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Research paper

Energy and geotechnical behaviour of energy piles for different design solutions

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HIGHLIGHTS

- Energy piles thermo-mechanical behaviour crucially depends on pipes configuration.
- Thermal power extracted from the ground increases with pile aspect ratio.
- Heat transfer rate fundamentally depends on fluid mass flow rate.
- Heat transfer rate is not markedly affected by operative antifreeze concentrations.

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ABSTRACT

Energy piles are heat capacity systems that have been increasingly exploited to provide both supplies of energy and structural support to civil structures. The energy and geotechnical behaviours of such foundations, which are governed by their response to thermo-mechanical loads, is currently not fully understood, especially considering the different design solutions for ground-coupled heat exchangers. This paper summarises the results of numerical sensitivity analyses that were performed to investigate the thermo-mechanical response of a full-scale energy pile for different *(i)* pipe configurations, *(ii)* foundation aspect ratios, *(iii)* mass flow rates of the fluid circulating in the pipes and *(iv)* fluid mixture compositions. This study outlines the impacts of the different solutions on the energy and geotechnical behaviour of the energy piles along with important forethoughts that engineers might consider in the design of such foundations. It was observed that the pipe configuration strongly influenced both the energy and the geotechnical performance of the energy piles. The foundation aspect ratio also played an important role in this context. The mass flow rate of the fluid circulating in the pipes remarkably influenced only the energy performance of the foundation. Usual mixtures of a water-antifreeze liquid circulating in the pipes did not markedly affect both the energy and the geotechnical performance of the pile.

1. Introduction

Energy piles (EP) are a relatively new technology that couples the structural role of canonical pile foundations to that of heat exchangers. These foundations, already needed to provide structural support to the superstructure, are equipped with pipes with a heat carrier fluid circulating into them to exploit the large thermal storage capabilities of the ground for the heating and cooling of buildings and infrastructures, particularly when these EPs are coupled to heat pumps. In these systems, heat is exchanged between the foundations and the soil in a favourable way, as the undisturbed temperature of the ground at a few metres of depth remains relatively constant throughout the year (being warmer than the ambient temperature in the winter and cooler in the summer) and the thermal storage capacities of both media are advantageous for withstanding the process. Geothermal heat pumps are connected to the piles and can transfer the stored heat and their energy input to buildings and infrastructures during the

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heating season. On the contrary, they can extract the heat from the conditioned spaces and inject it (again, in addition to their energy input) to the soil during the cooling season. Temperature values that are adequate to reach comfort levels in living spaces and advantageous for engineering applications (e.g., de-icing of infrastructures) can be achieved through this technology with a highly efficient use of primary energy. Traditionally, geothermal borehole heat exchangers have been exploited for this purpose. Recently, the use of energy piles has been increasingly spreading because of the savings in the installation costs related to their hybrid character and to the drilling process.

The EPs possess a twofold technological character that has drawn a dual related scientific interest in their behaviour. In fact, the energy performance of the energy piles can markedly vary for different *(i)* site layouts, *(ii)* foundation geometries, *(iii)* pipe configurations, and *(iv)* soil and foundation material properties. In addition, the geotechnical behaviour of the energy piles can strongly vary for different *(v)* restraint conditions and *(vi)* applied thermal loads. Consequently, these two fundamental aspects of the energy piles are interconnected and coupled through the thermal and mechanical responses of these foundations.

Over the years, a number of studies have investigated the thermal behaviour of vertical ground-coupled heat exchangers, focussing on the processes that occur inside (i.e., the tubes, infill material and fluid) and around (i.e., the surrounding soil) their domain. Analytical [1–11] and numerical [12–31] models of varying complexity have been developed for such purposes. Currently, various amounts of research have been increasingly performed for the analysis of the thermal behaviour of energy piles [32–49]. However, the three-dimensional, asymmetric and time-dependent characterisation of the thermal behaviour of such foundations, which involves the interaction between the fluid in the pipes, the pipes themselves, the pile and the surrounding soil, has often been considered in simplified ways that have been deepened only for specific case studies and have not been coupled with the mechanics of the problem. This latter aspect, i.e., the variation of the mechanical behaviour of both the foundation and the soil surrounding the energy piles due to thermal loads, has been investigated in recent years through several numerical studies in the field of civil engineering [50–60]. However, except for some of the very latest research [61,62], these studies generally simplified the numerical modelling of the complex thermal behaviour of the energy piles by imposing temperature variations or thermal powers to the entire modelled foundations, which were considered to be homogeneous solids, without the inner pipes and the circulating fluid. From a geotechnical and structural engineering point of view, this approach put the analyses on the side of safety (especially in the short-term) because the entire foundation undergoes the highest temperature variation and hence the maximum induced mechanical effect. However, from an energy engineering point of view, the physics governing the real problem has been markedly approximated. In particular, when dealing with models in which ground heat exchangers are coupled to the other building-plant sub-systems within a global thermodynamic and energetic analysis [63–65], the aforementioned simplifications may lead to inaccurate performance predictions and non-optimal design choices.

Energy piles, because of their bluffness, should be analysed as capacity systems capable of responding to a phase shift in a variation of the boundary conditions. More specifically, the thermal behaviour of the foundation should be investigated considering the complex pipes–pile–soil system as the heat exchange problem is governed by the temperature differences between these components. Together with these aspects, the coupled transient mechanical behaviour of the foundation should be analysed as it governs the bearing response for the superstructure. In this framework, looking at a thorough assessment of the interplay between the thermal and mechanical behaviour of energy piles, the present paper summarises the results of a series of 3-D numerical sensitivity analyses comprising the considered aspects for a single full-scale energy pile. This study is performed with reference to the features of the energy foundation of the Swiss Tech Convention Centre at the Swiss Federal Institute of Technology in Lausanne (EPFL), and investigates the roles of different *(i)* pipe configurations, *(ii)* foundation aspect ratios, *(iii)* mass flow rates of the working fluid, and *(iv)* fluid mixture compositions on the transient thermo-mechanical response of energy piles. This investigation focuses hence on the influence between the thermal and mechanical behaviours of energy piles under transient conditions considering different technical solutions applicable to such foundations. The adherence to physical reality characterising the numerical approach considered herein is corroborated by satisfying numerical predictions [66] of experimental tests [67,68] that have been recently performed at the site of interest.

The foundation is tested during its heating operation mode (the superstructure is heated while the ground is cooled). With respect to the considered design solutions, the energy considerations related to *(i)* the thermal response of the foundation in the short-term, *(ii)* the time constants for approaching the steady state conditions of the heat exchange and *(iii)* the heat transferred between the fluid in the pipes and the surrounding system are presented. Geotechnical aspects related to *(iv)* the stress distribution in the pile and *(v)* the displacements fields characterising the foundation depth are also considered.

In the following sections, the key features characterising the finite element modelling of the examined problem are first presented. The results of the numerical sensitivity analyses are then outlined. Finally, the thermo-mechanical behaviour of the energy piles and the related energy and geotechnical performances are discussed with reference to the simulated design solutions.

2. 3-D finite element modelling of an energy pile

2.1. The simulated site

The dimensions of the energy pile and the characteristics of the surrounding soil deposit considered in this study are those of an experimental site located at the Swiss Federal Institute of Technology in Lausanne (EPFL), under the recently built Swiss Tech Convention Centre. The experimental site includes a group of four energy piles installed below a corner of a heavily reinforced raft supporting a water retention tank. The foundation of the tank includes, besides the four energy piles, eleven other conventional piles that are not equipped as heat exchangers [67,68]. This study considers only one of the four energy piles with respect to a configuration denoted by a null head restraint and a null mechanical applied load on the top of the foundation, i.e., the one before the construction of the water tank. The energy pile is characterised by a height $H_{EP} = 28$ m and a diameter $D_{EP} = 0.90$ m (see Fig. 1). The pipes in the shallower 4 m are thermally insulated to limit the influence of the external climatic conditions on the heat exchange process. The characteristics of the soil deposit surrounding the piles (see again Fig. 1) are similar to those reported by Laloui et al. [53] as the considered energy foundation is placed in close proximity to the one referred in this study. The ground water table at the test site is at the top of the deposit. The upper soil profile consists of alluvial soil for a depth of 7.7 m. Below this upper layer, a sandy gravelly moraine layer is present at the depth between 7.7 and 15.7 m. Then, a stiffer thin layer of bottom moraine is present at a depth between 15.7 and 19.2 m. Finally, a molasse layer is present below the bottom moraine layer.