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Design tools for thermoactive geotechnical systems

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Session 5 Report: Design Tools for Thermo-Active Geotechnical Systems

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ABSTRACT: This paper presents a review of current design tools used for thermo-active geotechnical systems, along with validation efforts. The capabilities of available analytical methods used for the thermal and thermo-mechanical design of these systems are evaluated and shortcomings of the existing methods are identified. Although the analytical methods permit accurate prediction of the thermal stress and strain response of thermo-active piles from readily-available soil and concrete properties, current shortcomings consist of the ability of the methods to simulate cyclic heating and cooling effects, transient pore water pressure generation and dissipation, and the effects of radial stress changes. Recommendations are provided on how to properly address the current design requirements and the efforts to overcome shortcomings with the development of constitutive relationships from further full-scale and laboratory-scale experimental studies on thermo-active piles. Furthermore, the need for the development of both simplified analytical tools and advanced finite element models is emphasized. In addition, the existing analytical tools should be validated using field data from recently available case studies of thermo-active piles in varying soil deposits. An urgent need for an extensive design guide for energy geostructures was identified. The guidelines should be targeted towards practitioners and include field observations and measurements, as well as laboratory and numerical studies.

KEYWORDS: Analysis, design, thermal, thermo-mechanical, energy geostructures

1. Introduction

Validation of design tools for thermo-active geotechnical systems is imperative for the acceptance of such systems in geotechnical engineering practice. Geotechnical engineers, project owners, and project investors all desire confidence that the tools used for designing a thermo-active geotechnical system will produce a design that is sound from both thermal and geotechnical perspectives, while simultaneously yielding a degree of accuracy that is expected of the tools used for regular foundation and geothermal system design. This paper offers a summary of where the current state of practice resides in the validation of design tools for thermo-active piles, which have undergone the most development of the different types of thermo-active geotechnical systems. It summarizes the discussions and findings from the breakout session having the topic "Validation of Design Tools for Thermo-active Geotechnical Systems" held during the International Workshop on Thermo-active Geotechnical Systems for Near-Surface Geothermal Energy at the École

Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland in March 2013. Specific objectives of this session included:

a) Determination of which analytical methods are available and are being used in practice,
b) Identification of shortcomings/limitations of the existing methods and how they can be further refined and validated,
c) Identification of how to develop and verify new analytical methods,

d) Establishing the status of design guidance/regulations and identify related development needs.

The design of thermo-active piles from a thermal perspective involves selection of the heat exchanger geometry and layout (pipe size, location within the pile, etc.) to exchange heat in the most efficient manner possible, as well as selection of the appropriate heat pump that is properly sized for the system of thermo-active foundations used in a building. The heat pump selected will govern the entering and exiting heat exchange fluid temperatures, as well as the fluid flow rate, and should be properly sized to ensure sustainable energy use. This aspect of the thermal design is outside of the scope of this paper, but it is well understood from the perspective of designing ground-source heat pumps (Kavanaugh et al. 1997). The heat exchanger geometry and layout requires analytical tools that are easy to use by practitioners. The design of thermo-active piles from a thermo-mechanical perspective involves evaluation of whether the geometry and reinforcing cage layout of the foundation selected to meet the structural demand of the building are sufficient to withstand the potential stresses associated with thermo-mechanical soil-structure interaction. Further, another important design check is to evaluate if thermal deformations are sufficient to affect the architectural or structural behavior of the building. The thermo-mechanical design of thermo-active piles requires a different set of analytical tools as well as design criteria.

For the purposes of discussion, this paper delineates between the analytical tools for simulating the behavior of thermo-active piles and the design of thermo-active piles. Analytical tools refer to the methods of analysis used to develop a fundamental understanding of thermo-active pile behavior and to provide predictions of performance (stability and serviceability) for use in design. The design of thermo-active piles involves the use of predictions from the analytical tools and application of suitable margins (partial factors) to loads and resistances in order to ensure safety and serviceability of the thermo-active geotechnical systems. These two topics are discussed separately in this paper.

2. Analytical Tools

2.1. Thermal Analysis

Current analytical and semi-analytical models used in the design of borehole heat exchange systems are largely based on the principle of heat conduction, and have been developed using analog solutions for infinite and finite line sources (Ingersoll et al. 1954; Eskilson 1987), cylindrical sources (Man et al. 2010) and duct sources (Hellström 1989; Pahud 2007). Accordingly, they have been applied to geothermal heat exchangers in boreholes with uniform field geometries in spacing and length. A common component among all currently-used methods is the utilization of steady-state thermal resistance values for the borehole heat exchanger. As these methods are computationally very efficient, they have been implemented for many years into design codes such as EnergyPlus (Crawley et al. 2001) and eQuest (James J. Hirsch and Associates 2010). This is the case despite their known constraints, such as the fact that simplifying assumptions are required regarding the boundary conditions, heat injection patterns, and geometric configuration of the heat exchanger. Further, the entire soil stratigraphy at a site needs to be considered as a single composite system in the analysis. Despite these simplifications, these methods have been shown to provide reliable results in the design of borehole heat exchange systems (Kim et al. 2010).

These referenced methods have found wide application and favoritism given the large computational difficulties associated with modelling boreholes and borehole systems using continuum element methods such as finite element analysis. A three-dimensional analysis methodology using finite element modeling is described in Ozudogru et al. (2014a). Continuum element methods often require rather extreme aspect ratios of the heating/cooling element, i.e. borehole lengths of up to 150 m compared to borehole diameters of 0.15 to 0.20 m and heat exchange pipes of a few centimeters (25-50 mm). For example, the modeling of a single 0.15 m diameter borehole with a single u-tube of 32 mm diameter, surrounded by a 10 m by 10 m x 100 m block of soil, produces a three-dimensional mesh containing around 800,000 elements. This modeling effort would be even larger when a field of boreholes needs to be analyzed, and was found to be beyond the means of most engineering practitioners (Al-Khoury et al. 2010).

Beyond the relatively simple integration of analytical and semi-analytical methods, several limitations exist in the application of thermal analysis methods to heat exchanger piles. Loveridge (2013) identified that the duct storage method as implemented in the program PILESIM was the only method that had been validated in its application to thermo-active piles (Pahud and Hubbuch 2006). Other methods that assume finite line/duct sources show less reliable results for heat exchanger lengths less than 15 m and need to be used with caution. A second limitation recognized by Loveridge (2013) is the failure of current analysis programs to properly account for short-term thermal energy storage of the pile and the incorrect calculation of the temperature at pile-soil interface with respect to the pile interior. The thermal behavior of thermo-active piles was examined by Loveridge (2013) via monitoring results from sensors embedded in a large diameter (1200 mm) pile at the locations shown in Figure 1. The change in temperature between heat exchange loops placed at the center of the pile and a set of sensors close to the pile circumference is shown in Figure 2. Data showed that the temperature close to the heat exchange loops fluctuates significantly (depending on the heating/cooling demand) while at the pile-soil interface the temperature change is lower and the fluctuations are damped compared to those in the center of the pile. Thus, the current analysis programs are failing to take account of the short-term thermal energy storage of the pile and are incorrectly calculating the temperature at the circumference of the pile. This has not been a significant problem in the practice dominated by borehole heat exchangers, which have much smaller diameters, compared to thermo-active piles. However, it appears that special attention is necessary to investigate the thermal energy storage and thermal resistance of thermo-active piles, which have larger diameters than borehole heat exchangers.

The thermal resistance functions for thermo-active piles, which are referred to as “G-functions”, have recently been developed. These G-functions represent the solutions to the heat conduction equation for different characteristic heat pulses applied to a thermo-active foundation, and are specific to the geometry of the thermo-active foundation. An example of the G-functions for a thermo-active pile with heat exchange pipes located centrally within the pile are shown in Figure 3a. Similar functions for heat exchange pipes located near the edge of the pile are shown in Figure 3b. Accompanying numerical analyses confirmed that the temperature change at the pile-soil interface was smaller in magnitude and showed less variation with time than that for the heat exchange fluid (Loveridge and Powrie 2013). The upper bound solutions represent the case of a large diameter pile where the ground is less conductive than the pile concrete. The lower bound solution represents the opposite situation with a small diameter pile and the ground being more conductive than the pile. It was also noted that the temperature change at the pile-soil interface under assumed steady-state conditions is higher than that predicted for transient analysis, as shown in Figure 4. Loveridge (2013) also identified that more attention should be paid to the consideration of the thermal mass and transient thermal response of heat exchanger piles, as those factors could lead to: (1) Greater energy output for any given temperature change, (2) Reduced temperature change for any given thermal load, and (3) Reduced geotechnical risk. Other issues identified by Loveridge (2013) are the importance of the surface boundary, the differential temperature change in multiple pile "circuits", the effect of ground water flow, and ultimately the consideration of the development of new analytical tools for comprehensive analysis.

An issue of concern is the impact of having the heat exchange pipes located near the periphery of the pile rather than the center. Heat energy propagates into the pile as well as into the surrounding soil, so the transient behavior is still very important especially for large diameter heat exchanger piles. The effect of pile length to diameter (L/D) ratio is also important to consider in the long-term thermal response of the pile. Existing models such as EnergyPlus and eQuest need to be adapted to consider thermo-active piles, although analyses for thermo-active piles have been developed in research using analysis software such as MATLAB. End-users and designers require "friendly" versions of these methods with "single input variables". Regarding the analysis of heat exchanger piles, the need for testing protocols for the evaluation of parameters such as the specific heat capacity of concrete is still an issue that needs to be considered. Existing borehole models do not account for the influence of the thermal mass of the heat exchanger because it is so small and the heat exchanger reaches steady state relatively quickly. On the contrary, the transient response of heat exchanger piles can be considerable because of their larger diameters compared to geothermal boreholes. In addition, a means for accounting for the heat flux at the bottom of the pile is needed in analytical models, especially for small L/D ratios.

2.2. Thermo-Mechanical Design and Analysis

The thermo-mechanical analysis of thermo-active piles is far less developed than those used for thermal analysis, which benefited from lessons learned from vertical borehole geothermal heat exchangers. Although several different analyses have been developed over the past several years, their use in making design decisions is not yet at a mature stage. The thermo-mechanical analyses of thermo-active piles currently fall into three general approaches: (1) Empirical rules; (2) Load-transfer models, and (3) Full numerical methods (e.g., finite element analysis). Each of these approaches are discussed in the following sections.

2.2.1 Empirical rules

In the case of thermo-active piles, it has been suggested that the response could be bounded by two simple assumptions such that:

(i) The maximum change in axial load due to temperature change can be estimated by assuming that the pile is perfectly restrained.
(ii) The maximum deformation can be estimated by assuming that the pile is perfectly unrestrained.

Use of these empirical rules to design thermo-active piles provides a fairly blunt tool, and if relied on solely may lead to overly conservative design. Also, it has also not been validated across a range of ground conditions, pile types and thermal loads. For example, it is not capable of capturing phenomena such as soil downdrag, expansive soils, or changes in pile geometry with depth, all of which are commonly encountered in drilled shaft foundation applications. Additionally, heat exchange may have effects on the soil behavior as well, which may have potentially been observed in long-term field monitoring results on thermo-active piles (Murphy and McCartney 2014).

2.2.2 Load-transfer models

This type of model was originally developed to evaluate the distribution of stresses and strains with depth in a deep foundation by Coyle and Reese (1966). It assumes that the pile-soil interaction may be represented by load transfer rules (e.g., ensuring equilibrium and compatibility of displacements between the pile and soil), and has found wide use within the geotechnical industry for estimating the behavior of piles under vertical ("T-z" models) and lateral loading ("p-y" models). Appropriately calibrated, T-z models can be used to examine the distribution of axial stress, axial strain and axial displacement along a single pile due to mechanical loading. However, its extension to groups of piles where there are interactions between the piles is not straightforward. In this case, a model to consider the roles of foundation head restraint is needed.

The T-z method has also been applied to the analysis of thermo-active piles (Knellwolf et al. 2011) which was validated by using the results of field tests in EPFL (Laloui et al. 2006) and in Lambeth College (Bourne-Webb et al. 2009). In addition, the Thermo-Pile Software was developed using the load-transfer approach in Knellwolf et al. (2011). Ouyang et al. (2011) modelled the thermo-mechanical behavior of thermo-active piles by using an existing load transfer approaches coupled with thermal response and verified it with Lambeth College test results (Bourne-Webb et al. 2009). McCartney and Rosenberg (2011) considered the impact of thermally-induced changes in radial constraint on the prediction of the isothermal load transfer behavior of semi-floating thermo-active piles loaded to failure in the centrifuge. As with isothermal "T-z" models, additional features such as the degradation of the pile-soil load transfer function due to cyclic loading can also be included (Suryatriyastuti et al. 2014). This method has yet to be fully validated against observation of the response to cyclic loading of thermo-active piles across a range of ground conditions, pile types and thermal loads but can provide some idea of the potential significance of such effects.

2.2.3 Full numerical methods

This approach may include the use of boundary element, finite element and finite difference methods of calculation, and its generality should allow all types of energy geostructure systems to be modeled whereas empirical rules and load transfer models above can only be applied to single piles. However, the complexity of these methods needs to be recognized and the many issues associated with the modelling of geotechnical problems (Potts and Zdravkovic 1999, 2000) and heat transfer problems must be considered when implementing a solution (Al-Khoury 2012).

Few examples of the application of such methods exist in the literature; Laloui et al. (2006) applied the finite element method to model the response of a thermo-active test pile. However, most other numerical applications examining the behavior of thermally activate structures have been numerical parametric studies of particular problems; Di Donna et al. (2013) and Dupray et al. (2014) examined the thermal and thermo-mechanical behavior of a piled raft type foundation system used for seasonal heat storage in thermo-plastic and thermo-elastic soils respectively. Suryatriyastuti et al. (2012), Bodas Freitas et al. (2013) and Ozudogru et al. (2014b) examined the effect of various parameters on the predicted response of a single pile in an elastic soil during heating and cooling, using the finite difference and finite element methods respectively. Wang et al. (2014) evaluated the role of unsaturated soil conditions and the possibility that thermally-induced water flow in unsaturated soil layers may affect the thermo-mechanical response of a thermo-active pile. Olgun et al. (2014) investigated the radial stress increase around thermo-active piles and found that the magnitude of temperature-induced radial stresses is small compared to the in-situ normal stresses at the pile-soil interface. They therefore concluded that the effect of radial stress increases would likely have a negligible effect on thermo-active pile behavior.

Again, the application of these methods to the analysis of thermo-active geostructures has not been thoroughly validated. However, some advanced thermo-hydro-mechanical (THM) soil models have been validated for other applications, e.g. against thermal load tests for nuclear waste disposal which may give some insight and confidence in their application to this problem (Akesson et al. 2009, Gens et al. 2010). It appears that this prior experience on THM soil behavior can be benefited to investigate thermo-active pile behavior in numerical analysis methods.

2.3. Challenges for Analytical Tools

The following possible challenges in the use of analytical tools include:

- Validation, benchmarking and development of performance databases
- Level of detail required in design
- Long-term performance including cyclic thermal loading
- Irregular geometry
- Energy geostructures other than piles
- Coupling between structural, thermal, hydraulic, geothermic and geomechanical responses

Although there are now several studies of full-scale, instrumented thermo-active piles in different soil strata (Brandl 2006; Laloui et al. 2006; Bourne-Webb et al. 2012; Amatya et al. 2012; Olgun et al. 2012; Akrouch et al. 2014; Murphy et al. 2014; Murphy and McCartney 2014), there has not yet been a systematic validation of the available analytical methods using this data to evaluate their relative shortcomings or strengths. It was noted however that there are field and laboratory testing programs underway in the United States, the United Kingdom, Switzerland, Australia and Spain which will help establishing a performance database and therefore strengthen the understanding of these systems. It was also noted that this lack of validation data for thermal and thermo-mechanical interactions also applied to borehole heat exchangers.

Although the thermo-active geotechnical systems have been around for several decades, there have only been a few studies focused on the long-term monitoring of their performance (Brandl 2006; Adam and Markiewicz 2009; Murphy and McCartney 2014). Therefore, the need for greater commitment with respect to demonstrating the long-term monitoring of energy geostructures was raised, along with the point that we need to be monitoring the response of the soil as well as the response of the geostructure. There are also challenges in predicting and validating the long-term performance associated with cyclic loading of the thermo-active geotechnical systems that are transient in nature which adds a level of complexity over that of simple steady-state analyses.

Another challenge is the detail, or scale, required for the design. How fundamental must the understanding of these systems be in order to produce a sufficient and reliable design? In this regard, it is important to differentiate between simulation tools and design tools. With the high computing power available today, there is often considerable overlap between simulation and design tools, but due to the complex thermo-hydro-mechanical interaction of these systems it may be necessary to use complex simulation tools to develop simpler design tools.

Many times these tools must also account for irregular geometry. Most of the design tools currently available are designed for boreholes and/or fixed configurations, which does not always work for thermo-active piles. Additionally, there are structures other than thermo-active piles such as diaphragm walls, tunnel linings, etc. that design tools need to account for. High quality information is required in any validation and the need for having common testing and reporting protocols was raised as an issue that could be addressed, in order to ensure that the data collected was robust and ultimately, useable. Is there a call for a global database to promote validation?

Within the models there are several challenges. One is coupling the structural, thermal, hydro, and geomechanics components. A second challenge is choosing the appropriate boundary conditions in analysis. For instance, is temperature modeled as a variable or as a constant? This is still unresolved. Challenges associated with thermal analysis, away from validation, include dealing with temperature/thermal inputs especially at the surface boundary and the relative importance of transient versus steady state conditions in analysis. The importance of being able to include all system parameters in the analytical tool was highlighted. Important issues to consider are:

- Adjustment for grouting and concrete layers.
- Flexibility for circular or rectangular cross-sections.
- Flexibility regarding number of heat exchanger pipes and their location in the pile to get accurate thermal resistance.
- Flexibility for different pile depths and distances between piles to account for thermal interactions between piles.
- Implementation of all processes involved in the heat transfer within the heat exchangers (e.g. convection, flow velocity in the pipe system, etc.) and in the surrounding soil (convection, thermally-induced water flow, etc.)
- Thermal short-circuiting between pipes in a pile.

A number of challenges related to thermal analysis are still present. The differing calculation scales for the geothermal system and the surrounding soil, and how new analytical tools often use Duct Ground Heat Storage type methods where the geothermal borehole or thermo-active pile is built up as a one-dimensional element, which is implemented in a three-dimensional finite element mesh, Al-Khoury et al. (2005). Current design tools are mostly developed for systems with rotational symmetry; for other systems like diaphragm walls (i.e. planar structures) these tools could not be used. So, new tools are needed. One possibility is to adapt the design models for underfloor heating systems or the thermal resistance models used in analyzing thermal activation of concrete ceilings. Geothermal heat exchange systems in the US are based on ASHRAE Standard 90, and acceptable energy calculation procedures are implemented in standard energy analysis codes such as EnergyPlus and eQuest for conventional geothermal heat exchangers. However, we are some ways from accomplishing this for energy geostructures. Provision of design procedures and software that can accurately predict long-term performance and inform the designer how much additional ground heat exchanger might be needed beyond what energy geostructure elements can provide. Without this, thermo-active geotechnical systems that are designed based on wishful thinking about the long-term performance may lead to disappointment (or lawsuits) if they overheat or freeze.

3. Design

3.1. Current Design Recommendations

Currently, there are no national codes of practice that address the integration of heat exchange elements within geotechnical structures. Thus there is a clear need for fundamental understanding, practical tools, and how and where to apply safety margins. In terms of thermal design, decisions need to be made as to what design standard to use. The Association of German Engineers have guidelines for shallow geothermal installations (VDI 2001) only saying that piles may be treated in the same manner as boreholes and all other cases need to be considered individually. Guidance from the Swiss Society of Engineers and Architects (SIA 2005) on pile heat exchangers provides construction details (e.g. pipe arrangement, materials, etc.) and discusses some design considerations. In the UK, the Ground Source Heat Pump Association (2012) published a design guidance document for the UK market which considers the ultimate limit state and the serviceability limit state and provides “best practice” guidance covering design, installation and materials for projects incorporating thermally activated piles. In terms of design, the guidance discusses the roles and responsibilities of the various parties involved in the project, and key aspects of the thermal and geotechnical analysis of the foundation system.

Efforts have been made to develop a limit state design methodology based on work that has been undertaken within the French National Research Agency project “GECKO” (Burlon et al. 2013). This work has the objective of providing design tools and establishing a design methodology in accordance with the French standard for pile design and Eurocode 7, for validation of ultimate (ULS) and serviceability (SLS) limit states. The methodology involves the use of the load transfer method, assumed that temperature variations affect only the pile, that the sequence of mechanical and thermal loading has no effect, and that cyclic effects can be neglected while the mobilized resistance is lower than the creep resistance.

An example analysis was presented where a single thermo-active pile with a square section of width 0.6 m and length 15 m was initially loaded to a mechanical load close to the serviceability limit state (SLS) then a cooling episode of -12°C and heating episode of 20°C were applied. The results of the analysis are shown in Figure 5 for a free head pile where cooling resulted in additional head settlement and a reduction in the normal forces and heating resulted in an increase in normal forces along the example pile.

The load transfer model included the effect of pile-structure rigidity via the inclusion of a spring restraint at the head of the pile and was used to generate predictions of thermally induced pile axial load, N^{th} and pile head movement, w^{th} in response to variations of the change in pile temperature, ΔT (in this case, -15°C and +15°C) and pile head stiffness, k (zero to infinity). These predictions were collated into a design chart shown in Figure 6 which might be used for design of thermo-active piles with similar characteristics to those considered in the analyses. This approach needs to be integrated into existing limit state design procedures such that thermal loading effects could be treated as a variable load and that suitable combination ($\psi \leq 1$) and partial factors ($\gamma_f \geq 1.0$) would need to be derived (the treatment as a variable load appears to be driven largely by the prescription of permanent tensile forces in French practice).

In terms of evaluating the current status of design of thermo-active structures, a more fundamental understanding of the behavior of such structures may be needed before implementing the use of practical tools in design. Additional research is needed to understand how and when to apply safety margins in design of thermo-active piles. Even while this knowledge is being accumulated there is a need for guidance for practitioners who are implementing such systems and need to provide assurance as to the integrity of the system. The difficulties of obtaining observations to provide validation were also highlighted, as was the problem of clients questioning the safety of the system when they are told that monitoring is necessary to validate the design.

There are still two main issues that deserve further evaluation: (1) how the design process might be dealt within the context of limit state procedures and (2) the significance of thermal versus mechanical design. Regarding partial factors it was noted that these factors depend on the probability of the occurring load, and the discussion then considered whether thermal load effects should be treated as variable actions or permanent actions. It may be easier to treat thermo-mechanical effects on the thermo-active pile as a permanent (dead) load. Subsequently, the significance of the thermally-induced load in a pile with respect to the mechanical loading. The results used in the calibration of load transfer analyses at Lambeth College were for unrestrained piles (Ouyang et al. 2011); whereas in the case of a pile that is restrained, near-doubling of pile stress has been seen as in the field tests performed at EPFL (Laloui et al. 2006) and Virginia Tech (Olgun et al. 2012).

There was also a thought that perhaps there was too much emphasis on the mechanical response of the thermo-active structure and not enough on thermal loads and how such structures actually work as heat exchangers. In response to this, it was suggested that this may be because of the experience with boreholes (and the assumption that the knowledge from this is transferrable). Loveridge (2013) also indicated that while this is a sensible approach in many regards, (thermal) design in the UK may be rather conservative and the industry may be missing an opportunity in terms of selling these types of systems (i.e. being able to demonstrate the greater heat exchange potential). To facilitate green certification and implementation issues in different areas, it may be useful to base thermal design on climatic averages and/or extremes. A conclusion from this workshop session was that goals should include mechanisms for making sure we are collecting the right information from field testing and monitoring of operational systems and that we need a more rounded understanding in order to provide the building blocks for moving forward and developing an integrated approach to analysis and design.

3.2. Design Challenges

The future challenges for the analysis and design of thermo-active piles are as follows:

- How to design thermo-active piles from a holistic perspective considering the thermal and thermo-mechanical performance
- Simplified analysis/ rules that can be used easily by practitioners
- Training/ up-skilling for practitioners moving from geotechnical to thermal analysis
- Relevant limit states (especially geotechnical ultimate limit states)
- Modifications to safety margins / partial factors for load-resistance factor designs
- International standardization (ASTM International, Euro Norms, International Organization for Standardization (ISO))

The design of energy geostructures is multi-disciplinary, meaning that interdisciplinary communication and cooperation is often necessary. Methods for environmental impact calculations and life-cycle cost analysis for other building heating and cooling technologies are implemented in quite a few building performance simulation tools commonly utilized in the US and Europe. For vertical borehole heat exchangers, such models have been implemented in building performance simulation tools over the last 15 years. These tools are used to evaluate different system alternatives, justify investments in building energy conservation measures or renewable energy, demonstrate compliance with building energy codes, and qualify for green rating schemes such as the Leadership in Energy and Environmental Design (LEED) green certification program. The main challenge then is that the equivalent methods for energy geostructures do not yet exist to be implemented in building simulation programs and once available, they will need continuous development to support different types of energy geostructures, and they will need to be implemented and maintained in multiple building simulation tools.

4. Conclusions

While there has been significant progress in the development of design tools for thermo-active geotechnical systems, there is clearly an opportunity for further development and validation of these tools as the geotechnical community better understands these systems. The discussion session and the range of backgrounds of the attendees highlighted how the analysis and design of energy geostructures is indeed a multi-disciplinary process, where neither the thermal nor mechanical behavior can be ignored in favor of the other. It also highlighted a multitude of challenges that need to be overcome in order to place analysis and design on a sound theoretical footing. Some of these challenges include deciding which aspects of experience from the borehole heat exchange industry can be directly applied to energy geostructures, and where there will be a need for adaptation, building a suitable dataset of observations of energy geostructures from which the fundamentals of their thermal and thermo-mechanical behavior can be established and analytical and design methods can be validated, ensuring the correct parameters are observed and they are robust, establishing testing protocols, and transferring knowledge from research to practitioners so that tools are available for an integrated approach to thermal and thermo-mechanical design, and to inform the development of design guidance and codes of practice.

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LIST OF FIGURES

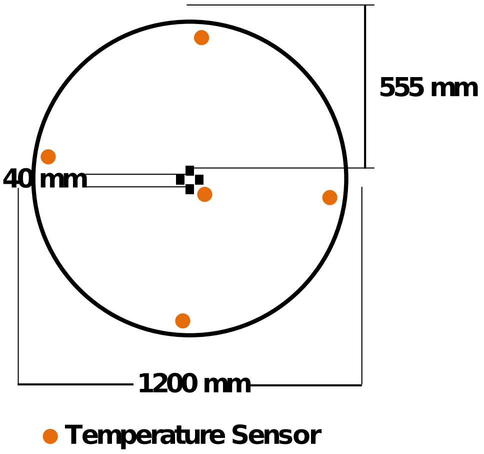


Figure 1. Plan view of an instrumented thermo-active pile (Loveridge 2013)

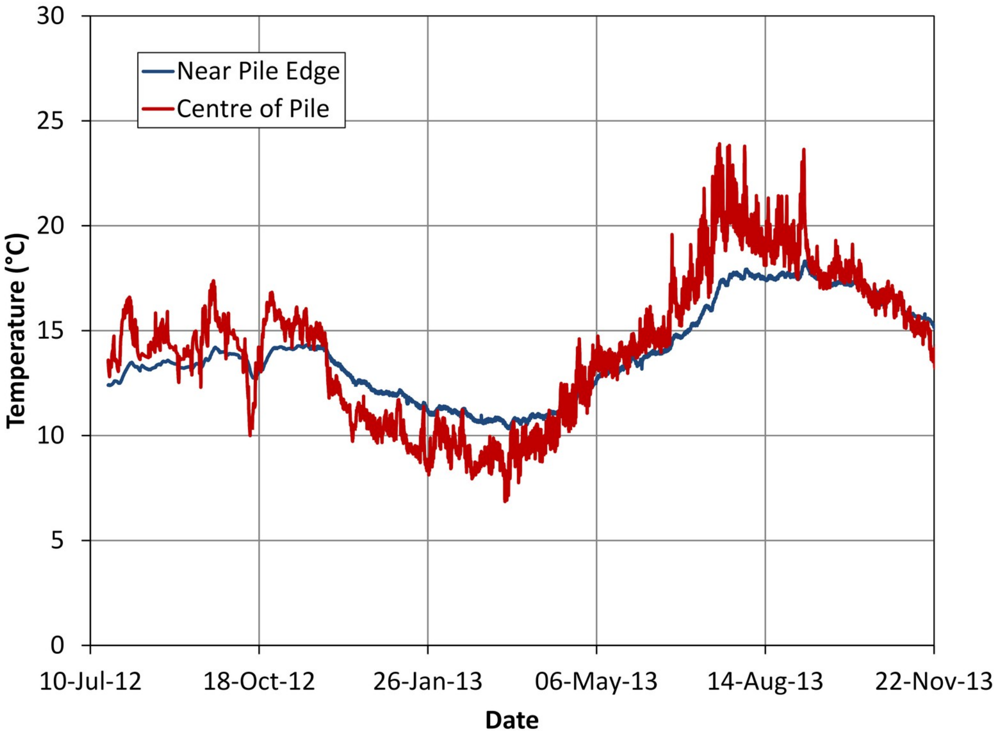


Figure 2. Temperature variation between central heat exchange loops and circumference (Loveridge 2013)

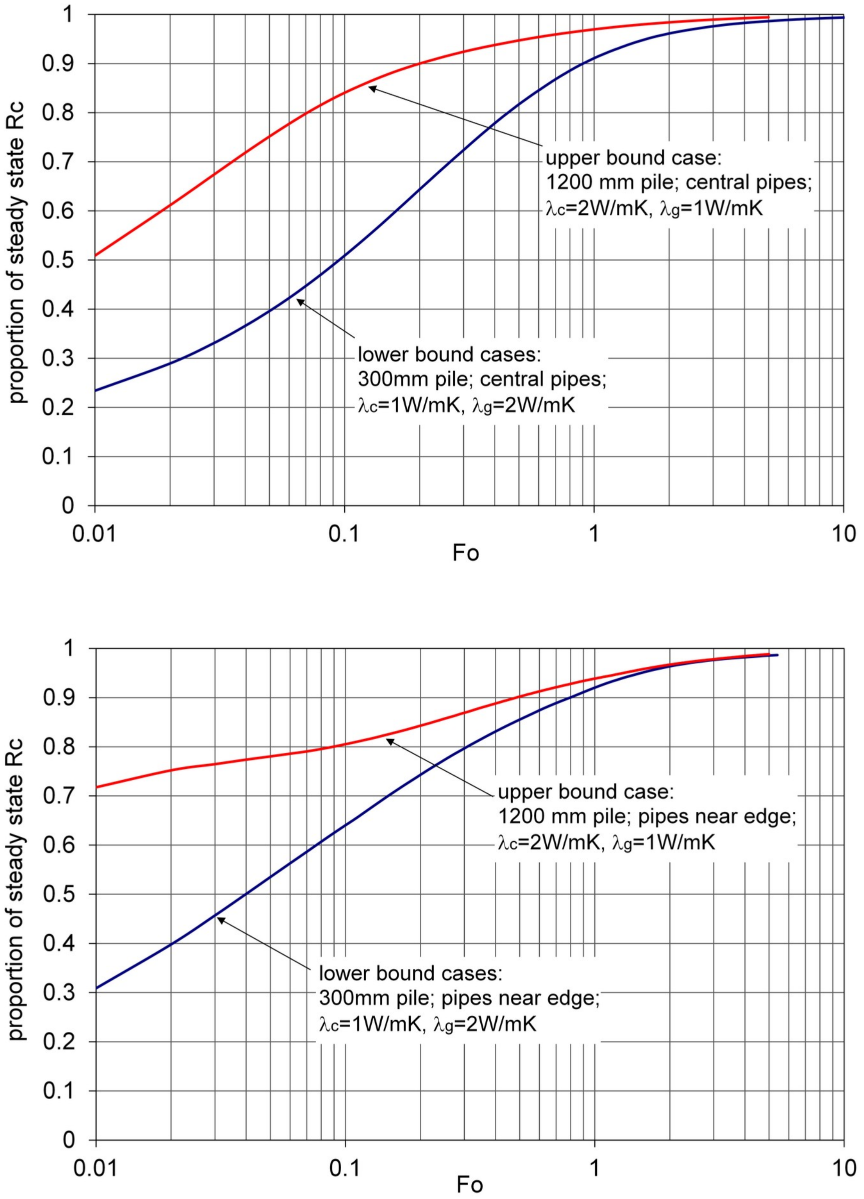
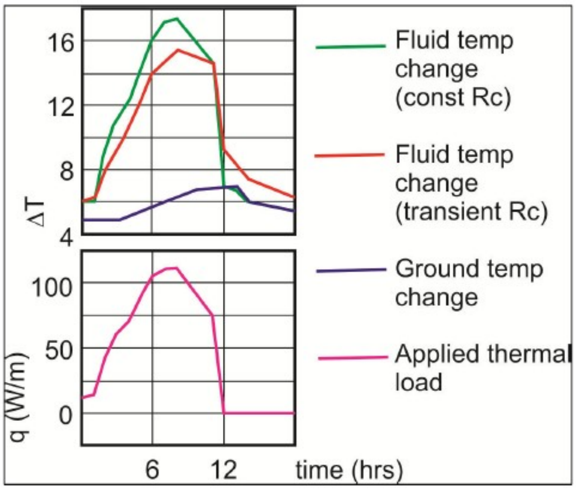


Figure 3. Concrete G-functions: proportion of steady state thermal resistance as a function of Fo; (a) Pipes placed centrally, (b) Pipes placed near the pile edge (Loveridge and Powrie 2013)



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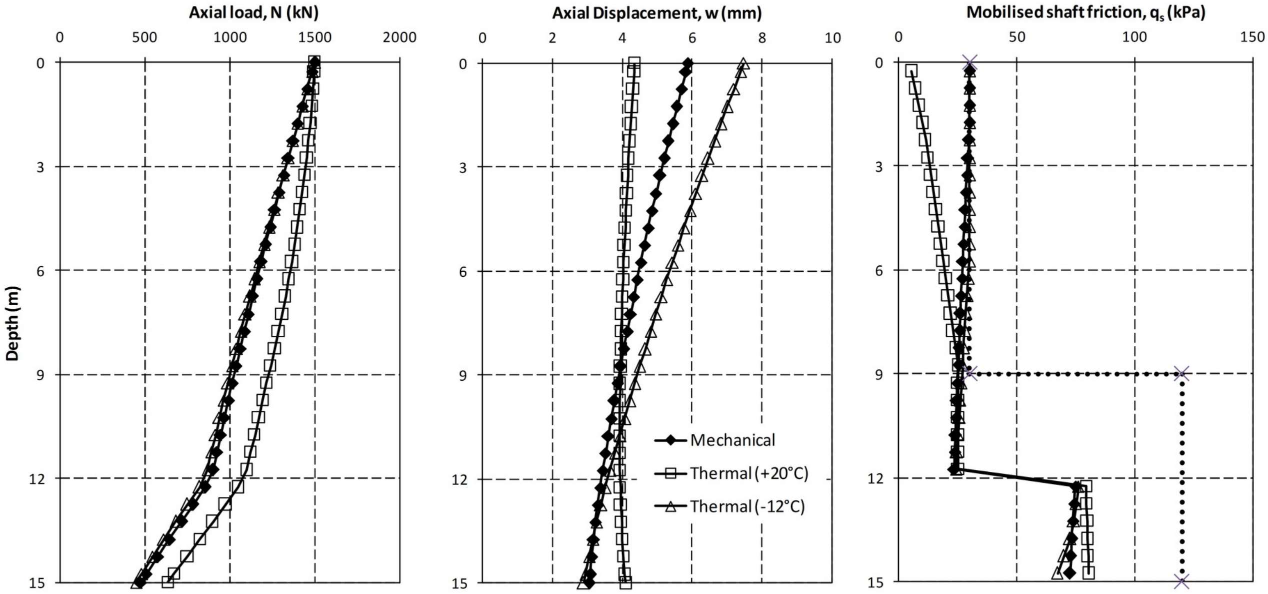

Figure 5. Response of a thermo-active pile under thermal load (free head condition), (Burlon et al. 2013)

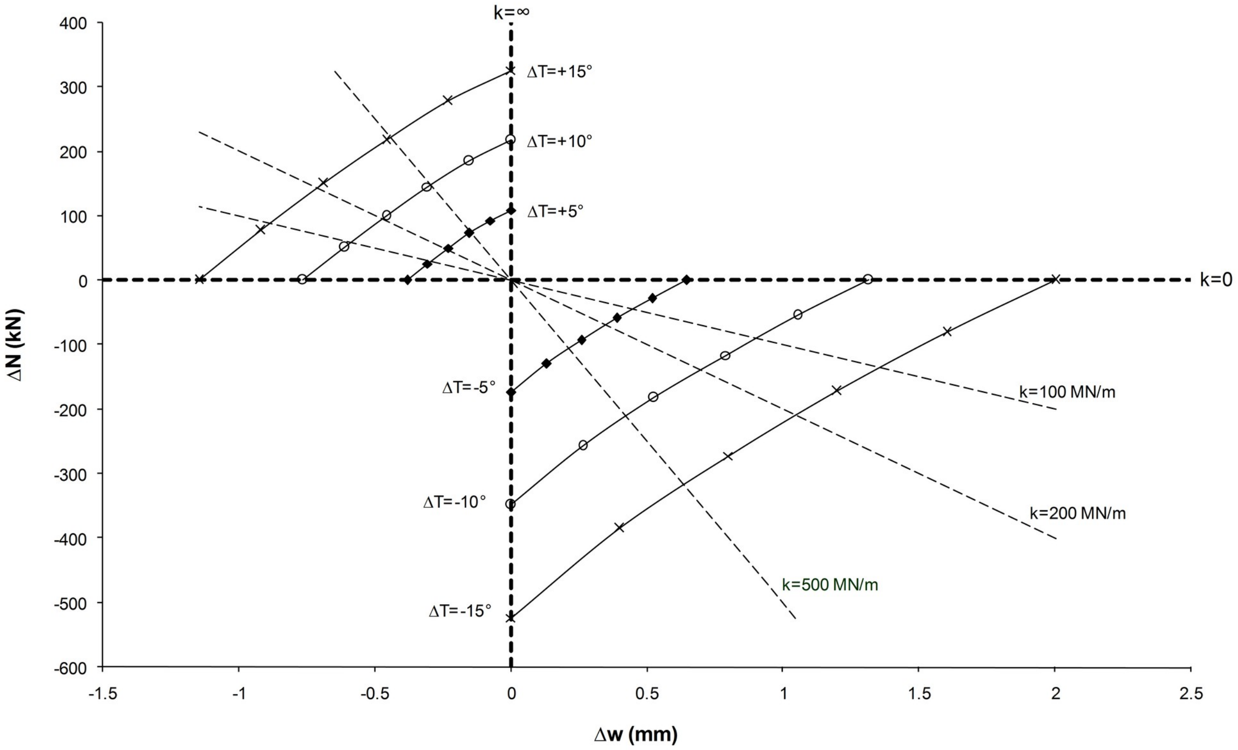

Figure 6. Interaction diagram relating pile axial load change and pile head movement as functions of applied temperature change and pile head fixity (Burlon et al. 2013)