHPs have an ang. Energy savings of 52% when compared to heating with electrical resistance, and the lifetime of a heat pump is around 15 years whereas the ground coils can be extended to 50 years. They concluded that in countries where GSHP sales are high there are extensive support from governmental policies, either by direct subsidizing implementation, by promoting research and development, or as part of a national effort to increase the use of a renewable energy platform towards the decrease of CO2 emissions.

Dincer (2000) describes the relation between renewable energy and sustainable development, presenting successful practical cases in this direction. Since a sustainable development requires a supply of sustainable energy resources, the main objective of the paper is to discuss environmental problems and to identify possible solutions focusing on renewable sources and technologies. It also anticipates patterns of future energy use and the consequent environmental impacts that the world may suffer given the escalating emissions of greenhouse gases (GHG). For instance, given the GHG the earth´s surface temperature has increased about 0.6°C over the last century. Major areas of environmental problems are described, as well as possible solutions with future use of sustainable sources. According to these authors the global demand for energy services is expected to increase by as much as one order of magnitude by 2050, while primary energy demand is expected to increase by 1.5 to 5 times. Therefore, an integrated set of activities should be hosted by governments, as the research & development of sustainable energy sources, technological assessments, development of standards, and transfer of knowledge to society. Some factors can however quickly enhance a sustainable global development, as public awareness, continuous environmental education and training, adoption of innovative energy strategies, promotion of renewable resources, financing, monitoring and development of evaluation standards and surveillance tools, and encouraging policies by part of public agents.

Spitler (2000) presented the technical basis of the program GLHEPRO used to design borehole heat exchanger (BHE) systems together with an example of use for a building in Ottawa. The design methodology is based on a simulation that predicts the temperature response of the BHE to monthly cooling and heating loads and peak loads over a period of years. The design automatically adjusts the BHE size to meet user-defined minimum and maximum heat pump entry fluid temperatures so that heat injection or extraction in the soil is balanced with heat/cooling loads required by the building. In essence the design process is based on a balance of energy, from one side the temperature of the fluid entering the pump via BHE heat transfer model & size/soil factors (with empirical estimations of the single borehole heat extraction/rejection rates per meter), from other side the same entering temperature that supplies the required thermal loads of the superstructure, that is based on pump characteristics and the relation of extracted soil heat x known building heat load (supplied by pump). It is an interactive process dealt by the software GLHEPRO.

Ahu-Hamdeh (2003) studied through laboratory tests the effect of water content and bulk density of the soil in its specific heat capacity and thermal diffusivity. He noticed that clayey soils have in general higher specific heat and volumetric heat capacities than sandy type ones for the same water content and density. The results also showed that thermal diffusivities vary with moisture content and soil texture. Empirical equations for the estimation of the thermal properties of the soils have been also provided.

Sanner et al. (2003) reviewed the early development of ground source heat pumps (GSHP) for commercial buildings in the Rhein-Main area of Germany, giving details of early developments in terms of plants, problems and special circumstances that arose during their implementation. For instance, the first GSHP of the Wetzlar area, birthplace of BHEs in Europe, was constructed in the Verolum plant unit. The owner of this plant, Mr. Helmut Hund was convinced of the potential of this new technology in the early 80´s and started research and development with support of the German Federal Ministry of R&D and Justus Lieb University. In 1985 a full-scale field experiment was installed adjacent to the Verolum building, studying two types of BHE in this installation, and opening space for the employment of this technology of building climatization in Germany and in Europe as well.

Boguslaw & Lukasz (2004) evaluated the thermal conductivity of soils through an extensive review on estimation methods. Several theoretical and empirical methods have been presented and tested against experimental values of thermal conductivity. They noticed that whereas heat capacity can be estimated with fairly good accuracy, there are still problems to estimate thermal conductivity on existing techniques. They concluded that the presented analytical methods can be alternatively used to determine the thermal conductivity of soils if no high temperature gradients occur in the soil and if it can be assumed that the effect of water vapor on the overall conductivity is neglected.

Clarke et al. (2008) described a new method to determine the thermal properties of samples of soils from routine geotechnical investigations, with a thermal cell. The schematics of the test and key components, the testing guidelines and the theoretical equations behind the interpretation were given. In this apparatus the temperatures within the bottom platen, at the base of the specimen, and at the top of the sample are measured together with the power consumption. While the ends of the specimen are maintained at different temperatures, heat can flow axially through the specimen in a 1D conduction type direction. Variation of temperature with time is determined so that theoretical equations can be applied. The authors noticed that the thermal conductivity varied with water content, density and mineralogy, and the test results yielded similar values to generic published data within 0-5 W/mK.

Boennec (2008) published a paper focusing on the challenges, opportunities and progress of the ground source heat pump industry in UK. According to this author in UK there is not a definitive design standard as in Germany or USA for GSHP, which is a challenge for the industry, in especial because as of 2007/8 the env. agency recognized “temperature” as a potential pollutant. For instance, with more systems designed together there is a risk of long-term below ground “global warming”, as it has happened in the

Stockton College project in New Jersey. His conclusion is that shallow ground energy systems are a very dynamic and exciting area of the civil and building industry that requires much more investment in training, research and development, so to offer to society a valuable high value product that combines sustainability and energy generation. Nevertheless, the technology was still new to the UK at the time of this publication.

Banks (2009) presented the background to the science of “thermogeology” and its importance in the proper exploitation of ground source heat. The paper reviews basic concepts of geohydrology as the geo-environmental heat reservoir and heat pumps, the exploitation of ground source heat via open and closed loop systems and described the key analogies between groundwater flow and heat conduction theories. For instance, the heat conduction is governed by Fourie´s law and is directly analogous to Darcy´s laws of groundwater flow. According to this author the shallow geosphere represents a thermal store that can be used for heating and cooling purposes, and thermogeology is just one of several key skills needed to design a GSHP to extract or reject heat in the ground. The hydrogeologist needs to interact with mechanical and electrical engineers, architects and planners to ensure effective collaboration in the design of such systems, recognizing the limits of this technical field.

Moel et al. (2010) presented an extensive literature review on the technology behind the GEP system and its current usage and potential feasibility for application in Australia. Environmental considerations including performance-dependent parameters of the subsurface are described. Temperature and ground water effects are also discussed, and design considerations are provided. The benefits and limitations of implementing these systems are summarized and the feasibility of GEP systems in Australia is explored. According to the authors, the major drawback in terms of design is the lack of a theoretical model to predict performance that can consider all the parameters that effectively affect the GEP system on the long run, as site thermal imbalances. They sustain that the Australian continent is vast and founded on distinct geological features, making imperative a better understanding of local specific geotechnical, hydrological and thermal conditions to better assess the performance of such systems, nevertheless in remote towns the GEP could be beneficial given its self-sufficiency and decentralized character. They conclude on the fact that potential challenges on long-term effects on ground temperatures, and other related environmental impact issues, must be better understood before further progress can be made with GEP systems for superstructure climatization.

Hueckel et al. (2011) investigated the effect of the temperature dependence of the internal friction angle of the soil in a medium influenced by a cylindrical heat source. The study was based on problems commonly found on buried structures with nuclear waste, that acts as heat source to the surrounding ground. They presented numerical analyses on the effect of temperature in terms of the time-dependent heat conduction, and permeability-dependent rate of dissipation of the thermally generated pore pressures of the soil. They noticed that the thermal increase of the internal friction angle was quite modest, say less than 20% in terms of the critical state parameter at 70°C, but it was enough to change/deviate the effective stress path of the soil near the heat source, approaching it to geotechnical failure conditions. At the onset of yielding occurring after 30 days of heating there was an abrupt and quite substantial change in axial effective stress distribution at the zone of influence of about 1.6 m in diameter around the heater. They concluded that designing heat source spacing based on field temperature alone can be inadequate, as thermoplastic effects increase thermally induced pore pressures and hence water flux. This short duration pore pressures increase can cause the eff. stress path to approach the critical state, surely reducing the structure's margin of geotechnical safety.

Haigh (2012) developed an analytical model based on unidirectional heat flow through a 3-phase soil element to determine the thermal conductivity of sands. Model results were compared against a large database of 155 test data and empirical predictions, demonstrating that the proposed method yielded lower errors in its predictions as compared to other (empirical) equations, for sands and void ratios greater than 0.33. Nevertheless, for void ratios lower than 0.33 the proposed method is unable to predict thermal conductivities. The authors noticed that the thermal conductivity increased with the degree of saturation of the soil, and with the decrease of its void ratio. They concluded that the proposed analytical method is better than the best empirical approaches in literature for a wide variety of sands.

Bourne-Webb (2013) described several literature results to draw out some significant responses on the behavior of GEP systems, and to identify gaps in knowledge requiring further research. According to this author, the main barrier to today´s better understanding of such structures is the lack on an extensive international database on well documented case studies on GEP testing and life performance, thus preventing a clear demonstration to clients, professionals and stakeholders that such technology is safe, viable and economic. It also prevents a better modelling of the technology, particularly on design and field performance efficiency. Moreover, there is a lack of design philosophies for GEPs since borehole heat exchangers may not be fully appropriated. Boundary conditions do affect the GEP axial stress and strain response, hence field tests should be interpreted and back calculated with care so to be used as guidance for GEP design, since real piles under restraining superstructures may behave in a distinct manner. Degradation of the pile resistance can be also a concern given the cyclic thermomechanical loads that are imposed on GEPs during their long lifetime. There is also a large influence of the boundary surface conditions on the axial stress response of GEP system during thermal loads. This effect does require attention on how field tests are interpreted and back calculated to be used in energy foundation design as an exposed pile head may not be applicable to piles rigidly fixed under a structure. The author concludes that it would be useful to establish a set of protocols with a common format for the design, execution and monitoring of GEPs for research groups willing to advance the knowledge on this particular technology – perhaps sponsored by an International Agency or a Learned Society as the ISSMGE.

Arboit et al. (2013) presented a literature review on known resources and application possibilities of geothermal energy in Brazil, at high and low enthalpy modes. According to these authors, South America has great part of its plate in a stationary mode, hence Brazil, situated in its middle, has more favorable conditions to explore low rather than high enthalpy energy sources, suitable for GEP systems. Nevertheless, given the predominance of hydric power and availability of other sources as natural gas, Brazil places geothermal energy to a secondary position. Low enthalpy resources have been identified in large number in parts of the Middle West and South of Brazil. At moment, studies are underway for thermal exploration of the extensive Guarany aquifer (840800 $km^2$) for heating purposes of water and agro-industrial processes, since this aquifer contains reservoirs of low enthalpy and with low thermal gradients, which turns it unable for electrical energy exploration. The use of geothermal low enthalpy energy for direct use, rather than for electricity, is still incipient but quite promising in special for GSHP systems with heating purposes. This may be the case of the Paraná basin (south and southeast of Brazil) where subtropical climate prevails.

Low et al. (2015) investigated two different laboratory methods to obtain the thermal conductivity of the soil, namely the steady state thermal cell and the transient needle probe. They noticed through several experiments that the thermal cell yielded consistently higher values, for instance around 40-50% higher than the needle probe most probably due to heat losses and radial x axial heat flow directions (hence anisotropic influence of the sample). The needle probe has fewer significant sources of errors but tests a smaller sample of soil than the thermal cell. On the other hand, both laboratory techniques gave much lower conductivities compared to the in situ thermal response test (TRT), as the latter technique gave almost twice values as the laboratorial experiments. This was caused by the fact that the TRT is a transient field test that takes on account a larger volume of soil, groundwater flow and layering conditions. They concluded that the TRT yields an overall better measurement on thermal conductivity besides being more expensive and time consuming.

Li & Lai (2015) critically reviewed the analysis method of heat transfer by borehole and pile ground heat exchangers, emphasizing the analytical models. They summarized, discussed and evaluated the major advances in this field including heat-source models, short-time models, energy pile models, and in situ TRT´s / parameter back-calculation. They reviewed a set of representative reports from 1990 to 2012 and focused on closed loops exchangers, more precisely borehole and foundation ground heat exchangers or GEPs. For GEPs several simplified methods have been developed to account for the heat transfer process, assuming for instance the concept of a steady state thermal resistance, or of the heat source method, or even empirical expressions for the temperature response. The usefulness of in situ TRTs is overestimated according to these authors, since from the point of view of model validation the data is inappropriate because the thermal properties of the soil are unknown and various incontrollable testing uncertainties do exist. Estimation of the thermal properties of the soil is actually an inverse problem of heat conduction. Besides, given the steady state assumption, the TRT method can only use the late stage of the test curve. The most widely used analytical tool for analyzing the heat transfer in a ground heat exchanger is the Kelvin´s theory of heat source on Laplace transform method. The authors concluded that the complex thermomechanical processes that occur in energy piles are far from understood, although recent progress in the heat transfer analysis of energy piles do provide a good starting point for solving this problem. One critical process is how the periodic expansion and contraction of concrete columns caused by heating and cooling processes affect the frictional forces of foundation piles, especially in the long-term system´s run.

Vieira et al. (2015) carried out an extensive assessment of the geothermal resources in Brazil, including recent surveys in the states of Tocantins, Mato Grosso and Pará. The paper results from data collection from 1100 sites as well as information on hydrothermal and energy use on 110 localities, all at an accessible depth limit up to 3 km. According to these authors, in this depth range, the total capacity of the low temperature geothermal systems under economic exploitation is estimated at 365 MWt, while an annual energy use should be around 6540 Tj. The authors concluded that the thermal sites are predominantly used for bathing and recreation despite their considerable potential for industrial applications and space heating. The Precambrian areas of the state of Goiás and Tocantins have been considered by them to be suitable for energy exploitation.

Sailer et al. (2015) compared distinct design procedures for vertical borehole heat exchangers (BHEs) in the light of different standard guidelines. In fact, distinct simplified and analytical procedures currently existent under European and USA guidelines, leading to differing assumptions and design parameters. The design depends on heating and cooling loads, the heat pump characteristics, ground parameters and parameters of the heat exchangers. They showed that most of the design methods relate to estimated values of heat extraction and ground conductivity, but the latter variable is mostly affected by thermal capacity, operation hours, BHE interferences, diameter, disposition and fill material of the borehole. The BHE length is generally determined with simplified equations and a tabulated heat extraction rate from the ground, according to existing guidelines. The determination of the heat extracted from the ground also uses simplified equations, based on pump characteristics as the coeff. of performance, the seasonal COP, hours of working and heat capacity. The results of a sensitivity analysis for a typical dwelling in London showed that the length of the BHEs could vary as much as 43%, depending on the guideline. The authors also observed that the right size of the system determines the long-term performance, and prevents collateral thermal effects, besides of guaranteeing high seasonal efficiencies. However, it has been shown that the size of a BHE depends on many parameters, some of which are not considered in all the identified guidelines. Another aspect of importance is the estimated energy demand of the system, since it has a major impact on the final dimensions of the designed BHEs and therefore needs to be carefully assessed. They concluded that given all the inherent uncertainties in designing using tabulated values, and the relevance of certain input parameters, it appears that analytical methods provide the most methodical form of designing BHEs for small systems. They concluded that ground parameters need to be evaluated with as much in situ data as possible, to ensure a sustainable and efficient BHE performance throughout the design life of the system.

Alkaff et al. (2016) presented an extensive and very interesting review on the underground structures that have been constructed in historical times with climatization purposes. The paper proposes a conceptual design of earth sheltered homes, and summarizes sheltered buildings worldwide constructed with some sort of thermal efficiency. The authors demonstrated that underground structures were originally found to be built for shelter, warmth and security against animal attack. Most of the ancient underground homes were in hot and arid countries, so the technique was initially applied for cooling purposes. The ancient wisdom of using the earth as temperature moderator against harsh weather has historically had an impressive potential to be used as the most efficient and cheap solution against other more inefficient ways of climatizing the system. They observed that one of the earliest cases of using such technique was found in excavations in the city of Kamitakamori, Japan, where 600.000 years old buried structures have been recently found. They have been used as shelter to rest, to conduct religious ceremonies and to store tools. More recent 20th – 21st. century underground buildings are also summarized, reinforcing the idea that mankind has always resorted to underground constructions as a way for a sustainable energy use in climatized inhabited structures. The authors concluded that underground structures show great potentiality to encourage sustainable development by increasing the surface plantation area while simultaneously minimizing the building´s energy consumption.

Lanahan & Tabares-Velasco (2017) evaluated systems for thermal energy storage, critically assessing their modeling, design and efficiency. According to their review the energy storage is most effective when diurnal with seasonal storage, and borehole thermal energy storage systems (BTES) are more widely used for heating than cooling. BTES effectively provides large amount of heat storage despite reduced the specific heat of the storage medium, mainly because of easily increased storage volume. In this regard, Switzerland is the world leader in BTES with an annual geothermal heat of around 1 TW. BTES can be coupled with ground source heat pumps (GSHP) in several manners to efficiently climatize the structure. GSHP and BTESs can also be coupled with solar thermal energy, so to maintain better soil temperature balances and to allow pumps functioning at high coefffs. of performance over lifetime. Since water thermal pollution can have negative impact on the environment, being harmful to many species, coupling BTES with solar panel systems are beneficial too. The authors noticed that the path to an effective thermal energy storage system design is by thorough evaluation of environmental site characteristics and soil properties. Proper design practices should integrate diurnal and seasonal storage so to yield a higher system´s performance. The modeling tools can range from in-depth analysis allowing for subsystem design, to whole building simulations that incorporate simpler subsurface heat transfer models into energy design analysis. A careful review on previous studies highlighted the fact that community scale BTES would require a "charging" period of few years for the design system´s optimal temperature to be reached, and most single residential scale BTES often do not require solar thermal panels because of low system demand, which thermal regeneration in the ground can occur naturally. They concluded that the energy storage is a critical component for future renewable energy grid performance, and that such technique presents considerably lower capital cost than other ways.

Fadejev et al. (2017) conducted an extensive review of all available scientific literature, design standards, guidelines and models on energy piles performance, configuration and design. Typical plant solutions, arrangements, thermal response test values, available numerical and analytical techniques and commercial softwares have been listed. According to these authors the GSHP capacity has grown 2.15 times during the years 2005/2010 and are currently adopted in around 80 countries worldwide. There is an abundance of research on borehole modeling, but energy pile modeling is much less studied. There is also a small amount of information regarding measured long-term performance of energy pile systems, but it seems that thermal interaction between piles appear when the distance between them is at least equal to the pile length. The thermal activation of all piles in a group may eventually not be efficient, so it is better to not activate all of them at the same time. For pile groups it is important to account for the thermomechanical behavior, and it is known that a properly sized GEP system should be characterized by overall system´s coef. of performance higher than 4.5. Thermal response tests can be performed to obtain site thermal properties for ground interpretation and modeling, and TRT results show that short term specific heat extraction/rejection rate is highly dependent on the amount of pipe surface area grouted into the pile structure, however the long term performance is more limited by the soil heat capacity. Software with no coupling capability with building simulation need interpretation of the building heating and cooling demand data in an hourly or monthly time basis. Most flexible software packages can be coupled with whole building simulation, and can be used for customized detailed plant modelling, nevertheless these software packages have a long learning curve and only experienced users are expected to utilize most advanced features. The numerical analyses should also account for the importance of heat transfer through the ground base floor of the structure when sizing GSHP systems with GEPs. They concluded that energy piles are frequently misinterpreted as boreholes, and design guidelines, sizing manuals and standards are available mostly for boreholes as well, thus enhancing the need to develop general procedures for early stage energy pile sizing that would allow quick estimates of required pile lengths and system performance with reasonable accuracy within the system´s conceptual design.

Vieira et al. (2017) carried out an extensive bibliographic review on the main methods and procedures to assess ground thermal properties for shallow geothermal energy systems, critically discussing most common thermo-hydro-mechanical processes and behavior for soil and rocks, usual laboratory and in situ thermal testing techniques, and the effect of scale in the determination of the thermal properties. The authors explored both steady-state and transient methods employed in the interpretation of laboratory testing results, comparing them with in situ testing derived values as those originated from thermal response tests. The focus of the paper is on the key thermal properties adopted in BHE designs, as the ground thermal conductivity and the ground heat exchanger thermal resistance. The importance of this thematic is quite high nowadays, given the target in Europe to transform the geothermal technology into a significant energy resource towards 100% of renewable heating and cooling scenarios by 2030. Based on the review the authors observed that here is a move to determine the thermal conductivity in soils through several techniques. They concluded that the large-scale TRT is a more representative manner although being more expensive and time consuming. The pile TRT for the GEP design can also be done in routine practice, but with a commitment to more time-consuming analyses such as numerical simulations to back-calculate the thermal parameters. Laboratory tests can be steady-state or transient in terms of the heat flow conditions. Steady-state tests require good experimental design to prevent excessive heat losses. They also require relatively long durations (hours) which means that moisture migration can occur in partially saturated samples. Therefore, for partially saturated fine soils, steady-state methods can overestimate the thermal conductivity if excessive heat losses occur, but it is perhaps more likely to underestimate due to moisture migration and sample drying. While transient tests (which occur in minutes) overcome both issues, they test a small and hence less representative volume of soil. The transient laboratory testing is preferable for fine sources and partially or fully saturated sands, and steady state testing is acceptable in dry sands and for coarser soils. Field tests generally lead to higher values of thermal conductivities when compared to laboratory ones. In terms of the behavior of energy geostructures, the thermal loading affects the hydro-mechanical behavior of both soil and structure and adds additional challenges for the estimation of the thermal properties. They finally stress that the complexities of accepted constitutive models remain a large academic pursuit in terms of daily use and parametrization and is a major challenge in practical GEP applications. The authors concluded that, given the absence of routine commercial test methods, those involved with structural design in practice will no doubt be required to make assumptions and potentially derive material parameters from the academic literature. Overcoming this gap remains the largest current challenge for the research community, and it will need to progress in parallel with the development of appropriate design methods and programs.

Brito et al. (2017) presented suggestions to improve the current Brazilian standard of thermal performance of buildings. They stated that the thermal response of an edification is not much affected by the superficial soil´s temperature when it varies around 2°C. In this respect it is possible to estimate such temperature via empirical correlations with known values of the average monthly air temperature of the region, either in summer or in winter conditions. Therefore, initial simulations of structural performance in regard to the energy demand could take advantage of such empirical approach, as the soil´s temperature, differently from the air temperature, is rarely measured or known. They also observed that it is paramount to consider climatic conditions, solar orientation, external colors, occupancy, ventilation, geometry and a standard 1 m/s wind velocity in the simulations of the thermal performance of edifications. They concluded that it is necessary to reassess or complement the climatic data from the Brazilian distinct regions, as the soil temperature under the building structures and the temperature from cities in bioclimatic zones that are not currently encompassed by the Brazilian standard.

Tsagarakis et al. (2018) presented an extensive overview about legislation issues on shallow geothermal energy systems (SGE) in Europe based on the individual reviews from

14 countries, i.e. Croatia, Cyprus, France, Greece, Italy, Latvia, Lithuania, Poland, Portugal, Serbia, Slovenia, Spain, Sweden, and Turkey. The authors discussed key national legislation issues as well as main points to be addressed in the eventual procedure of SGE integration in legal and technical issues. They noticed that a high diversity exists on legislation provisions together with regulation standards and institutional support amongst European countries. The diversity acts more as barrier for further development on the SGE market rather than encouraging integration. In this regard the authors emphasize that a specific and detailed legal framework is mandatory. Moreover, some fundamental steps must be taken to improve the effectiveness in design, construction and operation of SGE systems, namely by enhancing their awareness, their standardization issues, their common and understandable legal framework, and the mutual operational and administrative procedures within the global European market. For instance, one initial and single step relates to definitions, that means, each country has its own definition of shallow geothermal energy system that, obviously, must be unified. There is a diversity of denominations and a lack of relevant guidelines and rules for investment, operation and commercialization. Each country has also its independent criteria to be considered during permission of installation of SGE systems, which differ widely across the European continent. Lack of a recognized and grounded experience in promotion of this new technology is also noticeable, due to the relatively new application period. According to the authors the main effort to overcome the existing legislation barrier situation should be a common European regulative framework, in order to homogenize the latter in the different European countries. Furthermore, improvements in technical terms are also necessary, as the basis for standardization have been developed so far due to EU and other national initiatives. It is important to observe that the lack of a proper environmental provision can cause significant environmental issues and possible operational problems as losses in efficiency, lifespan etc. The authors firmly stated that it is also imperative that a common EU directive is placed to guide procedures and standardization of personal training, operation and design rules so to create a harmonized atmosphere in Europe for SGE application, as usually done in other fields of the civil engineering. They concluded that such constraints strongly affect stakeholders and consumer confidence in the technology, and severely hampers its further diffusion in Europe and elsewhere.

Sani et al. (2019a) presented an extensive review of literature on current principles and knowledge behind different design considerations, standards and government legislation for GEP systems. They discussed on detailed and general topics that are related to the design and implementation of GEPs, as the technological background, the environmental factors that affect the system´s performance, design considerations, thermomechanical behavior of installed GEPs, thermal performance of GEP systems and future prospects & research focus on this technology. From the review it is found that thermal properties are essential in design but affected by several factors, including testing techniques. Key findings on laboratory and field studies on the thermomechanical behavior of GEPs are thus provided. The thermal performance of the GEP system is also reviewed with literature case studies. The authors pointed out that the design must be made with an integrated assessment of the structure´s demand and the GEP´s predicted supply capacity in terms of thermal loads. Furthermore, emphasis should be placed in making sure that the foundation elements are not imposed with an excessive thermal load that is beyond the design capacity, rather it should be maintained within acceptable limits. Through a controls system, acceptable temperature limits should be set to enable a system switch off to guarantee long-term system performance, thereby protecting longevity and efficiency of the GEP system for the long life of the building. Additionally, a numerical modelling and simulation of the project, particularly projects of larger scale, comprising of the components of the GEP unit system (pile, pipes and heat carrier fluid) should be carried out with the total energy demand superimposed on the GEPs. This could be done with commercial numerical tools, thus allowing a better picture of how the system will perform under long range working conditions. This is the case since performance of the system can vary and was shown to depend on several factors as loop arrangement, position, fluid flow and type, diffusion aspects of the GEP elements and geological and hydrogeological conditions. Pile dimensions and pipe surface area also play a major factor on that. Heat fluid velocity is the least important factor. Using foundation elements as heat carrier bodies makes perfect sense and provides an ideal engineering-friendly and sustainable solution. They finally emphasize that future research should focus on the understanding of the behavior of such systems on a global scale and the effects of cyclic saturation and desaturation of GEPs. A simple user-friendly numerical tool to analyze the integrated coupled superstructure-foundation system is required, together with ways to encourage patronage of GEP systems worldwide.

# I.5 Key findings on research theses in Brazil and Portugal about GEP systems

*Key Findings on Research Theses (Table of Annex I.5)*

Assunção (2014) defended a MSc Thesis in the Technical Superior Institute from Lisboa, Portugal, in which a numerical study of a thermal active pile was performed using the numerical software ABAQUS 2D axisymmetric mode with the finite element model. The thermal analysis focused on some of the modelling aspects of the GEP problem such as the simulation of the heating of the pile and definition of the ground surface temperature. The thermal-mechanical analysis studied the effect, in terms of thermally induced stresses in the pile, of the relationship between soil and concrete coefficients of thermal expansion, of the ground surface temperature, and of the pile length to diameter ratio. The author has concluded that the relative values of the coefficient of thermal expansion for the soil, and the concrete, play a key role in dictating the direction and the magnitudes of the developed stresses in a pile subjected to thermal loading. If the soil is more thermally expansive than concrete, the ground surface temperature has a very important influence over the thermally induced stresses developed in the pile. For the same pile diameter, the longer the pile, the larger the thermally induced stresses will be. This phenomenon was believed to be caused mainly by the increased shear stress mobilized at the pile-soil interface which increased restraint on the pile. The author finally recommended that numerical simulations of energy piles should pay close attention to the correct definition of the ground surface temperature. Future recommendations on the subject are given, with particular emphasis to the study of the behavior of thermo-active piles through time via cyclic thermal loads according to heat and cooling systems, and the investigation of the influence of the soil and pile-soil interface thermal stiffness.

Bandeira Neto (2015) defended a MSc Thesis in the University of São Paulo – Escola de Engenharia de São Carlos, in São Carlos, Brazil. This study focused on the evaluation of the thermal response of isolated energy piles in an unsaturated tropical soil of Brazil, typical to many other parts of the countries' territory. According to the author, this was the first assessment of thermomechanical performance of heat exchanger piles in typical Brazilian soil and climate. Five field thermal response tests (TRTs) were conducted in the geotechnical research site of this university, composed of an unsaturated tropical medium that includes a superficial layer of colluvial clayey sand overlaying a residual sandstone saprolitic soil. The TRTs were performed on two drilled piles of 12 m length and respectively 25 cm and 50 cm diameter. The main objective was to obtain pioneering data about the thermal energy delivered by energy piles in the investigated soil and climate conditions. The effects of ground water table, flow rate, duration of the test, and number of heat exchanger U-pipes on the thermal properties of the energy pile were also evaluated in this study. Thermal variables for the soil have been provided with the research, being of great interest to further numerical simulations of GEP units in cooling GSHP systems in tropical and subtropical Brazilian cities. The derived heat exchange rate varied from 79 to 110 W/m, which is comparable to other commonly studied (saturated) sites from abroad. The authors have experimentally demonstrated that the increase of the diameter of the pile and quantity of heat exchanger pipes is beneficial to the heat flux. A thermal influence zone of around 4 pile diameters around the pile center has been detected, where thermal interference may be expected. The study finally demonstrated that GEPs in Brazilian tropical unsaturated conditions may be feasible, with good heat transfer potential for design purposes.

Orozco (2016) extended the results from the TRT tests from Bandeira Neto (2015) to other non-studied conditions for similar ground and system conditions. Through a joint cooperative work between the Universities of São Paulo and Brasilia, both in Brazil, the former author was able to use the thermal properties obtained in São Carlos, to calibrate and perform sensitive numerical analysis of the thermal response of energy piles immersed in a typical tropical Brazilian unsaturated soil. For the numerical analysis the COMSOL 2D finite element axisymmetric heat transfer and non-isothermal pipe flow modules were used and calibrated against the experimental site data. The thermal response, or heat flux variation, in the isolated GEP due to soil and concrete properties, pile geometry, groundwater level, pipe thickness and heat carrier fluid rate, were thoroughly evaluated. An additional assessment of the optimal relative distance between GEP piles in a group, given described thermal conditions, was further provided so to direct future investigations on the performance of pile groups within the Brazilian context. The analyses indicate that the flow regime was the principal variable to influence the final heat flux derived from the isolated pile, although other variables are also of importance for the improvement of the thermal efficiency of the system. Actually, there is a balance between flow, number and configuration of heat fluid carrier pipes and the derived thermal efficiency, that shall be searched for the given design conditions. The heat flux has also been shown to be quite sensitive to the temperature difference soil-fluid at the distinct stages of the numerical calibration of the model.

Sousa Júnior (2017) defended a MSc thesis at the University of Brasília extending previous work from Orozco (2016) in the same university The former author used the same numerical modelling technique as before, however with focus on the typical unsaturated porous soil deposit of the Federal District of Brazil. Since thermal properties of this material are not experimentally known, the author has inferred the thermal variables via recognized empirical relationships with the soil´s variable mineralogical content. For the particular subsoil conditions there is a predominance of the clay mineral caulinite, and oxides and hydroxides of iron and aluminum, besides of silica grains. In localized points of the Federal District, as in the at the research site of the University of Brasilia, a typical surficial layer of clayey sand on top to another of sandy clay with high porosity and low bearing resistance (total ≈10 to 20 m thick), that overlays a saprolitic/residual material derived from weathered slate, the mother rock of most of the region. Parametric analyses for 50 hs of continuous thermal operation of GEP groups at distinct configurations, from isolated conditions to 3 x 3 arrangements, were performed. Distinct pile diameters (from 30 to 60 cm), pipe loop configurations (from U to 3U), and soil humidity conditions were considered. In the latter case, maximum and minimum recorded experimental values were evaluated. The author observed that the thermal efficiency depends on the arrangement of the pile group, and the relative position of the piles among each other. Higher distances between piles do increase the thermal efficiency of the system, decreasing thermal interference, but this may be unfeasible given local foundation practices. The piles are thermally inter-related, forming thermal bulbs that decrease the heat exchange phenomenon. Besides, systems with more interconnected pipes in the same pile have more thermal interference, loosing efficiency, but this depends on the diameter of the pile itself, and the relative distance between pipes. For instance, for 30-40 cm diameter GEPs in this stratum it was noticed that 2-U loop configurations are enough to provide a high heat transfer with the surrounding soil, if 4 or more piles are thermally active in the group. Soil humidity is also of importance for thermal efficiency, although this variable cannot be directly controlled in the field. The heat flux of the GEP was shown to be controlled by the contact area between pile surface and soil, by heat interference from downwards and upwards fluid flow within U pipes, and by thermal overlapping effects between piles. It was finally concluded that, by assuming that thermal conditions of the study are accurate, the typical soil of the Federal District has potential for heat exchange with GEP systems, being technically feasible to be employed with this technology albeit unsaturated and porous. The thesis provided encouraging motivation for further research on the subject, particularly focused on real scale tests and laboratory assessment of this soil´s thermal parameters.

Ferreira (2017) defended a MSc thesis in the State University of North Fluminense, in Brazil, in a similar line as the thesis previously defended in São Carlos, where TRT were performed on the local soil. In this work the thermomechanical behavior was evaluated in 2 TRTs with a single-U loop pipe within a pile of 40 cm diameter and 12 m in length, immersed in Campo dos Goytacazes sandy silt sedimentary deposit. The TRTs had two distinct water flows, time intervals (140 x 115 hs) and thermal loads so to assess in different manners the heat flux per meter, the thermal conductivities and resistivities of the system. The field data was evaluated by the line source model to determine thermal properties of the energy foundation system, being clearly noticed that the thermal load caused changes in the energy pile stresses and strains, that were consequently monitored. In both tests there were obtained thermal parameters suitable for the use of energy piles. Average values of heat flux of 40-46 W/m, ground thermal conductivities of 2.1-2.4 W/mK and resistivities of 0.43-0.41 mK/W were respectively obtained. It was also noticed a growing pile deformation with the evolution of the test, at extremities, and maximum pile stresses of around 2.1 MPa. The mobilized shear stresses varied from around -50 to + 150 kPa on the worst-case test. The mobilized magnitudes of strains and stresses did not exceed the resistance limiting values for the pile´s material, not posing a hazard to its operational use. The average undisturbed ground temperature was 29,4°C coping with elevated air temperatures for this region. The tests have been somehow influenced by the external temperature effect, given insulation problems. However, although appropriate thermal conductivities for the ground were calculated, such high air and ground temperature levels seems to invalidate the use of GEP systems for cooling purposes in the region. More research on the subject is required, and an on-going second program of geothermal tests is under way by this same university.

Zito (2019) defended a MSc thesis in the Milan Polytechnic University in Milan, Italy with co-supervision from the Technical Superior Institute from Lisboa. The research aimed the understanding of the influence of thermal variations at the surface and inside geothermal systems, in terms of thermal performance and effects caused by the mechanical loads. Since the GEP system use is becoming widespread in Europe, and some gaps are still present for what concern their structural design, the present study tried to fill some of these gaps with an extensive program of 2D numerical simulations at different boundary conditions, and distinct thermal variables. The initial analysis focused on some of the modelling aspects of the problem such as the definition of the geometry, of the heating configuration of the pile and of the time period for the thermal dynamic equilibrium, by using numerical finite element analysis performed through ABAQUS software. The time factor, the periodic temperature variations, the geometry and the thermal activation of the pile were tested on different systems following the seasonal trends of Milan's climate, by performing both transient and steady-state simulations. The influence of the soil's thermal volumetric behavior on a GEP was examined through a parametric study. The variation in time of the ground surface temperature and then of the thermally activated pile temperature, showed important differences when the transient state results were compared to the steady-state ones, affecting both the direction (compression/tension) and the magnitude of the thermally induced stresses in the pile, of the displacements and of the heat flux. The effect of the coefficient of thermal expansion of the soil was found to have a key role in the observed behavior of the GEP, because a stress release and an increment in pile's deformations were noticed when the coefficient increases. The obtained results allowed the improvement of the set of information currently available on this technical field, more specifically on the thermomechanical behavior of single and groups of GEPs. The author observed that the initial thermal dynamic equilibrium simulation confirmed the theoretical prediction about temperature variations of soil with depth when a sinusoidal perturbation is applied, i.e., that the temperature profiles stabilize in the first 20 m of depth in any (Milan) summer or winter period through the years. It was concluded that it takes 10 years for the soil to reach this kind of equilibrium, hence mechanical stresses and strain will accumulate along this time due to the thermal activity inside the soil and should therefore be quantified. It was also proved that a transient 2D axisymmetric analysis is not time-consuming hence it is a better solution to choose. If a 3D system must be considered, for instance for including the absorber pipes inside the pile through a pipe's configuration, the transient analysis would result in time-wasting and the steady-state analysis should be used. Besides, the definition of a concrete slab is useful to better simulate the heat loss from a thermo-controlled building to the pile, through a concrete element that has its own thermal conductivity. The self-weight of the slab and the internal temperature applied to the concrete surface led to some deformation that must be added to those coming from the thermal activation of the pile. Regarding this specific effect, it was shown that a normal (non-active) pile can be subjected to some thermally induced stress and deformation, as the temperature of the soil surrounding it is affected by the heat loss coming from the thermo-controlled building. Finally, the author has shown that the behavior of the GEP was influenced by the thermal characteristics of the surrounding soil, therefore concluding that a methodic geotechnical and physical characterization of the ground must be carried out to properly represent the system´s behavior, either numerically or experimentally. Future studies in this area should allow for a better configuration of the boundary conditions, among other numerical issues, for instance by adding other structural elements of the overlying structure or other representative thermal effects within the problem, as the oscillating daily variation of temperatures during the operational period of the system.

## I.6 Conclusions on gathered bibliographic information

Based on a comprehensive bibliographic review on the subject of superficial geothermal energy structures (SGES), more specifically on interconnected ground source heat pumps (GSHP) and geothermal energy piles (GEP), or borehole heat exchangers (BHE), the following *key ideas, comments, research suggestions and conclusions* arise in each of following discussed themes:

(a) Responsibilities & Actors:

- ✓ The main energy source in Brazil is renewable, from hydropower. This does not exempt the country to its obligations with the signed Kyoto Protocol and with the international community, in terms of reducing greenhouse gas emissions (GHG) by 2020 and future accorded dates;
- ✓ No definitive guidelines, jurisprudence or legal basis exist for design, construction, commissioning and operation of GEP systems, although restricted rules in some countries do exist. Lack of public awareness, Governmental incentives or support, and political interest, also restrict further development of this technology in the world;
- ✓ On-going research is being carried out in many international Institutions regarding several aspects of GEP systems, from laboratory experiments to field case studies. A more interconnected definition of goals, objectives and share of individual material and personnel resources seem to be essential to amplify the outcomes, preventing natural redundancy of individual efforts. Academy, private companies and Governmental agents do have the responsibility to finance and foster this technology, so that it becomes soon available for society in a more widespread manner.

(b) Field Scale Performance and Behavior:

- ✓ Field measurements have shown that the GEP system offers a promising alternative to conventional climatization of superstructures, albeit involving a broader range of interdisciplinary aspects that vary from biological to engineering issues;
- ✓ GEP systems allow for the reduction of primary energy use of typical air conditioning units, with reasonable coefficient of performances of the GSHP for space heating. They help preventing or reducing emissions of GHG on the atmosphere;
- ✓ Geothermal energy piles do suffer from thermomechanical effects from the heat flux process, that invariably induce additional strains and stresses that superimpose to those from purely mechanical loads from the superstructure. Temperature variations also lead to additional friction mobilizations at pile shaft, at the pile-soil interface;
- ✓ Geothermal energy piles also suffer from additional displacements given the heat transfer process, that tends to stabilize on a long-term run of the system. Ratcheting phenomena will appear with continuous thermal cycles and will influence the pile-soil interface shaft friction;
- ✓ End restraints at either pile base or head also interfere with the pile thermomechanical effects, amplifying or decreasing thermally influenced strain and stresses. Such effects lead to a variation of the location of a neutral point on the pile shaft, where mobilized strains are zero;

- ✓ Geothermal energy piles dilate and contract during heat operations in longitudinal and radial mode, leading to changes in the pile shaft shear resistance (or interface friction) and in the horizontal stresses mobilized at the soil. Dragdown or expansion of the surrounding soil has also been reported in large-scale observations;
- ✓ Thermal cycles can have an impact on the bearing capacity of piles as they will change shaft friction due to the rearrangement of soil particles at the interface pile-soil and eventual densification underneath the pile base;
- ✓ The soil surrounding the GEP system will also be affected by the thermal effects of the heat flux between pile and soil, or by pore pressure changes or by creep/viscous related phenomena that includes expansion, contraction, drying, rearrangement or another soil occurrence. Granular soil is affected less than clay or silt, but the temperature sensibility of soil increases with its organic contents;
- ✓ Geothermal operation does not seem to provide detrimental effects either on the structural aspects or on the geotechnical behavior of the foundations, at least during the (limited time) monitoring periods of studied large-scale GEP systems. Nevertheless, it will modify the temperature of the soil around the system to a certain influence zone, possibly changing environmental conditions within this range. Recovery time is needed to allow excess temperatures to return to normal conditions, in some cases to much larger amounts as those from thermal load periods;
- ✓ Heat losses in the horizontal portions of pipes that connect the primary to secondary systems, via GSHP, do lead to efficiency losses in thermal operations;
- ✓ The average energy extracted or injected per meter of pile length is higher in intermittent mode than in continuous one, and balanced energy exchange systems do operate better than unbalanced systems, with higher efficiency at long-term periods;
- ✓ Heat losses are higher at the edges of the superstructure and lower through the central region of the floor slab, which indicates a thermal edge phenomenon. Ground temperatures and soil moisture contents have also shown to vary along depth in the geotechnical deposit, being approximately constant beneath a certain (shallow) depth below ground surface. Design of GEP systems should consider the superimposed effects of the heat flow from the structure and the thermal working loads within foundation elements;
- ✓ A small temperature difference between inflow and return-flow temperature (of around 2-3°C) of the absorber fluid seems to be enough for economical operation of pile energy systems. Operational fluctuation of the groundwater temperature should also be kept as low as possible (with a suggested $\Delta$T range lower than 5°C);
- ✓ Heat exchange between the pile and the soil depend on the configuration of the heat exchanger pipes, and the heat carrier fluid velocity or flow rate. Exchange rates tend to be high at the beginning of the operation process, decreasing afterwards due to variations in the temperature of the soil around the GEP system. Such systems can be designed with basis on field thermal response tests (TRTs), so to provide thermal variables of practical use;
- ✓ Energy pile groups are likely to lead to larger movements and lower stress changes compared to a single pile, depending on constraints and no. of piles in the group. Soil-structure interaction also happen with GEP groups, eventually leading to thermal saturation of the system depending on several aspects as operation time and mode (continuous or not), geometries, thermal loads and soil type. When thermally activating some piles of the group while keeping inert others, there is a compensating effect of mobilized stresses and strains within the group, so to keep a stable balance of forces and displacements;

- ✓ The monitoring of large-scale GEP systems and superstructures at long-time operation periods is fundamental to a better understanding of the intermingled influence of the system´s variables, as the superstructure occupation, GEP operation, environmental thermal (air, soil) changes, initial geotechnical conditions and biological/chemical aspects. Possible scenarios for a sustainable dynamic equilibrium and for a thermal optimization are solely viable with continuous monitoring of the whole system, including primary and secondary circuits;
- ✓ Field measurements indicate that an initial phase to optimize the interactions between the underground thermal energy storage medium, and the superstructure, is necessary to establish a well-regulated seasonal energy-balance for a lasting performance. Post-construction building monitoring of fluid temperatures and monthly heat extractions are certainly mandatory for this purpose;
- ✓ A better understanding of the residual thermal (structural) stresses within the pile from cyclic thermal loading, and the mobilized interface friction values and their possible decay with time are needed. Further research on the long-time behavior of the soil surrounding the system is also important, especially for soils sensitive to heat-related influence. Continuing studies are required on field-scale piles to determine how the pile displacement and soil properties are affected in intermittent and continuous operations, and how optimal durations of rest period could be adapted for different site and pump conditions. Understanding of the soil-structure heat exchange effects for cyclic thermal load operations of GEP groups in balanced and unbalanced energy environments seems to be critical for a rational operation of the system, and for better strategies of modelling, operation and future design.

(c) Laboratory Performance and Behavior:

- ✓ Close similarities between small-scale centrifuge or 1g experiments and large-scale field measurements have been found in terms of the thermomechanical behavior of GEP piles due to loading and boundary restraint conditions;
- ✓ Displacements from small-scale GEPs can have distinct directions during mechanical and thermal loadings and tend to stabilize after successive thermal cycles. Ratcheting and irreversible settlement can be observed after several cycles, with a hysteresis phenomenon in the temperature versus settlement paths;
- ✓ Distinct ratcheting patterns seem also to be related with the over consolidation ratio of the clay, besides of the no. of thermal cycle loads. According to experiments, a larger settlement in lightly over consolidated clay compared to highly over consolidated ones could be due to an accelerated creep rate at the pile-clay interface, caused by the thermal cycles;
- ✓ Nonlinear changes in stress with depth in isolated GEPs can be a result from mobilized side shear stresses during thermal loads. Degradation of shear stresses at interface appears to take place with increased number of thermal cycles;
- ✓ Energy pile response appears to be thermo-elastic under thermal cycles when the mechanical load is less than a certain fraction of the ultimate bearing capacity (in experiments for safety factors SF > 2.5), so conventional safety factors seem to ensure a stable pile response under thermal load. However, at mechanical loads above this limit (SF < 2.5) the response of the pile tends to show irreversible settlements;
- ✓ It seems that the irreversible settlement of the pile at high axial loads is associated with a modification of the mobilized skin friction along the pile-soil interface during

thermal cycles. The higher is the applied mechanical load, the higher tends to be the number of cycles required to stabilize the thermal induced displacements;

- ✓ In a thermal cycling process, the thermally induced axial forces in the GEP at the end of a heating phase is different (observed as higher) than that at the end of the subsequent cooling phase, yielding distinct phenomena during heating or cooling stages;
- ✓ Depending on the soil type, there seems to be an increase on the geotechnical capacity of the energy pile during thermal load, possibly due to a combination of radial stress increase and thermally induced water flows in the unsaturated soil medium. Therefore, axial load-displacement behavior of geothermal piles is likely to be affected by induced temperature cycles;
- ✓ Residual strains and stresses are introduced after heating and cooling cycles in GEPs, and side shear frictions can have distinct directions depending on boundary restraints and on the position of the neutral point;
- ✓ The GEP performance is controlled predominantly by settlement rather than bearing capacity;
- ✓ A zone of soil thermally influenced around the heated GEP has also been noticed in a similar fashion as observed for large-scale experiments. The influence zone seems to be extended to some diameters radially away from the axis of the pile (max. observed 6D) and few diameters below pile base (observed 2D);
- ✓ Different heat flux and thermomechanical behavior are found in a GEP with distinct heat fluid carrier pipe configurations. W-shaped pipes tend to allow more heat exchange between the pile and the surrounding soil than other configurations, with consequent higher mobilized internal stresses and strains. Heat flux is increased in coiled type pipe configurations when the spiral pitch is reduced;
- ✓ Thermal efficiency or heat flux intensity between pile and soil is intrinsically related to the degree of saturation of the surrounding medium and decreases as the saturation reduces (observed drops of 40% in efficiency). Saturation degree also influences the thermal conductivity of this material. Under unsaturated conditions the temperature at the pile-soil interface is higher than in saturated conditions when keeping all other variables constant, which causes a decrease in the temp. gradient between the heat carrier fluid and the pile wall, thus resulting in a decrease of the heat exchange rate;
- ✓ Drying around isolated piles in unsaturated soils due to heat exchange and moisture content variation can lead to variations of effective stresses at the pile-soil interface, hence increasing or decreasing the lateral friction;
- ✓ The behavior of an energy pile group when thermally loaded is distinct of a single pile in terms of mobilized axial stresses (and strains), since these stresses are a function of the restrained boundary condition of the pile, which is determined mainly by the lateral conf. pressure. Therefore, as pile interaction reduces the restrained condition of the pile group, the thermally induced axial stress is larger for the isolated pile in relation to the same pile in a group. The different confining pressure of the group also leads to distinct end restraints, that sum up to the additional restraint imposed by the group raft;
- ✓ Cyclic thermal loads on the GEP can also lead to cyclic pore pressure variations in the saturated clayey soil around the pile. Interface shaft resistances may also increase due to an increase in both friction angle and effective lateral stress due to thermally induced negative pore water pressures;
- ✓ Thermal efficiency of the GEP can increase (observed up to 30%) during thermal cycling, due to the presence of high thermal gradients at onset of the thermal loading reversal;

- ✓ Similar as field-scale experiments, intermittent GEP operation tends to improve the thermal performance with a more effective temperature variation trend, when compared to a continuous operation mode. The higher the thermal effusivity the better is the heat release rate, but slower is the temp. restoration of the soil near the pile;
- ✓ Small-scale experiments with geothermal energy pile systems proved to successfully calibrate simple or complex thermo-hydro-mechanical models for the numerical finite element simulation of this problem, with focus on thermomechanical behavior or thermal performance at short and long-term conditions. Small-scale tests often have advantages over full-scale tests in terms of cost, time, and control of conditions. However, in the tests reported to-date the mobilized shaft restraint appears to be rather low, which can be related to the fact that most of the tests were undertaken in granular materials rather than finer ones. Future research should therefore focus on tests with stiffer materials to allow a broader range of possible practical responses;
- ✓ A better understanding of ratcheting effects related to the settlement behavior of GEPs at serviceability cyclic thermal loads also needs to be further explored, particularly at long-term periods of operation.

(d) Numerical Performance and Behavior:

- ✓ Heating of the pile induces additional compression and increases mobilized shear stress, whereas cooling can induce a release of stress, possibly leading to a reversal of stress sign and eventually the development of tensile axial stresses in the pile. However, thermally induced stress changes tend to reduce with time as the surrounding soil reacts to changes;
- ✓ The mechanical behavior of the GEPs are affected in seasonal time since the piles are subjected by cyclic thermal loadings during annual operation. Repetitive heating and cooling cycles can cause degradation of shear resistance at the pile soil interface. Moreover, thermal cycles trigger measurable changes in soils conditions that should be considered in foundation design at long-term periods;
- ✓ Thermal loads at the energy pile head at which non-linear (mechanically derived) settlements begin to occur should also be avoided, since thermal loads in this (plastic) range can induce irrecoverable displacements;
- ✓ Irreversible and accumulated settlement in each year of thermal cycle, with a ratcheting phenomenon, also seems to take place during cyclic long-term continuous loading. In sandy materials the progressive stable state happens due to a densification process that occurs at each thermal cycle;
- ✓ Both thermal tensile and compressive stresses and strains can coexist in a GEP during either heat rejection or injection process, and this occurs because of the non-uniform temperature changes that seem to exist within the GEP cross section;
- ✓ The duration of the heat injection/extraction has direct influence on the time to achieve natural thermal recovery of the soil towards initial stage. In general, the recovery time is much higher than the initial loading stage (4 times more in some analyses). Resting phases during thermal load should also be specified, as it is remarkably favorable to decrease the mobilized axial forces along pile length;
- ✓ In GEP groups, the axial stresses generally tend to increase at the end of heating and decrease at the end of cooling, and they are always higher than due solely to mechanical loads. Greater loads are always noticed in the corner piles, as expected. It seems however that in an operational thermal load the displacements and stresses

on the piles are not critical, according to current (European Eurocode 7) standards. Geotechnical stability also seems to be ensured;

- ✓ Axial heat transfer alters the heat flux within energy piles, altering the thermal performance of the heat pump system. The pipe loop configuration also modifies the heat exchange between pipe and concrete keeping all other variables constant. Factors such as the number of loops, pipe location, soil, concrete, pipe, steel and plastic thermal conductivities do influence the magnitude of thermal interactions between pipes, hence affecting the flow mechanism or efficiency of the system;
- ✓ Connecting energy piles in parallel or in series also changes the system´s efficiency, depending on the pipe loop configuration. Restricted studies demonstrated that a serial connection of 15 piles with W-all around shaped pipes seems to perform better when compared to other configurations;
- ✓ The best scenario for heat conduction or efficiency in a GEP system is related to its number of heat exchanger pipes, followed by its length, having all other variables being equal. The amount of pipe surface available for convective heat exchange is fundamental for an efficient thermal flux. The least important factor seems to be the flow rate of the heat carrier fluid, provided that turbulent flow does take place;
- ✓ The operational stiffness of the soil and the ratio of coefficients of thermal expansion between soil and concrete also influence the heat transfer response. There is a complex interaction between the foundation and the surrounding soil that is influenced by both the thermal characteristics of the system´s materials and the restraints imposed by the boundary conditions;
- ✓ The thermal influence zone around an isolated GEP has been observed to be at distances of 10 diameters from the pile center. In a GEP group there is an overlapping thermal phenomenon, i.e. when multiple adjacent piles are used as heat exchangers there is an adverse thermal interaction between them. The interaction increases with increase in the aspect ratio and no. of piles, and decreases with enhanced pile spacing;
- ✓ The position of the pile in an energy pile group is also determinant to provide distinct thermally influenced axial stresses and strains compared to other positions. The presence of a top raft helps to somehow normalize settlement and loads due to the restraint effect;
- ✓ By thermally activating all the piles on a GEP group a beneficial mechanical outcome is obtained when compared to just a single pile, nevertheless the group may lose efficiency with time due to thermal losses, even in balanced energy systems;
- ✓ An unbalanced heating demand may decrease the efficiency of the pump system with time, due to thermal saturation of the soil, that after some years of exploration may not be capable of temperature recovering anymore. A soil with high thermal conductivity and low volumetric heat capacity can have a better ability to quickly recover from thermal saturation, due to an unbalanced GEP energy operation;
- ✓ The nature and distribution of temperature in a GEP group and its surrounding soil is dependent on the seasonal energy demand, and in a balanced system the region influenced by temperature changes within the soil mass is minimal. On the other hand, in an unbalanced climatic condition the system loses its efficiency over time, especially in larger pile grids. Preventive measures should be taken to face the efficiency loss, so to allow a sustainable use of the ground along large time periods;
- ✓ The decay of thermal power or efficiency of GEP groups is higher in the first days of operation, decreasing afterwards. The degree of decay has been shown to depend on the loop configuration of the pipe. In this regard, the design solution should take on

consideration the energy demand with respect to the thermo-hydraulic requirements of the heat pumps;

- ✓ Long-term performance of the ground heat exchangers is closely related to maintaining a constant ground temperature, but in extreme climates heat exchange efficiency may eventually drop after long term usage of the system;
- ✓ Water flow also improves heat exchange in a GEP system. Using energy pile foundations under medium groundwater flow enhances the productivity of system (calculated by around 20% in winter and 5% in summer mode) compared with a saturated condition with no groundwater flow. This happens because the water flow can transfer heat from surrounding areas and thereby modify to a large extent the ground temperature near the pile;
- ✓ An intermittent operation of a GEP group gives better performance than continuous operation in both cooling and heating modes, and differences between heat loads in intermittent and continuous operations increase in unsaturated materials, as the unsaturated soil zone becomes deeper. Lower hydraulic conductivities lead to lower heat transfer via convection, thus resulting in a high temperature build-up and consequent decrease of efficiency of the system;
- ✓ In situations where higher temperature changes are expected in the GEP due to high injection rates, or very low degree of saturations of the soil medium, it is advisable to implement an automated management unit to control the temperatures of the system;
- ✓ The performance of ground source heat pumps (GSHP) depend strongly on the depth related thermal properties, which will vary according to location of the water table. It also depends directly on ground thermal loads rather than building loads, but both loads are interrelated and to the characteristics of the selected pumps, hence are interconnected within the overall system´s thermal framework. According to some authors, one way to consider long-term effects is to perform a comprehensive energy balance analysis for the building and geothermal system using a commercially available computer package, or coupled superstructure-infrastructure FEM technique;
- ✓ In a GEP group there is a balancing phenomenon between neighboring nonactive and thermally active piles, regardless of head fixity conditions. It also affects the state of soil displacement contained within the group, so to keep an overall balance of forces. Heat diffusion also happens between nonactive and thermally active piles in a group;
- ✓ Appreciable efficiency losses are obtained when all piles are thermally active simultaneously, compared to few ones in a large pile grid, due to thermal saturation of the ground caused by interaction effects. Geothermal groups with combinations of active and nonactive piles simultaneously working together should be stimulated;
- ✓ Research on the interaction effects given the presence of repeated heating and cooling cycles either in balanced or unbalanced energy thermal regimes, typical of a GSHP system live cycle, should be encouraged. An optimization or desirability function approach should also be examined in future improvements of current design methodologies, so to obtain the number of GEPs to supply the thermal demand of superstructures with an optimal combination of active and nonactive thermal piles, taking on consideration performance efficiency and ground temperature values at long-term cyclic operations from usual thermal foundation structures.

(e) Miscellaneous Studies:

- ✓ The ancient wisdom of using the earth as temperature moderator against harsh weather has historically had an impressive potential to be used as the most efficient and cheap solution against other more inefficient ways of climatizing the system;
- ✓ The first documented suggestion for using ground as heat source was in 1912 in Switzerland, but at that time heat pump efficiency was poor and energy prices were very low. Commercial use started only after the first oil crisis in 1973. In 1985 a full-scale (BHE) field experiment was installed adjacent to the Verolum factory, in Germany, opening space for the employment of this technology of building climatization in Europe;
- ✓ The GSHP capacity has grown 2.15 times during the years 2005/2010 and are currently adopted in around 80 countries worldwide. There is an abundance of research on borehole modeling, but energy pile modeling is much less studied;
- ✓ Countries where GSHP sales are high have extensive support from governmental policies, either by direct subsidizing implementation, by promoting research and development, or as part of a national effort to increase the use of a renewable energy platform towards the decrease of $CO_2$ emissions;
- ✓ Clayey soils have in general higher specific heat and volumetric heat capacities than sandy type ones for the same water content and density. Thermal diffusivities also vary with moisture content and soil texture;
- ✓ There are still problems to estimate thermal conductivity of soils via laboratory techniques. However, existing analytical methods can be alternatively used to determine the thermal conductivity of soils if no high temperature gradients occur. Experimental conductivity values vary with water content, density and mineralogy, and published data is within 0 to 5 W/mK;
- ✓ Both the steady state thermal cell and transient needle probe can yield the thermal conductivity of soils in the laboratory. However, lab. values are lower compared to the in situ thermal response test (TRT), as the latter technique gives almost twice values as the laboratorial experiments. The TRT yields an overall better measurement on thermal conductivity besides being more expensive and time consuming;
- ✓ Design of GEP systems requires detailed analysis of building load, energy consumption and cost-efficiency study. Nowadays it is best carried out by electronic computer aided software, besides they often perform narrowly focused tasks. Software with no coupling capability with building simulation need interpretation of the building heating and cooling demand data in an hourly or monthly time basis. Most flexible software packages can be coupled with whole building simulation, and can be used for customized detailed plant modelling, nevertheless these software packages have a long learning curve and only experienced users are expected to utilize most advanced features. A simple user-friendly numerical tool to analyze the integrated coupled superstructure-foundation system is also required;
- ✓ Another aspect of importance is the estimated energy demand of the superstructure, since it has a major impact on the final dimensions of the designed system and therefore needs to be carefully assessed. It is paramount to consider climatic conditions, solar orientation, external colors, occupancy, ventilation, geometry and wind velocity in the simulations of the thermal performance of edifications with upmost precision as possible;
- ✓ In essence the design process is based on a balance of energy, from one side the temperature of the fluid entering the pump via heat transfer model & size/soil factors,

from the other side the same entering temperature that supplies the required thermal loads of the superstructure, that is based on pump details, performance coefficients and thermal comfort. It is an interactive process which guideline are not yet prescribed;

- ✓ The complex thermomechanical processes that occur in energy piles are far from understood, although recent progress in the heat transfer analysis of energy piles do provide a good starting point for solving this problem. One critical process is how the periodic expansion and contraction of concrete columns caused by thermal processes affect the frictional forces of foundation piles, especially in the long-term system´s run;
- ✓ The major drawback in terms of design is the lack of a theoretical model to predict a thermal performance that can consider all the parameters that effectively affect the GEP system on the long run, as site thermal imbalances. Potential challenges on long-term effects on ground temperatures, and other related environmental impact issues, must be better understood before further progress can be made with GEP systems;
- ✓ The complexities of accepted const. models remain a large academic pursuit in terms of daily use and parametrization and is a major challenge in practical GEP applications;
- ✓ The path to an effective thermal energy storage system design is by thorough evaluation of environmental site characteristics and soil properties. Proper design practices should integrate diurnal and seasonal storage so to yield a higher system´s performance;
- ✓ The main barrier to today´s better understanding of such structures is the lack on an extensive international database on well documented case studies on GEP testing and life performance, thus preventing a clear demonstration to clients, professionals and stakeholders that such technology is safe, viable and economic. It also prevents a better modelling of the technology, particularly on design and field performance efficiency It would be useful to establish a set of protocols with a common format for the design, execution and monitoring of GEPs for research groups willing to advance the knowledge on this particular technology;
- ✓ As of 2007/2008 the environmental agency of UK recognizes “temperature” as a potential pollutant. In fact, with more systems designed together there is a risk of long-term below ground “global warming”. It seems that designing heat source spacing based on field temperature alone can be inadequate, as thermoplastic effects increase thermally induced pore pressures and hence water flux around pile structures;
- ✓ Through a controls system, acceptable temperature limits should be set to enable a GEP system switch off to guarantee long-term performance, thereby protecting longevity and efficiency for the long life of the building;
- ✓ Brazil, situated in the middle of the South American plate has more favorable conditions to explore low rather than high enthalpy energy sources, suitable for GEP systems. Nevertheless, given the predominance of hydric power and availability of other sources as natural gas, Brazil places geothermal energy to a secondary position;
- ✓ A high diversity exists on legislation provisions together with regulation standards and institutional support amongst European countries. The diversity acts more as barrier for further development on the SGE market rather than encouraging integration. Such constraints strongly affect stakeholders and consumer confidence in the technology, and severely hampers its further diffusion in Europe and elsewhere;
- ✓ Given GHG emissions the earth´s surface temperature has increased about 0.6°C over the last century. Therefore, an integrated set of activities should be hosted by governments, as the research & development of sustainable energy sources, technological assessments, development of standards, and transfer of knowledge to society.

(f) Key Points for Future Research & Development:

1. International guidelines or legal jurisprudence for design, commission, operation, monitoring and investment of GEP systems are necessary;
2. Integration of research and investment efforts from academy, private sectors and public institutions are mandatory to further improved development of this technology;
3. Thermomechanical phenomena as stress, strain, lateral friction, pore-water pressure, temperature and densification changes do take place in the pile and in the surrounding soil due to thermal load. Physical, biological and chemical standards will invariably modify within an influence zone around the system and should be better accounted for;
4. Thermomechanical changes on the foundation system given normal GEP operations does not hamper the structural or geotechnical performance of the infrastructure if preventive measures are carried out (structural reinforcement of piles, assessment of end-bearing action, and so on). Guidelines for that in local standards are required;
5. The thermal efficiency of the system as a whole, i.e. primary and secondary systems, depend on several interconnected variables, as the operational mode (continuous versus intermittent operation), operational period (long-term versus short-term run of the system), loading demand (balanced versus unbalanced energy environments), loading characteristics (cyclic frequency, amplitude, duration), and thermal harvesting & resting periods (auxiliary backup systems, ground recovery time lags and so on). Pump characteristics, pile configurations and geometries, building energy demands and environmental issues also influence the system´s response. Understanding of the interplay of some or all these variables is key to better simulation design tools;
6. Thermal efficiency decreases with time in any operational scenario, given internal and external influences of several variables that slowly but continuously hamper GEP operation. Preventive measures, backup systems, or operational regulations should always be considered. Long-term monitoring of large-scale systems is highly needed;
7. A more documented set of well-regulated and instrumented GEP structures either in the field or in the laboratory is therefore required to advance further the knowledge in the various technical fronts of this (new) technology;
8. Unsaturated soils yield a worst heat flux scenario, or GEP efficiency, than saturated ones, for commonly studied deposits from the northern hemisphere. Laterized, tropical and weathered materials may provide different patterns of thermal behavior given its distinct mineralogical components, yet to be fully understood and explored. Research in this direction is vital in southern hemisphere countries;
9. Group behavior of GEP systems is always better than the behavior of an isolated energy pile, either in terms of thermal performance or thermomechanical effects, provided that thermally active and nonactive piles are simultaneously arranged in the system so to decrease thermal interference and ground temperature saturation. Simulations of group interaction are necessary for better understanding;
10. Several other (minor) factors related to both primary and secondary circuits also influence the heat flux around GEP systems and surrounding soil, as pipe configuration, expansion coefficients, reinforcement bars, boundary conditions, water flow and so on. Although complex to simulate, some of these factors must be accounted for in design;

11. Design methodologies via numerical analyses are not yet fully developed or disseminated in practical terms, given the high complexity of the proposed thermo-hydro-mechanical models, the limited knowledge on thermal parameters, and the lack of established testing standards either in the lab. or in the field. Coupling interactions between primary and secondary systems are yet not fully accomplished in design simulations, given the intricacies of the replication, lack of parameters, and inaccuracies of current estimates for superstructure thermal loads (or comfort temperatures) in long run periods of time. Without brainwork in this area, the usage of this technology will continue to be impaired by narrowed simulation schemes;
12. Cost-efficiency studies and the possible comparison with other techniques to climatize superstructures while reducing the emission of GHGs are rare in the literature, or practically nonexistent. Future building design and operation will invariably recur to simultaneous environmentally friend measures that will have to be interconnected somehow, as solar panels, photovoltaic cells, GEP systems, artificially intelligent systems and architectural supplements (as glazing windows, façade panels, insulation films etc.). Future integrated and interdisciplinary studies will be required;
13. The importance of this thematic is quite high nowadays, given the target in Europe to transform the geothermal technology into a significant energy resource towards 100% of renewable heating and cooling scenarios by 2030. In the Brazilian case, the subject is secondary given the lack of awareness, policies, resources and investment. Potential to explore low enthalpy energy sources has been demonstrated to be high in the Brazilian continent, but as of today this country still places geothermal energy to a secondary importance, with few exceptions for recreational use.

As general conclusion of the study carried out herein, one can say that a political and particularly a mental attitude shift towards the (serious) climate change challenge is urgently needed not only in Brazil, but in the whole American continent. It is the author´s personal opinion that, since the dinosaur's extinction, this may be the next global event with real potential for another annihilation of entire animal species in the planet, including the homo sapiens.

Finally, when comparing a possible next mass extinction event (MEE) with those from the past (say Cretaceous-Paleogene MEE, 65 million years ago) one can say that, as recently stated in a local Brazilian news media (O Globo newspaper, September 2019), the dinosaurs "at least were not warned by their puppies about the coming asteroid"…

# II. FINAL REMARKS

According to the approved PDE research plan submitted to the Brazilian National Council of Research and Development (CNPq), the 6 months leave from Prof. Cunha basically aimed, in general terms, “the conception, understanding and elaboration of research guidelines towards the establishment of geothermal energy piles”, either in the tropical unsaturated soil of the Federal District or in other regions of Brazil. Specific goals were listed as related to a better knowledge of the thermomechanical behavior of thermally activated piles, of the heat flux phenomena between pile-fluid-surrounding soil, and of state-of-art developments in this field.

The leave has taken place exactly after 20 years from the first postdoctoral stage of this Professor, in Australia 1999, when a new research line was established towards the development and implementation of piled raft foundations within his geotechnical research group on foundations, in-situ testing and retaining structures (GPFees, *www.geotecnia.unb.br/gpfees*). Today this pioneering Brazilian research line has rendered several fruits, and provided professionals, researchers and practical works in the Federal District as well as other areas of Brazil. Likewise, after the present leave a similar response is expected with the research line on the technology of geothermal energy piles.

The acquired knowledge certainly surpassed initial expectations, and it will surely help to focus on relevant aspects of this technology in current and future research theses supervised by this Professor, either in the University of Brasília or in other academic institutions of Brazil (as for instance on a recently started co-supervision in the Federal Univ. of Pernambuco). Increasing public awareness and knowledge diffusion will be sought, through extension activities and publications from the GPFees research group. A new technical course on this area is also aimed for 2020/2021, seeking students from both Civil and Environmental Engineering courses of this same university.

The short-term PDE from Prof. Cunha wouldn’t be so effective in properly targeting and successfully accomplishing the original aimed goals without the integrated efforts, and financial support, from several agents and sources. In the IST Lisbon the providential assistance from colleague Prof. Peter-Bourne Webb and PhD students João Figueira and Illés Zsombor is gratefully acknowledged. In the University of Brasília, the continuous interaction with the on-going PhD student Charles Chaves and the former MSc student Roberto Sousa Júnior shall be also mentioned and thanked. The financial support from the University of Brasília, by the kind paid leave, and from the Governmental agency CNPq by its scholarship, is of immeasurable value.

A debt to the Brazilian Nation and gratitude to the Portuguese Country has been established and shall be finally asserted herein.

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# ANEX 1. SUMMARY TABLES OF RESEARCHED BIBLIOGRAPHY

Table of Annex I.1. Key findings on field scale studies on the thermo-mechanical behavior and thermal performance of geothermal thermally active (energy) piles (GEP)

| Reference | Key Findings on Thermomechanical Behavior |
|---|---|
| **Vienna Univ. of Technology**<br>**Bad Schallerbach, Austria**<br><br>**Brandl, 2006** | • The heat developed during hydration of fresh concrete pile imposed residual stresses within the pile.<br>• Heat extraction (winter mode) result in pile contraction, thus, decreasing the base pressure at the pile toe.<br>• Excessive heat extraction could lead to ground freezing which results in heave development around the pile.<br>• Thermal strain-induced cracking of the GEP could occur due to shrinkage and during hydration of fresh concrete.<br>• Heating/cooling piles as a group induces lower axial thermal stresses at the pile head, compared to heating/cooling a single pile in the group.<br>• The axial load transmitted to the pile toe remained constant during thermal load application. |
| **EPFL – École Polyt. Fédérale de Lausanne**<br>**Switzerland**<br><br>**Laloui et al. 2006**<br>**Laloui & Moreni, 1999**<br>**Bourne-Webb et al. 2009**<br>**Amatya et al. 2012** | • Increase in temperature results in additional friction mobilization.<br>• Thermal variation affects the mechanical behavior of the GEP in two ways: (i) increase in friction mobilization due to temperature increase; and (ii) addition of thermal compressive stresses in the GEP.<br>• The vert. stress developed due to coupled thermo-mechanical load is twice that due to pure mechanical loading.<br>• Thermal cyclic loading result in the expansion and contraction of the GEP, thus causing the development of strains which are thermo-elastic in nature.<br>• Axial load induced in a GEP under thermal load depends on the end restraint at the pile-head and pile-toe.<br>• Axial load induced in a GEP fully restrained at the top and bottom (e.g. Lausanne test-pile), under thermal load, increase uniformly over full depth.<br>• Stiff silty/clayey soils (i.e. lower part of Lausanne soil profile) exhibit larger mobilization of shaft resistance per unit temperature change in comparison to that mobilized in soft clayey soil (i.e. upper part of Lausanne soil). |
| **Skanska Ltd. & Univ. of Cambridge**<br>**Lambeth College, United Kingdom**<br><br>**Amis et al. 2008**<br>**Bourne-Webb et al. 2009**<br>**Amatya et al. 2012** | • The extreme cooling phase was unable to lower the average pile temperature below freezing, however, the local temperature close to the loops was below freezing.<br>• The extreme cooling phase increased the test-pile settlement by about 2 mm. The extreme heating phase resulted in the recovery of the pile-head after it was displaced during the extreme cooling phase.<br>• About 50% and 80% temperature reduction at the borehole and anchor pile location, i.e. 0.5m and 2.15m from the test-pile, were observed relative to that in the test-pile during the heating and cooling phases.<br>• Thermal cyclic loading increases and decreases the shaft resistance mobilized at the pile surface.<br>• Axial load developed in a partially restrained GEP (London test-pile) increases non-uniformly with depth.<br>• Tensile forces induced due to extreme cooling cycle are unlikely to cause cracking in mass/plain concrete piles.<br>• A GEP subjected to a thermal load induces thermal axial stress in the pile that was between about 50–100% of the theoretical fully restrained values.<br>• The type of restraint at the pile head and the toe, i.e. load of super structure and stiff ground or rock, could alter the magnitude of the stresses developed within the GEP. |

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| **Texas A & M University**<br>**USA**<br><br>**Akrouch et al. 2014** | • Increase in soil temperature results in an increase in pile creep rate.<br>• Heat extraction in cooling-dominated climates increases the viscous mechanism of clays, resulting in long-term pile displacement effect.<br>• The displacement of an energy pile is 2.35 times that of a non-energy pile after 50 years of continuous heat injection operation.<br>• Long-term energy pile displacement can be minimized by limiting the initial settlement. |
| **Monash University**<br>**Australia**<br><br>**Wang et al. 2013**<br>**Wang et al. 2014**<br>**Singh et al. 2015a** | • Radial expansion and contraction of the GEP was observed during the heating and cooling phases.<br>• Pile shaft shear capacity increases due to heating and regains back to its initial state after cooling.<br>• The radial thermal strains are found to be uniform and do not change with depth. |
| **University of Colorado**<br>**USA**<br><br>**McCartney & Murphy, 2012**<br>**Murphy et al. 2015**<br>**Murphy & McCartney 2015**<br>**McCartney & Murphy 2017** | • During heating and cooling operations, the thermal axial strains observed were within acceptable limits.<br>• Total strains measured due to thermo-mechanical loading were well within the range acceptable in the industry.<br>• The trends and magnitude of induced axial strains and stresses, in the piles, are unlikely to cause any structural failure.<br>•8 full scale GEP were constructed for a new building at US air force academy. 3 have been instrumented demonstrating thermo-mechanical induced stress up to 25% of the total compressive strength of concrete. Max. upward displacement was small and not caused engineering problems to superstructure.<br>• Unsaturated sandstone deposit, with measured conductivities from 2 to 2.3 W/mK. Cooling and heating with similar behavior and no hysteresis or permanent thermo plastic locked-in deformations.<br>•Heat exchange through horiz. Portion of loop contributes to efficiency. Rates of 210-260 kPa/°C were observed.<br>•Deeper portions of foundations cooler more rapidly and temperature has changed less underneath building slab than outside.<br>•2 full scale GEP beneath an 8-story building over 658 days, with heat extraction loads of 91-95 W/m. Max. thermo-mechanical axial stress of around 10 MPa, within structural limits. During heating the greatest increase axial stress was at toe. The mobilized shear stress followed a nonlinear profile. Displacements within limits of maximum 2mm upwards in heating and 1mm downwards in cooling.<br>•Foundations of L13.4 &14.8m Dia 91cm on fill/sand/gravel + claystone deposits. Data of 2 cycles of heating and cooling. Contractive strains are observed over time near the toe of both piles indicating that a temporal process is superimposed atop the thermal expansion and contraction of the GEPs, along 5 years measuring period of heat pump operation.<br>• Analyzed piles remain thermo-elastic besides of the dragdown effect, with mechanical stresses close to the maximum compressive stresses (of design) of the concrete. |

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| **University Paris-Est**<br>**France**<br><br>**Szymkiewicz et al. 2015** | •3 boring CFA piles were instrumented and thermally and mechanically loaded. Sandy soil at north of France. L12m and Dia 52cm.Heating cooling cycles of 14 days, 7 days each.<br>•Influence of thermal cycles almost negligible in terms of displacement, but thermal cycles had a positive impact on bearing capacity of piles.<br>•Only friction was responsible for the capacity increase, due to rearrangement, i.e. densification, of the soil particles at soil-pile interface. |
| **Univ. Science and Tech. Beijing, Tsinghua Univ. and Inst. Found. Engineering**<br>**China**<br><br>**You et al. 2016** | • Thermal axial stress distribution along the pile is non-uniform due to partial restraint at the pile head (gravel cushion) and toe (sandy-silt).<br>• Cooling cycle induces pronounced pile settlement and a decrease in its bearing capacity. Thus, Cement fly gravel energy piles should be carefully designed for cooling purposes. |
| **CEDEX & Universitat Politecnica de Valencia**<br>**Spain**<br><br>**Santiago et al. 2016** | • An uplift heave was observed at the pile head during the heat injection process which nearly returned to its initial state after the test has ended.<br>• The pile thermal strain and its resistance indicated that the GEP behaved in a thermo-elastic way and is greatly influenced by the surrounding soil.<br>• Using precast piles as GEPs would not cause any structural problem to the overall pile capacity. |
| **Belgian Building Research Institute**<br>**Catholic Univ. of Leuven**<br>**Belgium**<br><br>**Allani et al. 2017** | •Full scale test campaign coupled with Plaxis 2D finite element analyses. 5 screw type GEP of L11.5m and Dia60cm with single U shaped loop was tested.<br>• Shaft friction prevented pile partially to dilate, leading to increase in axial stress of around 0.8-2 MPa during heating and 0.4-1.3 MPa during cooling. Pile head displacements very small, < 3mm, and deformations around 60% of free movement value.<br>•Good agreement between measured and numerically estimated values of load and temperatures.<br>•Compared to mechanical loads, the thermal axial load increase varied from +50% to +250%. |
| **Instituto Superior Técnico**<br>**Portugal**<br><br>**Bourne-Webb & Bodas Freitas, 2019** | • There is a balancing between movement and the alteration of internal stresses within the pile, supported by large scale tests and numerical models.<br>•Cooling and heating of groups are likely to lead to larger movements and lower stress changes compared to a single pile depending on constraints and no. of piles in the group.<br>• If external loadings exceed the available shaft resistance then cyclic ratcheting will develop, however the response of the pile appears to stabilize with time.<br>•After occupation of structure and thermal activation some time will take to reach a new dynamic thermal equilibrium, just altering pile-soil interactions. |
| | **Key Findings on Thermal Performance** |
| **Cardiff School of Engineering**<br>**England**<br><br>**Thomas & Rees 1999** | •Comprehensive site experiment designed to monitor the thermal performance of real ground flor slabs during 1.5 years in a modern building. Seasonal and diurnal ground and air temperature responses were monitored. Experiment at West Building of the Cardiff school of Eng. complex, with 150 mm concrete ground floor slab.<br>•Ground temperatures varied significantly up to 3 m depth, but underneath slab an insulation effect occurred. Determination of thermal transmittance of each slab floor was derived. Moisture content variation was negligible in the 2m of soil underneath the ground slab. Temp. variations did occur at the edge of the building. |

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| **Universidad Tecnica Federico Santa Maria Universidad Nacional del Nordeste Chile, Argentina Roth et al. 2004** | •First TRT performed in Latin America at the solar energy lab of UFSM in Valparaíso. A 9 days test was carried out in a borehole 16.9 m and 15cm dia. with U pipe tubbing. It was grouted with 12% bentonite mixture and led to the conductivity and thermal diffusivity of the surrounding soil and borehole thermal resistance.<br>•Values of 1.8 W/mK and 0.3 mK/W were respectively found for the conductivity and borehole resistance. |
| **Vienna University of Technology Austria<br><br>Brandl, 2006** | • Pile diameter, thermal and hydrological properties have a significant impact on the amount of heat that can be obtained.<br>• Similarly, concrete composition, such as cement fineness and additives, influence the heat exchange rate of GEPs. |
| **Technical University of Braunschweig Germany<br><br>Schnurer et al. 2006** | •Assessment of 10 buildings in Germany in terms of their thermal performance (continued by Kipry et al. 2009 work). Analysis is made in terms of geological conditions, system configuration, energy performance, investment and operation costs. VW library building at Univ of Berlin and Energy Forum building in Berlin are exemplified.<br>•It is possible to fit underground thermal energy storage (UTES) systems into today´s building energy concepts. They are ideal to be combined with low temp. heating or high temp. cooling schemes like concrete activation ceilings. For high temp. systems (fluid temp 17/22°C) it is required modern architectural & structural façades, or UV screening (as blocking shades), that can keep most of the external thermal loads out of the offices. |
| **Hokkaido University Japan<br><br>Hamada et al. 2007** | • The heat rejection rate for the U-shape, double U-shape and indirect double-pipe types were 53.81, 54.76 and 68.71 W/m, respectively.<br>• The U-shape energy loop (polyvinyl chloride pipe, 34 and 28.8mm outer and inner diameter) was found to be the best option in terms of economic efficiency and workability. |
| **Tongji University China<br><br>Gao et al. 2008a, 2008b** | • The double and triple U-shape pipe configurations possess double and triple flow rate and produced 28% and 56% more energy output than the W-shape configuration.<br>• The W-shape configuration with reference flow rate of 0.342m$^3$/h results in 43% higher energy output compared to the same configuration at a flow rate of 0.171m$^3$/h.<br>• W-Shape pipe configuration was found to be the most thermally efficient if costs are not considered. |
| **Technical University of Braunschweig Germany<br><br>Kipry et al. 2009** | •10 buildings in Germany constructed between 1990/2002 with contemporary architecture standards and equipped with geothermal systems as BHE and GEPs have been monitored after construction. Results indicate that the systems work worse than expected, given inaccuracies in design and lack of experience, realization and operation of such systems. Hence an initial phase to optimize the interaction between systems is important.<br>•Due to slowness and the slight temp. diff. between ground heat storage and the geothermal apparatus the overall system reacts in a very sensitive way to errors and failures. Care in design with a well-regulated seasonal energy-balance is mandatory for a lasting performance. Control post-construction strategies should be implemented together with building monitoring (as inlet/outlet temperatures and monthly heat extraction). |
| **Chalmers University of Technology Sweden<br><br>Javed & Fahlén 2011** | •Nine 80m deep borehole exchangers at 4 x 4 m grid configuration in rock were tested over a period of 48 to 260 hs have their TRT results compared in terms of ground conductivities and borehole resistances. Uncertainties in the order of 7 to 20% can be derived, and effects of temp. variations in TRT results are negligible.<br>•Overview of methods to estimate ground temperatures, conductivities and resistances are presented. |

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| **Saga University**<br>**Japan**<br><br>**Jalaluddin et al. 2011** | • The double-tube type has the highest heat exchange rate followed by multi-tube and lastly the U-tube, being the least.<br><br>• The efficiency of the double-tube decreases due to closer spacing between inlet and outlet pipes which is filled with water as compared to sand used in the U-tube GEPs.<br>• The double-tube configuration had a larger contact surface area of $8.73m^2$, hence resulted in higher heat transfer rate, compared to $4.15m^2$ and $6.28m^2$ for the U-tube and multi-tube types, respectively.<br>• The double-tube and multi-tube showed an increase in heat transfer rate with increasing flow rate. |
| **Korea Adv. Inst. Science and Technology**<br>**South Korea**<br><br>**Park et al. 2013**<br>**Yoon et al. 2014** | • The heat exchanged by the 3U-shape in intermittent mode decreased by 51.7% compared to continuous operation.<br>• Similarly, the W-shape in intermittent mode decreased by 46.4% compared to continuous mode.<br>• In intermittent operation, the 3U-shape produced a heat exchange rate that is 15% higher compared to the W-shape configuration. However, their performance for continuous operation was found to be similar.<br>• The thermal conductivities of the GEP and the borehole were 2.32 and 2.15 $Wm^{-1}K^{-1}$, respectively.<br>• A simple analytical equation that could estimate the equivalent ground thermal conductivity was proposed which had a variation of 5–10%.<br>• The multipole and equivalent diameter analytical methods were found to accurately estimate the thermal resistance of the GEP and GHE (geothermal ground energy). |
| **EPFL- École Polyt. Fédérale de Lausanne**<br>**Switzerland**<br><br>**Mimouni & Laloui 2015** | •Full scale thermomechanical tests were done on 4 GEPs with 90 cm dia. and 28 m built on the EPFL campus, underneath a water retention tank. Four piles were simultaneously or separately heated to check pile-structure-soil interactions. A TRT was performed on one pile and thermohydraulic response of the soil was monitored.<br><br>•Heat from piles has not induced significant pore pressure variations, but evidenced group effects when comparing the thermomechanical responses of the single pile tests. Max. stresses never exceeded 15% of avg. concrete strength. TRT has demonstrated that U loop in series are more efficient than in parallel. Soil-structure interaction effects are visible as base compression increases in heated pile but decreases in unheated ones. |
| **Monash University**<br>**Australia**<br><br>**Singh et al. 2015a, 2015b**<br>**Faizal et al. 2016** | • Heat propagation in soils occurs in a radial direction.<br>• The soil needed about 4 times the heating test time to recover to its initial temperature.<br>• Heat exchange rate of the GEP and the surrounding soil is directly related to the difference in inlet and outlet HCF temperature and its flowrate.<br>• Increase in soil temperature induced by thermal load does not significant influence on the heat exchange rate of the GEP.<br>• The energy extracted during 8 and 16 h was 40.9% and 14.8% higher than the 24 h heating mode.<br>• Thus, the average energy extracted or injected per meter pile length is higher in the intermittent mode than in continuous mode. |

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| **Univ. Science and Tech. Beijing, Tsinghua Univ. and Inst. Found. Engineering China**<br><br>**You et al. 2016** | • The thermal pile test indicated that circulating water at a velocity of 0.5 m/s presents the best cost-effective solution, in terms of heat exchange rate.<br>• The heat exchange rate in cement fly-ash gravel energy piles is positively proportional to the inlet water temperature, observed during thermal performance test.<br>• Average heat exchange rate per meter in intermittent operation is 20% higher compared to continuous operation, and the total heat energy exchanged dropped by 14%.<br>• The thermal pile tests reached a steady state at around 40 h, compared to TRTs that stabilizes at 72 h.<br>• The heat injection and extraction rate for the group of piles decreases by 5% and 20% compared to single piles, during thermal pile test.<br>• Temperature contour distribution indicates that the radial temperature influence for a single pile spreads more than 4 m, so spacing between piles should not be less than 8 m. |
| **University of Padova Italy**<br><br>**Zarrella et al. 2017** | •TRT on a GEP of dia. 62 cm L 20 m in Venice, equipped with double U circuit. It was interpreted via both infinite line source model and inverse numerical analysis. Differences founds in thermal conductivity (2.8 x 1.5 W/mK) come from distinct hypotheses of such methods, as the infinite model does not account for axial heat conduction.<br>•Standard TRT can be carried out but infinite line source model may lead to errors in derived conductivity. |
| **Instituto Superior Técnico Portugal**<br><br>**Bourne-Webb et al. 2019** | • In isolated thermally activated piles there is some relationship between internal thermal stress changes and pile deformations.<br>•when assessing the impact of thermal activation of pile foundations, only considering the thermal loading may not be conservative, as the effects of heat flow from the building, which occurs in any case, must also be taken into account. |

Table of Annex I.2. Key findings on laboratory studies on the thermo-mechanical behavior and thermo performance of geothermal thermally active (energy) piles (GEP)

| Reference | Key Findings on Thermomechanical Behavior |
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| **University of Colorado, USA**<br><br>**McCartney & Rosenberg, 2011**<br>**Goode & McCartney, 2015**<br>**Stewart & McCartney, 2012**<br>**Stewart & McCartney, 2014** | • Heating an energy pile from 15° to 60°C increases its shear capacity by 40%. However, that temperature range is unrepresentative of real-life practice.<br>• The thermal axial stresses were found to be greater in end-bearing piles in silt than in semi-floating piles in sand, because of the greater restraint provided at the pile toe and by the compacted silt.<br>• Heating of semi-floating GEPs in compacted silt result in an increase in ultimate shaft capacity of the piles, however, heating the pile in the sand is insignificant to the overall capacity. Possibly because of the compaction of the silt soil during pile installation.<br>• Heating process induces higher compressive strains in the pile, which are greater than that developed due to pure mechanical load.<br>• The strain developed along the pile length varies and it depends on the magnitude of mobilized side friction.<br>• Centrifuge tests on scale-model GEP foundation installed in an unsaturated stiff layer with end-bearing boundary conditions, heated at 62°C with maintained load of 439 kPa.<br>• Greatest thermal axial stress occurs near base, above null point. Nonlinear change in stress with depth results from mobilized side shear stresses. During each subsequent heating stage GEP expands slightly less. Changes in soil behavior during transient cycles does not have a major impact on response. Thermo-hydro-mechanical effect in soil layer did not affect GEP behavior, besides of thermally induced water flow have been noticed. |
| **University of Paris-Est**<br>**France**<br><br>**Kalantidou et al. 2012**<br>**Yavari et al. 2014**<br>**Nguyen et al. 2017** | • The pile behaves in a thermo-elastic manner when the load is less than 40% of the pile ultimate resistance.<br>• When the applied mechanical load exceeds 40% of the ultimate resistance, permanent settlement develops.<br>• More than 70% of the pile load is resisted at the pile toe.<br>• The magnitude of the measured soil pressures below the pile toe were significantly influenced by the coupled thermal and mechanical load.<br>• The mobilized pile surface friction increased during initial mechanical loading and was significantly modified during subsequent thermal cycles.<br>• The pile behaves in a thermo-elastic way, when the constant axial head load applied is within 30% of the piles surface resistance. However, a significant cumulative permanent settlement could occur with an increased axial force at the pile toe, for a higher pile head load exceeding 30%.<br>• Thermal cycles induce an irreversible settlement of the pile.<br>• The first thermal cycle induces a higher magnitude of pile settlement, which decreases and gradually becomes negligible with more subsequent number of thermal cycles.<br>• The axial force developed at the end of a heating phase is higher than that at the end of subsequent cooling phase. |

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| **Hong Kong University of Science and Tech.**<br>**Hong Kong**<br><br>**Ng et al. 2014**<br>**Ng et al. 2015** | • Pile embedded in lightly over-consolidated clay undergoes a more pronounced ratcheting settlement pattern with a reduction in severity due to thermal cycles, compared to the pile embedded in heavily overconsolidated clays.<br>• A cumulative settlement of 3.8%D (D-diameter) was observed in the pile installed in lightly over-consolidated clay, compared to the 2.1%D associated with piles in heavily over-consolidated clays, after five heating and cooling cycles. The larger settlement in lightly over-consolidated clay may be due to accelerated creep rate at the pile-clay interface caused by the thermal cycles.<br>• Both the energy piles (EP1 and EP2), installed in lightly and heavily over-consolidated clay, continued to settle under thermal load application at a reduced rate.<br>• The ratcheting settlement of piles in clays could be problematic to the serviceability of the energy piles and structure in the long run.<br>• The neutral point located below mid-depth moves downward due to increase in temperature.<br>• Under pure heating load, there was additional mobilized base resistance due to constrained vertical expansion.<br>• Heating EP1 and EP2 continuously for 4 months, without axial load, resulted in pile heave by 0.4%D and 1%D. These are 32% and 21% lower than the theoretical displacement values calculated.<br>• Similarly, heating EP2 continuously for 4 months, under coupled thermal and mechanical load, resulted in initial pile displacement of 1.4%D, which later settled to 0.6%D due to 4 months heating. This led to volume contraction due to the thermal collapse of larger pores.<br>• Subjecting EP1 and EP2 to 37 °C and 52 °C resulted in 13% and 30% increase in pile capacity compared to the reference pile (i.e. EP1 with no thermal load applied).<br>• Increase in pile capacity, when a pile is heated to 37 °C, was achieved through the increase in mobilized shaft resistance. However, when a pile is heated to 52 °C, the applied vertical load is resisted by the larger resistance mobilized at the toe. |
| **University of Dundee**<br>**Scotland**<br><br>**Minto et al. 2016** | • New thermally enhanced plaster-based model concrete was developed and tested to realistically reproduce both thermal and mechanical properties of a GEP at prototype scale in centrifuge testing.<br>•Addition of copper powder was effective to enhance thermal properties while simultaneously maintaining its ability to mimic the mechanical properties of the concrete. 6% is the optimum percentage, where the effects of temperature on mechanical properties up to 50°C is negligible. New suggested GEP model is then a mixture of plaster, silica sand, water and copper powder. |
| **The Pennsylvania State University**<br>**USA**<br>**Kramer & Basu 2014**<br>**Ahmadipur & Basu, 2017** | • An increase in the GEP temperature results in additional effective stress development at the pile toe.<br>• Also, temperature increase leads to an increase in lateral confinement and mobilization of additional shaft and base resistances around the GEP. |

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| **Chongqing University, Hohai University**<br><br>**China**<br><br>**Wang et al. 2016**<br>**Wang et al. 2017**<br>**Peng et al. 2018** | • Under the same heating power, the horizontal earth pressure for the W-shape GEP was 1.18 and 1.24 higher than the spiral and U-shape GEP, respectively.<br>• The W-shape GEP had higher thermal strain along pile depth, followed by spiral type GEP under the same heating power.<br>• Settlement accumulation was observed after each cycle. The W-shape GEP had −0.585mm (0.56%D) at the end of the third cycle, thus indicating that attention should be paid where repeated heating–cooling cycles are involved.<br>• Experimental results form 1g small scale model groups embedded in sand, with nonthermal piles incorporated. Temperatures scaled down to a 5-year period profile from Nanjing region. Cyclic thermal applied loads.<br>• Behavior of group is distinct of a single pile in terms of developed axial stresses, and could be explained by higher lateral confining pressures on GEPs. Thermomechanical behavior of a GEP is also controlled by end restraint boundary conditions. In the case where not all piles are thermally active it was noticed non uniform displacements due to pull out resistance, during heating, and skin friction differences, during cooling.<br>• Axial pile stresses are basically a function of restrained bound. conditions controlled by lateral conf. pressures.<br>• Small scales 1:20 concrete piles in a large tank separated by 10 dia., during heating and cooling operations, fully immersed in dry sand, either with or without applied vertical load.<br>• Thermal cycles have induced thermal stresses in the piles and residual stresses after cycles. Horizontal soil pressures also changed. Heave under no load was 143% of that under vertical applied load, after heating, and 64% after cooling. Axial stresses increased along depth but always lower than the tension limit of the concrete, based on Chinese code. Axial loads increase during heating, around 42% of those from mechanical load, and decrease during cooling, also inducing settlements.<br>• Pile and soil temperatures within 1 dia. of pile axis changed considerably. Pile tip resistance increased during heating and decreased on cooling, likewise horz. soil pressures. Side shears had different directions at upper and lower parts of the pile. Developed thermal loads are distinct under no applied x applied pile load conditions. |
| **University of Wisconsin-Milwaukee**<br>**Virginia Polytechnic Institute**<br>**USA**<br><br>**Yazdani et al. 2019** | • 5 small scale pile load tests at 1g lab scale were performed to understand shaft resistance effect on a summer mode operation, in which ground is a heat sink. Load-displacement curves were drawn and pore water pressures surrounding the GEPs have been monitored. Fully saturated normally consolidated kaolin was employed.<br>• It was observed that heat can improve axial capacity and that cyclic and non-cyclic heating can cause differences in shaft resistance. Heating also increases the initial stiffness of the GEP curve.<br>• Interface shaft resistance growth may be explained by an increase in interface friction angle and eff. lateral stress due to thermally induced negative pore water pressures during heating operation. |

| | **Key Findings on Thermal Performance** |
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| **The Pennsylvania State University**<br>**USA**<br><br>**Kramer et al. 2015** | • Thermal efficiency of a GEP system increases with an increase in heat carrier fluid velocity, however, it results in higher electrical energy usage. Thus, could be detrimental on its seasonal performance.<br>• No residual temperature changes remained in the soil where the applied heat injection and extraction rates are equal.<br>• Thermal cycles have positive influence on heat transfer efficiency of a GEP. The first cycle (e.g. heat injection) enhances the soil thermal potential which results in higher heat exchange rate during the subsequent opposite thermal cycle process (heat extraction). |
| **University of Sheffield**<br>**England**<br><br>**Black & Tatari 2015** | •Small scale model of GEP using the technique of transparent soil and image analysis methodology, i.e., relationship between pixel intensity and soil temperature, to define the heat flow in the soil along the pile.<br>•Heating zone of influence is observed to extend to a radial distance of 1.5 diameters from the GEP. |
| **Texas A & M University**<br>**USA**<br><br>**Akrouch et al. 2015, 2016** | • Pile thermal performance could increase by up to 40% in sand depending on the degree of saturation.<br>• The varying water table in sand decreases thermal exchange efficiency by up to 0.43, when at the pile toe. However, little significant difference was observed in sandy-clays. |
| **Yangzhou University**<br>**China**<br><br>**Yang et al. 2016**<br>**Fei & Dai 2018** | • The heat energy rejection rate increases linearly with an increase in inlet fluid temperature.<br>• A reduction in pitch size (vertical spacing between two helixes) could lead to an increase in total heat rejection rate per unit length of the GEP.<br>• The thermal effusivity of a GEP (or ability to exchange thermal energy with its surroundings) has significant influence on its heat rejection rate and on the soil temperature restoration rate.<br>•1g small scale model with dry sand and mortar GEP subjected to 3 thermal cycles of 15°C. Ultimate pile resistance after thermal cycles does not decrease significantly but the accumulation of the free head pile settlement should be considered in design. Additional 3D numerical sensitivity analyses are carried out. |

Table of Annex I.3. Key findings on numerical studies on the thermomechanical behavior and performance of geothermal thermally active (energy) piles (GEP)

| Reference | Objectives & Tool/Model | Key Findings on Thermomechanical and Performance | Properties |
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| **Choi et al. 2011** | Effect of varying thermal properties of unsaturated soil on the intermittent operation of a GEP<br><br>ABAQUS 3D FEM | • Intermittent operation is more adequate for unsaturated conditions under unbalanced thermal conditions and vertical GEPs, since it affects less ground temperatures than continuous operations. It gives better performance in both heating and cooling modes. Differences between heat load in intermittent and continuous operation modes increases as unsaturated zone is deeper, i.e. as water level varies.<br>•Thermal interference between adjacent GEPs depend on the depth of the water table as well as distance between GEPs. Small changes in temperatures for distances > 20 radius. | DGEP=75cm<br><br>L=40m<br>U tube 2.5 cm<br>weathered granite<br>30/40% quartz |
| **Peron et al. 2011** | New geotechnical method for GEPs based on load-transfer approach - continuation<br><br>Finite-Difference 1D model | • Extension of the previous work of this same research group (Knellwolf et al 2011) in which a Java programming developed a new software based on load-transfer mechanism to account for mechanical and thermal loads on single GEPs. Similar parametric runs.<br>• Heating of the pile induces additional compression and increases mobilized shear stress, whereas cooling can induce a release of stress, possibly leading to a reversal of stress sign and eventually the development of tensile axial stresses in the pile. There is an interplay between changes in friction mobilization and additional efforts within the pile, caused by variations in temperature and prevailing soil-pile-structure interactions. | DGEP = 50 cm<br>L = 10m<br><br>Floating,<br>semi-floating and<br>end-bearing piles |
| **Knellwolf et al. 2011** | New geotechnical method for GEPs based on load-transfer approach<br><br>Finite-Difference 1D model | • Java programming to develop a new software based on load-transfer mechanism to account for mechanical and thermal loads on single GEPs. Calibration with similar pile and soil characteristics as Lambeth College & EPFL experiments. Match between numerical and experimental values are good.<br>• Heating induces additional compression and increases shear stresses at interface, whereas cooling may induce tensile axial stresses with a decrease of shear stresses. There is an interplay between stresses, displacements and boundary restraints. | DGEP = 50 cm<br>L = 10m<br><br>Floating,<br>sem-floating and<br>end-bearing piles |
| **Suryatriyastuti et al. 2012** | Effect of temperature induced mechanical behavior of GEPs under different soil–pile interface conditions: perfect contact and sliding contact scenarios<br>FLAC 3D, FDM 3D | • The stresses and displacements obtained at the soil-pile interface for sliding contact are lower compared to that developed under perfect contact condition.<br>• Application of thermal load alters the shaft friction mobilized at the soil-pile interface. | Single square GEP<br>Width, B = 0.6 m<br>L=15 m<br>Loose sandy soil |

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| **Arson et al. 2013** | Impact of pile de-bonding on the thermal and geotechnical performance of GEPs considering 2 cases: perfect contact and debonding (with 1.6mm between pile and soil)<br><br>FEM 1D | • The presence of an air film (1.6 mm) at the soil–pile interface acts as an insulator between pile and soil, hence, yielding a decrease in heat transfer between the pile and the ground, compared to the case of perfect adhesion.<br>• De-bonding causes a reduction in efficiency on the geothermal heat pump, thereby breaking the energy balance of the system.<br>• De-bonding has a mechanical effect on the adhesion between the pile and soil, which results in loss of friction at the soil-pile interface. | 1 GEP<br>DGEP =0.45 m<br>Expansive clay |
| **Zarrella et al. 2013a** | Comparing the performance of a helical-tube and double-U-tube BHEs with balanced and un-balanced thermal load and effect of axial heat transfer<br><br>GeoHP-Calc with CarM Model and Digithon building software | • The helical-tube GEP require about 50% shorter length than that of the double-U-tube.<br>• The effect of axial heat transfer on the double-U-tube heat exchanger, and a helical-tube with a balanced heating-cooling load, is negligible.<br>• In a helical tube with an unbalanced thermal load demand, the axial heat transfer effect results in about 10% lower annual electrical energy consumption.<br>• The seasonal COP values of 3.7 (cooling) and 5.3 (heating) were obtained when the axial heat transfer is neglected against 4.3 (cooling) and 5.6 (heating) when the axial heat transfer effect is accounted for. | Helical tube:<br>BHE=0.5 m, L=12m<br>Dhelix=0.38m, Pitch height=0.1m,<br>Double-U-tube:<br>parallel connection<br>BHE=0.14 m,<br>L=60m |
| **Zarrella et al. 2013b** | Comparing the performance of a helical-tube, double-U-tube and 3-Utube GEPs and effect of pitch height in a helical pile: 75, 150 and 300 mm<br><br>GeoHP-Calc with CarM Model and Digithon building software | • The helical tube produced a 23% and 40% higher thermal performance compared to the 3U-tube and double-U pipe configurations at peak load, respectively.<br>• Decreasing the pitch from 150mm to 75mm produced a 14% increase in peak load. However, the peak load decreases by 14% after increasing the pitch spacing from 150mm to 300 mm. | Helical tube:<br>BHE=0.5 m, L=12m<br>Dhelix=0.36m<br>Pitch height=0.15m<br>Double-U-tube:<br>parallel connection<br>BHE=0.14 m,<br>L=60m<br>3-U-tube:<br>parallel connection<br>BHE=0.5 m, L=12m |
| **Loveridge & Powrie 2013** | Development of g-functions for GEP systems with an isolated pile at distinct conditions<br><br>COMSOL 2D Axisymmetric<br>ABAQUS 3D FEM | • Paper presents g-functions that capture the short-germ transient variations of pipe/fluid behavior in addition to heat transfer and heat storage within the concrete pile. By combining 2D and 3D model outputs, and the finite line source heat transfer method, the overall avg g-functions were derived for lower and upper bound combinations related to differing pile and pipe arrangements.<br>• A numerical example of the method indicates that GEPs must operate across smaller temp. ranges than BHEs, and in long term scenarios there is a net imbalance of heat transfer with respect to injection and heat extraction. | DGEP = 30, 60 & 120 cm<br>L/D = 15 to 50<br>2 soil conductivities<br><br>Distinct time spans |

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| **Park et al. 2013** | Comparing the performance of W-tube and 3-U-tube GEPs with respect to heat exchange rate and ground temperature increase<br><br>ABAQUS, 3D FEM | • The W-tube and 3-U-tube resulted in heat exchange rate of 87 W/m and 42 W/m respectively, after 3 months cooling.<br>• Thermal resistance decreases with denser HDPE pipes i.e. 0.131 mK/W and 0.098 mK/W for W-tube and 3-U-tube respectively.<br>• An increase in heat carrier fluid velocity resulted in increase in amount of exchanged heat.<br>• The average exchanged heat increases linearly with higher temperature difference between the heat carrier fluid and the ground. | W tube:<br>parallel connection<br>DGEP=0.4 m,<br>L=13.25m<br>3-U-tube:<br>parallel connection<br>DGEP=0.4 m,<br>L=13.75m<br>Weathered granite soil deposit |
| **Bodas Freitas et al. 2013** | Investigation of the thermomechanical response of a single pile<br><br>ADINA 2D Axisymmetric | • Axial stresses in the pile will depend on the coeff. of expansion of the soil and its relation to equivalent one from concrete. Axial loads and interface shear stresses increase with soil Young modulus. Boundary conditions are also of extreme importance in simulations.<br>• Zero thermal flow or constant temperature at interfaces do also interfere with results. Hence thermomechanical behavior is influenced by distinct restraints imposed by mechanical and thermal conditions. | DGEP = 1 m<br><br>L = 30 m<br><br>OC clay |
| **Suryatriyastuti et al. 2014** | Effect of cyclic temperature change on the mechanical behavior of GEPs<br><br>FLAC 3D, FDM 1D & 3D | • Repetitive heating and cooling cycles cause degradation of shear resistance at the pile soil interface, which decreases the pile shaft capacity for restrained and unrestrained piles.<br>• A thermal cyclic fatigue effect (strain ratcheting and stress relaxation) were observed at the end of the analysis. | Square GEP<br>Width, B = 0.6 m<br>L=15 m<br>Loose sandy soil |
| **Dupray et al. 2014** | Response of group of GEPs for seasonal heat storage under thermomechanical Load<br><br>Lagamine<br>FEM 2D Axisymmetric | • Higher temperature (in the range of 40 °C) storage does not affect the overall efficiency, which decreased at a rate of 1.4% per °C, between the mean annual temperature and initial ground temperature.<br>• Heating/cooling group of piles together has a positive impact on the geotechnical behavior compared to heating/cooling individual secluded piles.<br>• The heating phase results in a decrease in horizontal effective stress, while the cooling phase leads to an increase in mean effective stress. | 4 GEPs<br>DGEP =0.8 m<br>L=20 m<br>Clay soil |
| **Olgun et al. 2014** | Investigation of increase in pile load capacity at higher temperatures due to attributed thermal radial expansion<br><br>2D FEM plane strain<br>plane stress<br>COMSOL | • Radial contact pressures typically increase less than 15 kPa, which can not fully explain the increase in shaft resistance during heating stage. Effect of temperature is to increase stiffness on pile load-settlement response.<br>• Piles expand almost freely at interface, and radial strains occur due to thermal expansion of both soil and concrete with compensating effects.<br>. Increase in contact pressures for transient analysis is however higher than for stationary ones due to the thermal expansion of the soil. | DGEP = 60 cm<br>Variable stiffness<br><br>Undrained stiff clay |

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| **Loveridge & Powrie 2014a** | Investigate the heat transfer in a GEP<br><br>COMSOL, 2D-Planar FEM | • Installing HDPEs at the center in a CFA pile results in lower magnitude of temperature distribution at the pile circumference. Thus, leading to reduced influence associated with pile movement in geotechnical design.<br>• CFA GEPs with loops at the center possess larger thermal resistance than rotary bored piles. | CFA GEP<br>Rotary bored GEP<br><br>DGEP=0.6m |
| **Loveridge & Powrie 2014b** | Development of G-functions for multiple interaction GEPs with exemplified cases<br><br>ABAQUS 2D Axisymmetric<br>MATLAB software | • Extends a previous work from the same authors in 2013 that have generated G-functions for isolated piles with distinct aspect ratios based on a numerical procedure. In the present case, G-functions of the pile group will be the avg. response of all piles, interacting with each other, each particular interaction with its respective G-function that depends on pile/soil thermal characteristics, thermal load, center-to-center distances and elapsed time.<br>• If multiple adjacent piles are used as heat exchangers there will be adverse thermal interaction between them. The interaction will increase with increase in aspect ratio and no. of piles and decrease with pile spacing. It is not always advantageous to equip all piles as thermal active ones. Overall energy of group is always greater than from a single pile but the produced energy per piles decreases as the interactions increase. | DGEP= 1.2m<br>L/D = 5 to 50<br>s/D = 1 to 100<br><br>Nondimensionalized values based on ground conductivity and diffusivity |
| **Jeong et al. 2014** | Investigation of thermomechanical response of pile groups with distinct geometric and geotechnical factors<br><br>3D COMSOL FEM | • Evaluation of group response due to distinct configurations and spacings, soil types and base restraints. Thermal load causes little change in mechanical behavior, not influencing much the capacity. Patterns of axial load distribution is similar in sands and clays, but sands have higher values due to greater thermal conductivities. End bearing piles develop smaller settlements and have larger axial loads than floating ones. Pile cap induces significant reduction in axial load due to restraint to vertical displacement in cooling mode.<br>• Axial load on GEPs depends on pile location, as center, corner or edge, but pile failure or excessive settlement is unlikely to occur due to thermomechanical loads. | DGEP = 50 cm<br>L = 20 m<br><br>Raft B = 6.5 m<br><br>s/D = 3 & 5<br><br>Sand / clay |
| **Rotta Loria et al. 2015** | The impact of different magnitudes & combinations of mechanical and thermal loads<br><br>Lagamini Software<br>FEM 2D Axisymmetric | • Increase in the thermal and mechanical load increases the magnitude of the vertical load transmitted through the pile toe.<br>• A plastic strain developed at the soil-pile interface at larger magnitudes of thermal and mechanical load, thus inducing a large effective horizontal stress, which ultimately affects shaft resistance.<br>• The null point moves up and down depending on the magnitude of the thermo-mechanical load applied, and it corresponds to the stress distribution occurring in the surrounding soil. | 3 GEPs<br>DGEP =0.88 m<br>L=19.6 m;<br>Saturated Toyoura sand |

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| **Cecinato & Loveridge 2015** | Effect of different factors on the thermal performance of GEPs<br><br>ABAQUS, 3D FEM | • The most important factor is maximizing pipe contact surface area (i.e. higher number of pipes). But, placing pipes close together could lead to pipe-pipe thermal interaction.<br>• Higher concrete thermal conductivity results in greater heat energy exchange.<br>• Heat carrier fluid flow velocity has not much significant impact on overall heat energy exchange, provided turbulent flow is maintained.<br>• Influence of pile diameter and length; concrete cover; concrete thermal conductivity; number and diameter of HDPEs; Heat carrier fluid, flow velocity have been assessed. | DGEP = 0.3 m; L = 26.8 m; U-loop<br><br>London Clay |
| **Batini et al. 2015** | Effect of different pipe configurations; GEP geometrical aspect ratio; Heat carrier fluid flow rate and the variation of antifreeze volume in the HCF on the thermal performance of GEP<br><br>COMSOL, 3D FEM | • Pipe configuration is the most important factor in terms of heat transfer efficiency.<br>• W-shape pipe showed 54% higher heat transfer rate compared to single U-shape pipe.<br>• The double U-shape is the least advantageous because it has double fluid flow rate. Also, it induced greatest concrete cooling, stress and displacement in the pile.<br>• Increasing the pile length and diameter linearly increase the amount of exchanged heat.<br>• Increasing fluid velocity from 0.2 m/s to 1 m/s resulted in increased heat transfer rate by 11%, with no increase in vertical stress within the pile.<br>• Adding low antifreeze concentration to the fluid does not affect the heat transfer rate when compared to pure water. However, adding 25 or 50% of Mono-Ethylene-Glycol decrease the heat exchange rate by 6 and 11% respectively.<br>• The heat transfer rate decreased by 30% for single U-shape compared to the first day of operation, while up to 45% for double U and W-shape pipes. | DGEP=0.9 m; L=28 m; 1-U, 2-U & W-shape loops; Dbar=40mm Alluvial sandy-gravelly moraine soil |
| **Olgun et al. 2015** | Investigated the effect of long-term thermal cycles on the temperature distribution within and around the GEP<br><br>COMSOL 2D-Planar FEM | • The nature and distribution of temperature around a GEP and its surrounding soil is dependent on the seasonal energy demand.<br>• In a balanced system (e.g. Charlotte, North Carolina), the region influenced by temperature changes within the soil mass surrounding the GEP is minimal, hence, resulting in high efficiency over long-term.<br>• In an unbalanced climatic condition (e.g. Chicago, Illinois and Austin, Texas), the system loses its efficiency over time especially in larger pile grids. | DGEP=0.6m |

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| **Loveridge & Cecinato 2015** | Comparison of the energy performance of CFA piles and that of rotary bored piles<br><br>ABAQUS 3D FEM | • Rotary bored piles are more efficient than CFA piles when equipped with the same number of pipes, because of the pipes situated near the pile periphery.<br>• Rotary bored piles offer more room for installing a higher number of pipes in the pile cross-section, which maximizes its efficiency.<br>• A CFA can be fitted with 4 HDPE pipes than the conventional two pipes commonly used. But, a turbulent fluid flow regime should be maintained in the pipes.<br>• The current norm of installing CFA piles with steel bar for rigidity has no detrimental effect on thermal performance. However, using spacers to avoid bunching of the pipes would improve the system performance. | CFA GEP<br>Rotary bored GEP<br>DGEP=0.9 m;<br>L=25 m, 2-U-loops<br>Dbar=40mm<br><br>London Clay |
| **Gashti et al. 2015** | Investigated the effects of groundwater flow on the GEP performance<br><br>COMSOL 3D FEM | • They discouraged the use of other secondary methods to forcefully recharge the soil in situations where groundwater flow exists.<br>• In winter operating mode, the amount of heat extracted increases by up to 20%.<br>• In summer operation, GEP performance increases by 5% due to groundwater flow effect. | DGEP=0.6m<br><br>L=20m |
| **Suryatriyastuti et al. 2015** | Comparison between a single GEP and an GEP group with different boundary conditions<br><br>FLAC 3D FEM | • Thermo mechanical loads, at applied loads of 1/3 of ultimate. Thermal cycles of ±10 °C. Cooling the piles induces loss of mobilized shaft and base resistances while heating generates greater mobilized values. Degradation in pile capacity with cycles due to repetitive stress reversals is noted.<br>• In a group where not all piles are thermally active the presence of cap permits to transfer induced displacements to the group in a more uniform manner, however neighboring piles will receive redundant excess forces induced by temperature variations to satisfy static group equilibrium. The balancing phenomena will occur regardless of head fixity conditions. It also affects state of displacement. Long-term effects are important. | DGEP = 60cm<br>L = 15 m<br><br>Single pile and<br>3 x 3 group<br><br>Sandy soil |
| **Salciarini et al. 2015** | Investigation of mechanical and thermo mechanical effects of an existing piled raft system with GEPs<br><br>COMSOL 3D FEM | • Significant axial load changes can be experienced by both thermally active and nonactive piles on the raft, and the load distribution reaches their peak at a very early stage of the thermal process, when differences among active and nonactive piles are at largest. 4 different energy piles layouts are further studied and commented.<br>• Behavior is similar for 4 systems up to 1-month operation, but efficiency decreases faster on systems with more piles due to higher thermal interference. Appreciable efficiency losses after few months of operation. Load is transferred from thermally active piles to nonactive ones. Peak axial load variations within 2-4 weeks. | DGEP = 1 m<br>L = 25 m<br>Raft D = 16 m<br>T = 2 m<br><br>Sand/clay strata |

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| **Abdelaziz et al. 2015** | Long term analysis of ground heat exchangers with equivalent sine wave thermal loads<br>Change-point statistical analysis<br><br>2D COMSOL Axisymmetric | • Heat balance method to obtain superstructure energy demands further to be compared to ground thermal loads. Statistical method is considered to transform varying hourly thermal loads into representative sine waves, in balanced or unbalanced manner.<br>• Long term performance of ground heat pumps depends directly on ground thermal loads. Office building example is provided to demonstrate the new technique. Long term performance of the system was found to be independent of the initial thermal load. | DGEP = 50 cm<br><br>Building thermal demand in 3 distinct USA locations |
| **Ng et al. 2016** | Behavior of semi-floating GEPs on the change in horizontal stress due to thermal cycle<br><br>ABAQUS FEM<br>2D-Axisymmetric | • Repeated pile expansion and contraction impose cyclic shearing at pile-soil interface, thus decreasing horizontal stress. This decreased the shaft resistance capacity and led to an additional mobilization of base resistance to balance the reduction in shaft capacity. The settlement reaches a stabilized state after some repeated cycles.<br>• Amplitude of thermal cycles and pile diameter govern the magnitude of shearing at the soil-pile interface.<br>• The horizontal stress reduction after 50 thermal cycles decreases by up to 90% and is independent of the pile length for the range of pile length considered: 20m to 35 m. | DGEP=1–1.75 m<br>L=20–30 m;<br>L/D GEP = 20;<br>Toyoura sand |
| **Saggu & Chakraborty 2016** | Thermomechanical response of GEP groups in sand with active and non-active thermal piles<br><br>ABAQUS 3D FEM | • 4 different combinations of thermally active and non-active piles in the group and spacings. Axial stresses and displacements were assessed. Heating caused redistribution of loads within piles, with high values at corners. Displacements increase when piles have closer spacings in between, with an increase of 47% in relation to solely mechanically loaded group. Design should be made with at least 4 diam. between piles.<br>• Axial stresses increased at end of heating in active piles and decreased in non-active ones, and vice versa on cooling. Distinct displacement directions are noted for corner and middle piles. Not recommended to mix active and non-active piles together in group. | DGEP = 1.0 m<br>L = 20 m<br><br>Top Raft<br>15.5 x 12.9 x 1.2 m<br><br>Ottawa sand |
| **Di Donna et al. 2016** | Response of GEPs in a group to different magnitude of thermomechanical load and effect of pile head restraint<br><br>Lagamine<br>FEM 3D | • Increase in temperature increases the stresses and displacements induced in the pile.<br>• Vertical displacement of +1mm (contraction) was observed when piles were mechanically loaded separately, and −1 mm (expansion) when individually heated due to thermal strain.<br>• Heating one or three GEPs together induces higher compressive stress in the order of 7 MPa, compared to heating the four GEPs together (4 MPa). | 4 GEPs<br>DGEP =0.9 m<br>L=28 m<br>Alluvial/ sandy-gravelly/moraine soil |

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| **Mehrizi et al. 2016** | Comparison of heat transfer between 3 HDPE configurations and impact of connecting 15 GEPs in series and in parallel<br><br>FLUENT/Gambit, 3D FEM | • W-Shape all round or 6-U-shape pipe configuration result in higher heat exchange efficiency by 20.63% and 35.5% compared to 1-W-shape and 1-U-Shape pipe.<br>• Inlet water temperature decreased by 4% and 4.27% when 10 and 15 piles were connected in parallel. Thus, connecting more than 10 piles in parallel is not economical.<br>• Connecting 6 piles in series greatly increased the amount of heat transfer by 4.54%. A moderate increase of 0.67% when 7–11 piles were connected. However, connecting 12–15 piles resulted in 0.13%. Thus, it is ineffective connecting more than 11 piles.<br>• There is 65% and 73% increase in heat energy output for piles connected in parallel and series, compared to a single pile. | 1-U-shape<br>1-W-shape<br>W-shape all round or 6-Ushape<br>DGEP=0.6 m<br>L= 20, 25 & 30m<br>Sandy silt |
| **Bourne-Webb et al. 2016** | Investigated the impact of a limited set of thermal and thermo-mechanical parameters on the thermo-mechanical behavior<br><br>ABAQUS Axi-symmetric 2D | • Difference between initial ground temp. and thermal conditions by superstructure establishes initial thermal effect on foundations, that must be accounted for.<br>• Response from pile in field test is distinct from those in operational thermal conditions.<br>Incorrect predictions are found with the coeff. Thermal expansion is ignored or wrongly assumed.<br>• Conservative values are obtained when the soil is assumed to be thermally inert. | DGEP=1m<br><br>L=15, 30, 45m<br>Distinct surface Ts<br>Distinct Coef T.Expansion<br>Isolated pile<br>Thermal analysis |
| **Abdelaziz & Ozudogru 2016** | Influence of non-uniform distribution of thermal strains and stresses in a GEP subjected to transient thermal loads<br>COMSOL, 3D FEM | • They showed that both thermal tensile and compressive stresses and strains were found to coexist in a GEP during either heat rejection or injection process. This occurs because of the non-uniform temperature changes that exist within the GEP cross section. | 1 GEP<br>DGEP = 0.5 m<br>L=10 m<br>Silty clay |
| **Tsetoulidis et al. 2016** | Investigation of thermomechanical response of single pile and pile group<br><br>ABAQUS 3D and Axisymmetric FEM | • Axial forces on pile depend on the no. of thermally active piles. Cooling increases interface shear stress at top and decrease at bottom. Settlements are small in magnitude but greater than those due to mechanical load. Corner piles have higher axial mobilized loads. Heating causes redistribution of axial loads at pile heads and depends on pile position and active or non-active status.<br>• Impact on the settlement increase only noticeable in pile groups. Small change of pile capacity due to thermal loading is due to slight increase/decrease at pile-soil interface. | DGEP = 60 cm<br>L = 23 m<br><br>s/D = 3<br><br>Similar soil conditions as Lambeth College |

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| **Vieira & Maranha 2016** | Thermomechanical analysis of a single pile in typical Lisbon conditions<br><br>2D FLAC Axisymmetric | • Mechanical effects of thermal action in isolated pile with elastoplastic FEM analysis and transient heat flow under 5-years cyclic seasonal atmospheric temp. trend of Lisbon.<br>• Thermomechanical response is reversible and elastic, but GEP suffers irreversible settlement in each year of thermal cycle. Yielding at interface limits load transfer to pile and thermal actions should be considered in structural design. Monitoring is fundamental. | DGEP = 60 cm<br>L = 20 m<br><br>NC saturated clay |
| **Kawuwa et al. 2017** | Response of the soil surrounding a GEP to heating load<br><br>COMPASS, 2D-Axisymm. FEM | • The duration of the heat injection/extraction has direct influence on the time to achieve natural recovery.<br>• The soil requires about 4 times the heating time to naturally recover towards its initial state. | DGEP=0.6m<br>L = 30 m<br>London Clay |
| **Olgun et al. 2017** | Investigated the long-term performance of GEPs under different myriads of climatic conditions<br>COMSOL 2D-Planar FEM | • The estimated heating–cooling amplitudes are linearly proportional to the resulting GEP temperature in a long-term thermal operation process i.e. 30 years.<br>• The heat exchange efficiency of the GEP system is expected to decrease after a long-term usage. | DGEP=0.15 m |
| **Wu and Gan 2017** | Thermomechanical behavior of a small-scale GEP with coupling effect of thermal expansion in soil and pile<br><br>ABAQUS 2D Axisymmetric FEM | • Individual and multiple thermal loading cycles have been applied for short- and long-term performance. 30 cycles at distinct applied loads from 0-60% of ultimate capacity, obtaining stationary settlement after several cycles. Relative settlement is small compared to the one solely from mechanical load.<br>• Higher mechanical loads results in a higher irreversible thermal settlement. Temperature induced settlement is stabilized in the first 3 cycles, and the first cycle in the simulation had the largest irreversible increment. Resulting settlements progressively achieves a stable state due to a densification process that occurs at each thermal cycle. | Centrifuged<br><br>DGEP = 20mm<br>L=600mm<br><br>Saturated speswhite China clay |
| **Rotta Loria & Laloui 2017** | Design charts for displacement of GEP groups via displacement interaction factors<br><br>COMSOL 3D FEM | • Integrates resents analyses with displacement factors due to thermal loads on floating and end bearing piles and presents design charts for practical application. Numerical results are validated with comparison with full 3D thermomechanical FEM analyses.<br>• Method is extended to yield equations and procedures to analyze a group of piles in which some or all are subjected to thermal loads, and a 3 x 3 example is provided.<br>• Interaction among piles increase with the presence of a bearing rigid strata, but experimental evidence is clearly needed for further validation of this methodology. | DGEP = 1m<br><br>Distinct L/D, s/D<br><br>n x n groups floating and end-bearing piles |

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| **Gawecka et al. 2017** | Thermomechanical behavior of a energy pile in clayey deposit under distinct modelling conditions<br><br>Axisymmetric FEM model | • Thermo-hydro-mechanical model from Imperial college adopted in FEM analysis of a single pile subjected to distinct conditions of modelling, thermal loads, soil thermal conductivities and permeabilities.<br>• Thermally induced stress changes tend to reduce with time as surrounding soil reacts to change. Modelling can have impact on results, for instance if they are coupled or uncoupled in thermo-hydro-mechanical terms. Changes in permeability and conductivities do not significantly alter results when compared to modelling approaches.<br>• Changes in radial stress can have an impact on shaft friction but magnitudes are very small. Thermally induced pile deformations and diffs. in the coeff. of thermal expansion of soil and water particles do lead to generated excess pore pressures around the GEP. | DGEP = 60 cm<br>L = 23 m<br><br>Similar soil conditions as Lambeth College |
| **Salciarini et al. 2017** | Parametric analyses of a GEP group with active and non-active piles at distinct configurations<br><br>ABAQUS 3D FEM | • Parametric study that assessed influential aspects of thermal soil properties (conductivity and expansion coeff.) and GEP group layout (active and non-active GEPs).<br>• Axial loads in thermo-active piles depend on the pile spacing between them. Significant thermal interactions occur between closely spaced piles. Thermally induced displacements can be high in the presence of a high no. of active piles. Thermal conductivity and coeff. expansion of the soil do influence the final results.<br>• Presence of a relatively rigid raft in contact with soil is responsible for axial load variations in non-active piles of same order of those from thermally active ones. | DGEP = 60 cm<br>L = 25 m<br>S = 2.5 m<br><br>Raft 5 x 5 m<br><br>OC stiff clay |
| **Sani et al. 2018a,b 2019b** | Heat flow mechanism in a GEP and performance of a CFA pile and heat flow characteristics in a CFA pile<br><br>COMPASS 2D-Planar FEM | • Installing central steel in a CFA GEP contribute to higher heat transfer between the inlet and outlet pipes.<br>• Utilizing plastic bar of adequate strength provides an economical and energy efficient solution to installing loops in CFA GEP.<br>• Increasing the shank spacing between inlet and outlet pipes increases the GEP efficiency.<br>• Heat transfer between the inlet and outlet loops become significant after a steady state is achieved i.e. 3-5 days.<br>• Increasing the number of installed HDPE loops lead to a higher magnitude of heat transfer between the pipes in a GEP.<br>• The circumferential temperature distribution varies with increasing number of installed loops.<br>• The normalized thermally active region for a GEP, fitted with 1−4 loops, spans out radially to about 7 m. | CFA GEP<br>Rotary bored GEP<br><br>DGEP=0.6m<br><br>London Clay |

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| **Sani et al. 2018c** | The study investigated the use of GEPs for heat storage in unsaturated soil domain<br><br>COMPASS, 2D-Axisymm. FEM | • The heat injection process results in drying up of soil next to the GEP, thus resulting in soil with lower saturation.<br>• Soil with lower saturation result in lower thermal conductivity. However, with an advantage of having a higher volumetric heat storage capability. | DGEP=0.6m<br>L = 30 m<br>Unsaturated swelling clay |
| **Sani & Singh 2018** | Response of unsaturated soils to heating load<br><br>COMPASS, 2D-Axisymm. FEM | • The mag. of temperature observed in the soil decreases with increase in soil saturation.<br>• Temperature changes in the soil decreases significantly in the first 10 days following the heating test.<br>• The magnitude of temperature build-up decreases with increase in soil granularity due to higher hydraulic and thermal conductivity.<br>• The thermally active region in the domain increases with soil granularity. | DGEP=0.6m<br>L = 30 m<br><br>Unsaturated clay, silt and sand |
| **López-Acosta et al. 2018** | Numerical analysis of the thermomechanical behavior of an isolated pile in Veracruz state<br><br>2D THERMAL PLAXIS FEM | • Different combinations of thermomechanical loads are carried out for subsoils conditions prevailing in a Mexican state. Magnitude of induced stresses is significant but their effects on foundation performance depends on sustained load level.<br>• Thermal loads represent 6-27% of mechanical loads depending on prevailing designed safety factors of pile. Small 40 kPa/°C was observed, with pile relatively free to expand. | DGEP = 60 cm<br>L = 15 m<br><br>Sandy Coatzacoalcos soil |
| **Rotta Loria et al. 2018** | 2 new analytical models to determine the vertical displacement of GEP groups<br><br>3D COMSOL FEM | • Extension of previous work from same research group (Rotta Loria & Laloui, 2017) where interaction factors between GEPs are estimated via layer and continuous models. Comparison with 3D FEM numerical results for distinct L/D, s/D conditions are provided.<br>• Displacement increases with decreasing s/D and increasing stiffness ratio pile/soil and increasing thermal exp. coeff. ratios soil/pile | DGEP = 1m<br><br>L/D = 25, 50<br>s/D = 3,5<br><br>5 x 5 group |
| **Cui & Zhu 2018** | Evaluation of coef.performance of ground source heat pump (GSHP) with ground energy piles<br><br>3D FEM finite volume method | • Piles and U tubes are discretized to investigate a GSHP performance in a 2-storey building in UK for 10 years. A transient heat flow model is also adopted. 16 GEPs operating in distinct 4 periods per year according with climate conditions.<br>• Unbalanced heating and cooling modes led the final temperature of the soil to be lower than its initial, decreasing coef. performance with time. Soil with high thermal conductivity and low volumetric heat capacity has the ability to recover quickly from thermal saturation. | DGEP = 30 cm<br>L = 10 m<br><br>Sand/clay/gravel layers |

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| **Mroueh et al. 2018** | Design charts for isolated GEPs under distinct thermomechanical conditions<br><br>Analytical load transfer functions | • Design diagrams that account for the rigidity of the structure and the consequences of ground thermo-volumetric strains and variable and cyclic thermal variations are provided to estimate the GEP axial loads. Temperature amplitude has show to be a key parameter in the analysis but the temperature rate is more important.<br>• For fixed head piles the GEPs should have rest phases as this is remarkably favorable and should be accounted for to decrease the induced axial loads. | DGEP = 52 cm<br>L = 12 m<br><br>Saturated sand |
| **Alberdi-Pagola et al. 2018a** | Method to obtain g-functions for multiple precast pile heat exchangers<br><br>COMSOL 3D FEM | • g-functions are dimensionless response factors that describe the change in temp. in the ground around GEPs for an applied thermal load. Therefore, it is a research based on simpler semi-empirical model to numerically obtain g-functions valid for 20 years of operation of GEP systems, in isolated and group arrangements with different pile spacings, and with 3 distinct thermal conductivities for the soil.<br>• The presented g-functions incorporate the thermal resistance coefficients from both pipes and surrounding pile concrete, together with the ground factor, all in terms of a normalized time span and temperature change. | Quadratic Shape<br>L/D = 15, 30, 45, 53<br>Single U Loop<br>W-Shaped Loop<br><br>20-year time scale |
| **Alberdi-Pagola et al. 2018b** | Optimization procedure for sizing and arrangement of GEP groups<br><br>MATLAB subroutine based on g-functions | • Optimization of a pattern of GEP group with a desirability function, that minimizes the number of GEP based on g-functions that provide overall return of ground loop temp. and long-term avg. fluid temperature. Procedure maximizes GEP spacing with required thermal load of structure. Example case that could have less 32% GEPs is provided.<br>• The desirability function allows more conditions to be considered in future designs so that the optimization of the no. of GEPs will be done to rationally supply energy demands. | DGEP = 30x30 cm<br>L = 15 m<br><br>Postglacial clay over sand/gravel |
| **Wang et al. 2019** | Analysis of the characteristics of a pile with cyclic temperatures<br><br>2D Axi-symmetric FEM software | • Cyclic heating and cooling lead to additional displacements and axial forces along the pile, that also depends on the applied vertical pile load levels.<br>• A zero or neutral point exists at which additional displacements caused by temperature variation are zero at the relative pile´s shaft depth. Displacements have opposite direction upwards and downwards from the neutral point.<br>• At the nonlinear plastic load displacement range of the GEP curve additional thermally induced displacements are irrecoverable. | DGEP=100cm<br><br>L=40m<br><br>Thermomechanical effects |

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| **Sutman et al. 2019** | Incorporation of soil-pile load-transfer approach into the numerical thermomechanical response of GEPs<br><br>COMSOL 2D Axisymmetric FEM | • Good agreement between model and site experimental results in terms of cyclic thermal behavior. Employment of load transfer approach via full scale tests yields satisfactory results. Temperature changes were balanced in the FEM analyses.<br>• Cyclic thermal procedure is crucial in the presence of structural load, and monotonic thermal analysis yields higher mobilized shaft resistance and axial displacements.<br>• Displacements related to temperature variations are generally minor compared with that from structural loads. | DGEP= 45.7 cm<br><br>L = 15.2 m<br><br>cast in place pile Richmond clay/sand profile |

Table of Annex I.4. Key findings on miscellaneous knowledge related to soils and geothermal thermally active (energy) piles (GEP)

| Reference | Key Findings on Miscellaneous Knowledge | Main Subject |
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| **Rawlings & Sykulski 1999** | • 1st.documented suggestion for using ground as heat source was in 1912 in Switzerland, but at that time heat pump efficiency was poor and energy prices were very low. Commercial use started after 1st. oil crisis in 1973.<br>• Design requires detailed analysis of building load, energy consumption and cost-efficiency study. Nowadays it is best carried out by electronic computer aided software, besides they often perform narrowly focused tasks.<br>• Countries where GSHP sales are high have support from governmental policies, either by direct subsidizing implementation, by promoting research and development, or as part of a national effort to increase the use of a renewable energy platform towards the decrease of CO2 emissions. | Detailed literature-based review on GSHP systems with focus on applications, benefits and costs |
| **Dincer 2000** | •Paper describes the relation between renewable energy and sustainable development, presenting successful practical cases in this direction. It anticipates patterns of future energy use and the consequent environmental impacts that the world may suffer given the escalating emissions of greenhouse gases. Major areas of environmental problems are described, as well as possible solutions with future use of sustainable sources.<br>•Global demand for energy services is expected to increase by as much as one order of magnitude by 2050, while primary energy demand is expected to increase by 1.5 to 5 times. Therefore, an integrated set of activities should be hosted by Governments, as the research & development of sustainable energy sources, technological assessments, development of standards, and transfer of knowledge to society. Some factors can however quickly enhance a sustainable development, as public awareness, continuous environmental education and training, adoption of innovative energy strategies, promotion of renewable resources, financing, monitoring and development of evaluation standards and surveillance tools, and encouraging policies. | Extensive review on key aspects of the field of renewable energy and its intimate relation to the world´s sustainable development |
| **Spitler 2000** | •Technical basis of the program used to design BHEs and an example of application in a building in Ottawa. The design methodology is based on a simulation that predicts the temp. response of the BHE via g-function curves (finite line source heat model) to supply monthly cooling and heating loads over a period of years. Design software automatically adjusts BHE size to meet user-defined min/max heat pump entry fluid temperature, based on a predefined set of ground thermal values and pump characteristics.<br>•Design process is based on a balance of energy, from one side the temperature of the fluid entering the pump via BHE heat transfer model & size/soil factors, from other side the same entering temp. that supplies the required thermal loads of the superstructure, that is based on pump characteristics and the relation of extracted soil heat x known building heat load (supplied by pump). It is an interactive process dealt by the software. | Presentation of the theoretical basis behind the software GLHEPRO for commercial design of borehole heat exchangers |

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| **Abu-Hamdeh 2003** | • Effect of water content and bulk density on the specific heat and thermal diffusivity of soils.<br>• Thermal properties are necessary for modelling transport of heat.<br>• Clayey soils have higher specific heat than sandy soils.<br>• Moisture content increase in clayey soils increase specific heat.<br>• Difference in mineralogy makes sandy soils to have a higher thermal conductivity and diffusivity than clayey soils, that can be estimated through empirical equations. | Laboratory studies of thermal characteristics of soils |
| **Sanner et al. 2003** | •Early development of GSHP in the Rhein-Main area of Germany is discussed, with details of the plants and problems that arouse from their implementations. The pioneering plant of the Verolum building in Schwalvach, 1st. commercial application of a GSHP with borehole heat exchanger in Germany, is described.<br><br>•Velorum plant owner, Helmut Hund, was convinced of the potential of this new technology and started research and development of the technique, with support from the Fed. Ministry of R&D and Justus Lieb Univ.<br><br>•1st. TRT in Germany as a basis for sizing a borehole heat exchanger field was carried out in the summer of 1999 for the German air traffic control center in Langen, close to Frankfurt. Early experience has demonstrated that GSHP systems in commercial applications offer some economic and environmental advantages. | Historical review of the development of heat pump plants in Germany |
| **Boguslaw & Lukasz 2004** | •Several theoretical and empirical methods have been presented and tested against experimental values of thermal conductivity. They can in general be successfully used in practice if no high temperature gradients occur in the soil and if it can be assumed that the effect of water vapor on the overall conductivity is neglected.<br><br>•Whereas heat capacity can be estimated with fairly good accuracy, there are problems to estimate thermal conductivity on existing techniques. Thermal conductivity also varies considerably with the soil saturation. | Evaluation on the calculation methods of thermal conductivity of soil via statistical / physical models |
| **Clarke et al. 2008** | •Thermal properties of samples of soil obtained from routine geotechnical Investigations can be derived by a new laboratorial technique that employs thermal cells and theoretical model curves for temperature decay. Heat transfer is obtained by adjusting cooling curve until it matches experimental one.<br>•Thermal conductivity varies with water content, density and mineralogy. Results are within 0-5 W/mK. | New laboratory test and interpretation approach to obtain thermal variables of soil samples |

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| **Boennec 2008** | •In UK there is not a definitive design standard as in Germany or USA, which is a challenge for the industry, in especial because as of 2007/8 the env. agency recognizes "temperature" as a potential pollutant. For instance, with more systems designed together there is a risk of long-term below ground "global warming".<br>•Shallow ground energy systems are a very dynamic and exciting area of the civil and building industry that requires much more investment in training, research and development, so to offer to society a valuable high value product that combines sustainability and energy generation. Technology is however still new to the UK. | Challenges, opportunities and progress of the ground source heat pump industry in United Kingdom |
| **Banks 2009** | •Paper reviews basic concepts of geohydrology as the geoenvironmental heat reservoir and heat pumps, the exploitation of ground source heat via open and closed-loop systems, key analogies between groundwater flow and heat conduction theories, and future research directions.<br>•Shallow geosphere represents a thermal store that can be used for heating and cooling purposes, and thermogeology is just one of several key skills needed to design a GSHP to extract or reject heat in the ground. The hydrogeologist needs to interact with mechanical and electrical engineers, architects and planners to ensure effective collaboration in the design of such systems, recognizing the limits of this technical field. | Background to the science of "thermogeology" and its importance in the proper exploitation of ground source heat |
| **Moel et al. 2010** | •Technological background, environmental considerations, and thermal issues as the heat transfer process and the soil´s thermal properties are discussed together with design and performance considerations. Benefits and limitations and some successful experiences of this technology around the world are further explored. Major drawback in terms of design is the lack of a theoretical model to predict performance that is able to consider all the parameters that effectively affect the GEP system on the long run, as site thermal imbalances.<br>•Potential challenges on long-term effects on ground temperatures and other related environmental impact issues must be better understood before further progress can be made with GEP systems. The Australian continent is vast and founded on distinct geological features, making imperative a better understanding of local specific geotechnical, hydrological and thermal conditions to better assess the performance of such systems, nevertheless in remote towns the GEP can be beneficial given its self-sufficiency and decentralized character. | Literature review on the technology behind the GEP system and its potential feasibility for usage in Australia |
| **Hueckel et al. 2011** | •Time-dependent heat conduction and permeability-dependent rate of dissipation on thermally generated pore pressures in fine soil materials are investigated by a 2D thermo-hydro-mechanical FEM model.<br>•The thermal load of a cylindrical heat source within the soil mass causes pore pressures to develop with a substantial modification on the surrounding distribution of axial effective stresses. Water flux is also influenced.<br>•Despite short duration of the pore pressure increase, it causes the eff. stress paths to approach the critical state reducing substantially the geotechnical structure´s margin of safety. Hence, designing heat source spacing solely based on field temperature is inadequate as thermoplastic effects do take place. | Numerical investigation on effect of temperature increase in clayey materials |

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| **Haigh 2012** | •Analytical model is developed based on unidirectional heat flow through a 3-phase soil element, being compared against a database of 155 test data and empirical predictions. The proposed method showed lower errors in its predictions as compared to other (empirical) equations, for sands and void ratios > 0.33.<br>•Thermal conductivity increases with its degree of saturation, and with the decrease of the void ratio. True value of the soil grain´s thermal conductivity changes the overall value of the bulk element of soil. | New analytical model to obtain the thermal conductivity of soils |
| **Bourne-Webb 2013** | •Main barrier to today´s better understanding of such structures is the lack on an extensive international database on well documented case studies on GEP testing and life performance, thus preventing a clear demonstration to clients, professionals and stakeholders that such technology is safe, viable and economic.<br>•There is a lack of design philosophies for GEPs since borehole heat exchangers may not be fully appropriated. Boundary conditions do affect the GEP axial stress and strain response, hence field tests should be interpreted and back calculated with care so to be used as guidance for GEP design, since real piles under restraining superstructures may behave in a distinct manner. Degradation of the pile resistance can be also a concern given the cyclic thermomechanical loads that are imposed on GEPs during their long life time.<br>•It would be useful to establish a set of protocols with a common format for the design, execution and monitoring of GEPs for research groups willing to advance the knowledge on this particular technology. | State-of-Art review on significant aspects of GEPs in terms of site behavior, physical understanding, design and research perspectives |
| **Arboit et al. 2013** | •South America has great part of its plate in a stationary mode, hence Brazil, situated in its middle, has more favorable conditions to explore low rather than high enthalpy energy sources, suitable for GEP systems.<br>•Given the predominance of hydric power and availability of other sources as natural gas, Brazil places geothermal energy to a secondary position. Low enthalpy resources have been identified in large number in parts of the Middle West and South of Brazil. At moment, studies are underway for thermal exploration of the extensive Guarany aquifer (840800 $km^2$) for heating purposes of water and agro-industrial processes.<br>•The use of geothermal low enthalpy energy for direct use in Brazil, rather than for electricity, is quite promising particularly for recreational tourism and GSHP systems with heating purposes. | Literature review on known resources and application possibilities of geothermal energy in Brazil |
| **Low et al. 2015** | •Comparison between laboratorial results from the steady state thermal cell and transient needle probe against a site TRT on a central London development.<br>•Measured thermal conductivity obtained by thermal cell is consistently higher than that using needle probe by around 40-50%, due to heat losses and radial x axial flow directions (anisotropic) effects. However, both lab. tests yield much lower conductivities compared to in situ TRT, possibly due to sample size, orientation and disturbance. TRT yields an overall value of soil conductivity, but almost twice as value of needle probe. | Comparison between distinct laboratorial and in situ techniques to derive thermal conductivity |

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| **Li & Lai 2015** | •Review on a set of data from 1990-2012 on closed loops GEPs and borehole exchanger heaters. It summarizes and evaluates major advances in this field including heat-source models, short-time models, energy pile models, in situ TRTs and back calculation of thermal parameters.<br>•Most widely used analytical tool for analyzing heat transfer on a ground heat exchanger is the Kelvin´s theory of heat source on Laplace transform method. In GEPs the length-to-diameter ratio is important, and it should take longer to reach a steady state than borehole exchangers. Hence heat-source method is highly likely to be the only viable theoretical method because various arrangements of heat transfer channels exist.<br>•The complex thermomechanical processes that occur in energy piles are far from fully understood. | Critical review on the analysis of heat transfer by borehole and foundation pile ground heat exchangers, emphasizing analytical models |
| **Vieira et al. 2015** | •Results of surveys carried out in the states of Tocantins, Mato Grosso and Pará with 110 localities at an accessible sampling depth of maximum 3 km. Results indicate an economic exploitation of around 365 MWt. •Low enthalpy systems with temperatures lower than 90°C are the most common type of geothermal reservoirs in Brazil. They are more significant in areas of thermal springs and sediment covers, being predominantly used for recreation purposes nowadays, rather than space heating.<br>•Precambrian areas in the state of Goiás and Tocantins are considered suitable for energy exploitation. | Assessment of geothermal resources in Brazil and their possible uses |
| **Sailer et al. 2015** | • Distinct simplified and analytical procedures currently existent under European and USA guidelines are presented and compared with a hypothetical example case of a typical structure in London. It is shown that most of the design approaches relate to values of heat extraction and ground conductivity, but the latter variable is affected by thermal capacity, operation hours, BHE interferences, dia & disposition and fill material.<br>•BHE length is determined with simplified equations and a tabulated heat extraction rate from the ground. It is finally suggested that analytical design methods are used even for small systems given large deviations of up to 43% between tested techniques. | Comparison of distinct design procedures for vertical borehole heat exchangers (BHEs) |
| **Alkaff et al. 2016** | •The paper summarizes ancient sheltered underground structures worldwide, constructed as a form to protection against harsh weather and as an efficient solution for thermal energy modulation and conditioning.<br>• Most of the ancient underground homes were located in hot and arid countries, so the technique was initially applied for cooling purposes. One of the earliest cases was found in excavations in the city of Kamitakamori, Japan, where 600000 years old buried structures have been recently found. They have been used as shelter to rest, to conduct religious ceremonies and to store tools. More recent 20th – 21st. century underground buildings are also summarized, enhancing the underground technique as a way for a sustainable development.<br>•Underground construction at both ancient and modern era has shown to have a great potentiality to encourage minimization of the structure´s energy consumption, enhancing climatization and efficiency. | Historical review on the usage of ancient and modern underground structures for temperature climatization |

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| **Lanahan & Tabares-Velasco 2017** | • BTES is most effective when diurnal with seasonal storage. It effectively provides large amount of heat storage despite reduced specific heat of storage medium, given easily increased storage volume. GSHP can be coupled with BTES technology in several manners.<br>• water thermal pollution can be negative impact on the environment.<br>• vertical piping is advantageous due to higher temperatures at lower depths in winter & opposite in summer.<br>• Switzerland is the world leader in BTES with annual geothermal heat of 1TW<br>. | Literature review on borehole thermal energy storage (BTES) systems |
| **Fadejev et al. 2017** | •Typical plant solutions and configurations, laboratory and site-specific calibration tests, and commercial software are presented and commented. Main applications of GEP models for practical usage are also discussed. Thermomechanical behavior of GEP groups must be accounted for. Most of design and installation guidelines and manuals are for borehole systems not GEPs, hence limited in use.<br>•Urgent need to develop general procedures for GEP sizing that could account for thermal interferences, long-term behavior, heat transfer through floor structure and coupling capabilities with energy hourly time-step demands from building simulation software. | Thorough review of available scientific literature on design standards and guidelines on energy pile performance, sizing and modelling techniques |
| **Vieira et al. 2017** | •Critical review is provided on laboratory and in situ thermal tests to determine soil conductivity and GEP thermal resistance in either steady-state or transient heat flow, together with a discussion on scale effects on measurements, and thermo-hydro-mechanical processes and its assessment in soils and rocks.<br>•Large scale TRT gives more representative thermal parameters although being more expensive and time consuming. Field tests do also lead to higher values than laboratory ones. Pile TRTs are suggested for GEP design but coupled to extensive numerical validations and further simulations of the system.<br>•Thermal loading affects hydromechanical behavior of both soil and structure, adding challenges for the estimation of thermal properties, and enhancing complexities of constitutive models for GEP performance. | Thorough review on the main procedures to determine ground thermal properties of soils and their thermo-hydro-mechanical behavior |
| **Brito et al. 2017** | •The thermal response of an edification is not much affected by the superficial soil´s temperature when it varies around 2°C. In this respect it is possible to estimate such temperature via empirical correlations with known values of the average monthly air temperature of the region, either in summer or in winter conditions.<br>•It is paramount to consider climatic conditions, solar orientation, external colors, occupancy, ventilation, geometry and a standard 1 m/s wind velocity in the simulations of the thermal performance of edifications. | Suggestions to improve the current Brazilian standard of thermal performance of buildings |

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| **Tsagarakis et al. 2018** | •Reviews discuss national legislations as well as experts experience in the procedures of SGES integration, together with legal and technical issues. High diversity on jurisprudence exists, and no EU overall directive exists, thus acting as a barrier for further development on the SGE market. Awareness, standardization, legal framework and guidelines are essential steps to improve effectiveness in design and operation of SGES.<br>•Lack of a common framework and proper environmental provisions act as impeding factors for investments. | Extensive overview on legislation issues on shallow geothermal energy systems (SGE) in Europe based on reviews from 14 countries |
| **Sani et al. 2019a** | •Comprehensive review on several topics that are related to the design and implementation of GEPs as the technological background, the environmental factors that affect the system´s performance, design considerations, thermomechanical behavior of installed GEPs, thermal performance of GEP systems and future prospects & research focus on this technology.<br>•From the review it is found that thermal properties are essential in design but affected by several factors, including testing techniques. Design must be made with an integrated assessment of the structure´s demand and the GEP predicted supply capacity in terms of thermal loads. Performance of the system can vary and was shown to depend on several factors as loop arrangement, position, fluid flow and type, diffusion aspects of the GEP elements and geological and hydrogeological conditions. Pile dimensions and pipe surface area also play a major factor on that. Heat fluid velocity is the least important factor. Using foundation elements as heat carrier bodies makes perfect sense and provides an ideal engineering-friendly and sustainable solution.<br>•Future research should focus on the understanding of the behavior of such systems on a global scale and the effects of cyclic saturation and desaturation of GEPs. A simple user-friendly numerical tool to analyze the integrated superstructure-foundation system is required, together with ways to encourage patronage of GEPs. | Extensive review of literature on current principles and knowledge behind different design considerations, standards and government legislation for GEP systems |

Table of Annex I.5. Key findings on available research theses on geothermal thermally active (energy) piles (GEP) in Brazil and Portugal

| Reference | Objectives & Approach | Key Findings on Research Theses | Details |
|---|---|---|---|
| **Assunção, R.M. 2014** | Understanding of the thermomechanical behavior of isolated energy piles<br><br>ABAQUS Software<br>FEM 2D Axisymmetric | • A comprehensive thermal and thermomechanical numerical study of an active isolated GEP was performed using a numerical tool and focusing on the effects of the derived stresses and strains on both pile and soil. It was studied the relation between soil-concrete coeffs. of thermal expansions, soil and pile conductivity values, L/D slenderness ratios, particular modelling features and the influence of the ground´s surface temperature.<br>• Relative values of thermal exp. coeffs. play a key role dictating direction and magnitudes of developed stresses. Ground surface temperatures have also a key influence on thermally induced stresses if soil is more expansive than concrete.<br>• For the same pile diameter, the longer the pile the larger is thermal induced stresses when thermally activated. | MSc Thesis<br><br>Instituto Superior Técnico<br><br>Lisboa |
| **Bandeira Neto, L.A. 2015** | Field behavior of thermally active piles via TRT tests in the city of São Carlos in tropical unsaturated soil<br><br>2 Field Thermo Response Tests<br>1-2 U loop, L12m, Dia 25 & 50cm<br>Lateritic sand over saprolite | • 5 TRTs were carried out with distinct water flows, time intervals (48 x 229 hs) to assess several influential factors on the derived results of heat flux per meter, thermal conductivities and resistivities, as the pile diameter, the soil saturation, the system´s flow, the thermal loads and the resting times. Average values of 79-110 W/m, 2.8-4.2 W/mK and 0.08-0.14 mK/W were respectively obtained. Relatively high conductivities for an unsaturated soil, explained by the high thermal conductivity of the quartz, that composes 60% of the mineral matrix of this soil, laterized in situ with 20% of oxides.<br>• First TRT equipment developed in Brazil. Water flow influences the heat flux but not the conductivities. Thermal influence up to 2 m (4dia) around pile. Increasing dia. and no. of pipes is beneficial for the heat transfer. Good results within the world´s measured range, giving good perspectives for future usage in the Brazilian unsaturated laterized soils. | MSc Thesis<br><br>Univ. de São Paulo – EESC<br><br>Brazil |
| **Orozco, H.C. 2016** | Numerical assessment of a thermo response test in a laterized tropical soil<br><br>COMSOL 2D Axisymmetric | • Validation of a numerical simulation of a real TRT in a laterized and unsaturated clayey sand deposit in São Paulo, similar in geotechnical terms to typical deposits in the Brazilian Mid West region. Modelling sensitivity analyses were carried out and calibrated the model for further parametric simulations.<br>• Parametric analyses of an isolated GEP in a similar tropical soil was conducted at distinct conditions of diameter, length, pipe configuration, water level, thermal conductivities of concrete and soil, inlet temperature, flow regime and pipe thickness.<br>• The analyses indicate that the flow regime has been shown to be the principal variable to influence the final heat flux derived from the isolated pile, although other variables are also of importance for the improvement of the thermal efficiency of the system. | MSc Thesis<br><br>University of Brasília<br><br>Brazil |

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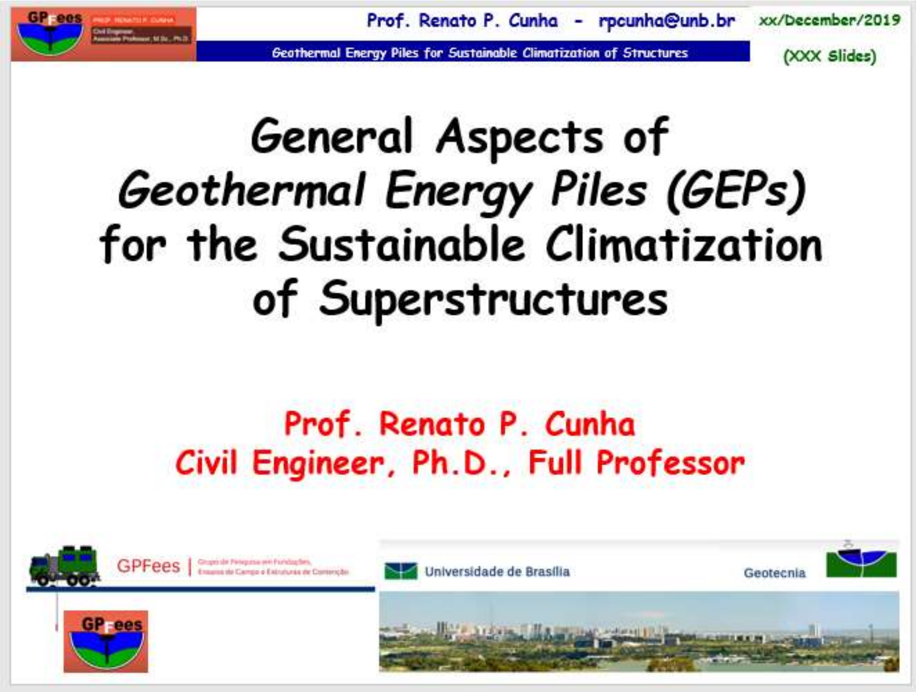
| **Sousa Júnior, R.P. 2017** | Parametric studied of GEP groups in the tropical soil of the Federal District of Brazil<br><br>COMSOL 3D FEM Modules Heat Transfer and Pipe Flow | • Extension of previous work in the same university from Orozco (2016), using the same numerical modelling with empirical assessment of the thermal properties of the subsoil conditions at the city of Brasília. Parametric analyses for GEP groups at distinct configurations (isolated to 9 pile groups), distinct pile diameters (30 to 60 cm), pipe loop configurations (U to 3U) and soil humidity conditions (max and minimum values at research site) were varied and cross compared for 50 hs of continuous thermal operation.<br>• It was observed that the thermal efficiency depends on the arrangement of the pile group, and the relative position of the piles among each other. Higher distances between piles do increase the efficiency, decreasing thermal interference. Besides, systems with more interconnected pipes in the same pile have more thermal interference, hence loosing efficiency, but this depends on the diameter of the pile itself and relative distance between pipes. For instance, for 30-40 cm dia. in 4 or more pile groups, 2U pipe configurations are enough to provide the better heat transfer with the soil. Soil humidity is also of importance for thermal efficiency, although not directly controlled in design. | MSc Thesis<br><br>University of Brasília<br><br>Brazil |
| **Ferreira, M.S. 2017** | Field behavior of thermally active piles via TRT tests in the city of Campo dos Goytacazes, assessing potential of this technology and stress states<br><br>2 Field Thermo Response Tests Single U, L12m, Dia 40cm pile Sandy/Silt sedimentar deposit | • TRT with two distinct water flows, time intervals (140 x 115 hs) and thermal loads were carried out, assessing heat flux per meter and thermal conductivities and resistivities. Average values of 40-46 W/m, 2.1-2.4 W/mK and 0.43-0.41 mK/W were respectively obtained. It was also noticed growing pile deformations with the evolution of the test, at extremities, and max. pile stresses of around 2.1 MPa. Mobilized shear stresses of around -50 to + 150 kPa on the worst case measured in TRT2.<br>• Temperature of local soil, around 29°C invalidates the use of GEP systems for cooling purposes in the region. Ambient temperature has influenced the tests somehow. | MSc Thesis<br><br>Univ. Estadual Norte Fluminense<br><br>Brazil |
| **Zito, M. 2019** | Parametric study of thermally active piles in isolated and group configurations subjected to both mechanical and thermal operations with time and temperature variations<br><br>ABAQUS Software FEM 2D & 3D Axisymmetric | • Thesis focus on modelling aspects of the soil-pile-structure behavior during thermal activation, simulating the influence of time factors, temperature variations, geometry and thermal activation of piles in different arrays, and transient vs. steady-state conditions.<br>• Effect of thermal variations at the surface and inside the geothermal systems is significant and potentially of the same magnitude of that induced by the mechanical loads.<br>• Variation in time of both ground surface and GEP temperature showed important differences between transient versus steady-state results of magnitude of thermally induced stresses and their directions (compression and tension), as well as displacements and heat flux. Coeff. of thermal exp. of soil has a key role in pile behavior.<br>• Stabilization of temperatures within soil profile can be reached in 10 years of continuous operation, where mechanical and thermal stresses will be accumulated during this period. Steady-state analyses can lead to totally misleading results with respect to transient.<br>• Stresses and deformations are modified as the temperature of the superficial soil is affected by the heat loss coming from the thermo-controlled building. Therefore, a concrete slab is useful to better simulate this aspect, besides of implementing a better redistribution of the design load that takes place in real piled raft foundation systems. | MSc Thesis<br><br>Politecnico di Milano<br>&<br>Instituto Superior Técnico<br><br>Italy & Portugal |

# ANEX 2. SAMPLE OF TECHNICAL COURSE ON THIS SUBJECT

## General Aspects of Geothermal Energy Piles for the Sustainable Climatization of Superstructures

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Geothermal Energy Piles for Sustainable Climatization of Structures

## Main Objectives of the Course

- Familiarization with the notion and main principles of the technology, its possibilities and drawbacks;
- Visualization of key findings in literature on the subject through a selected and commented state-of-art bibliographic review;
- Establishment of known aspects of recently defended Brazilian and Portuguese theses on the subject;
- Understanding of the general principles of design and associated background for simulation & analysis;
- Support on the conception and elaboration of research guidelines towards the study of geothermal energy pile systems in Brazil.

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Geothermal Energy Piles for Sustainable Climatization of Structures

## Course Program and Chronogram

| | MAIN LECTURE TOPIC | APROXIMATE TIME | |
|---|---|---|---|
| | | Weeks | Hours |
| | **Individual Lectures by Professor** | | |
| PASSIVE APPROACH | Historical Background<br>Overall Conception and Components | 1 | 4 |
| | Key findings on Field and Lab. Studies<br>Summary and Main Conclusions | 2 | 8 |
| | Key Findings on Numerical Studies<br>Summary and Main Conclusions | 2 | 8 |
| | Miscellaneous Knowledge<br>Summary and Main Conclusions | 2 | 8 |
| | Key Findings on Theses in Brazil and Portugal<br>Future Research and Development | 2 | 8 |
| | Theory and Design Considerations<br>Commented Case Histories | 2 | 8 |
| | Final Remarks and Wrap-up | 1 | 4 |
| | **Student Group Presentation on Selected Paper - Oral Seminar** | | |
| ACTIVE | Laboratory and Field Knowledge | 1 | 4 |
| | Numerical Knowledge | 1 | 4 |
| | Case Histories | 1 | 4 |
| | Theory and Design | 1 | 4 |
| | TOTAL COURSE LOAD | 16 weeks | 64 hours |