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# Impact of thermal solicitations on the design of energy piles

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ABSTRACT

Energy piles present a double function as bearing elements supporting the loads transferred by constructions and heat exchanger elements delivering the energy for heating and cooling. In comparison to conventional piles, they are subjected both to thermal and mechanical loadings, which affect their behaviour. Energy pile design also requires efficient and unambiguous approaches to provide the most appropriate verifications. Despite of their increasing implementation across Europe, some gaps are still present regarding their mechanical design; especially concerning the effects of the imposed cyclic thermal solicitation in the pile due to the successive periods of heating and cooling. Very few details can be found about the choice of the thermal solicitation that the designer has to consider for the design of an energy pile: number of cycles, cyclic thermal amplitude, influence of the thermal loading order, etc. In this objective, this paper includes the study of a single energy pile installed in saturated sandy soil affected by different combinations of thermal loadings. Based on the analysis of the pile displacements and the distribution of the axial forces, some recommendations are given to better appreciate the impacts of the choice of the imposed thermal solicitation in the pile.

## 1. Introduction

Energy piles installed as foundation elements for buildings can transfer heat between the surrounding ground and the supported building by means of the heat exchanger tubes that are connected to the steel reinforcements. They have been used since 1980's [1], and their installation is still increasing beside other types of thermoactive geostructures as diaphragm walls and tunnel linings. Even though the implementation of energy piles is gaining more acceptance, there are still some questioning concerning their thermo-mechanical behaviour, which restrains the development of efficient and unambiguous design procedures. Moreover, the lack of precise design procedures appears as an obstacle against the spread of thermoactive geostructures since this increases the cost and the duration of projects.

The robustness, the serviceability and the durability of energy piles are the fundamental issues that the design procedures have to deal with. Many complex situations have to be considered due to the interaction between energy pile, heat pump and building. Among these latest, an important issue is related to the change of temperature into energy piles that are already subjected to mechanical loading of the building. Indeed, they are subjected to many successive heating and cooling phases with variable periods depending on the energy needs and climatic conditions. In practice, on daily projects, the engineers in charge of the mechanical design of energy piles have to deal with a very frequent significant problem which is the choice of the thermal solicitations. Several questions may be related to this issue: what is the number of cyclic thermal loadings in terms of heating and cooling to be considered? What are the amplitude and the mean of these loadings? What is the shape of the thermal loading: crenel solicitations, sinusoidal solicitations? Is it really required to perform a transient analysis? etc.

The thermal solicitation is indeed a complex issue involving the thermal exchanges with the ground including conduction and advection, and the interaction between the energy pile, the ground source heat pump, and the building. Most studies consider only permanent situations or the greatest temperature difference for designing energy piles [2]. A coupled transient thermo-mechanical approach enables to account for the possible effects of changes in the pile and in the ground in terms of temperatures, strains and stresses throughout the thermal cycles ([3,4]), but the choice of thermal solicitations is not clearly addressed. The spatial and the temporal evolutions of the temperature into the ground are difficult to be considered, but the design of energy piles requires a clear overview about their influence. For example, Laloui et al. [5] show that the applied thermal load leads to increase twice the total axial load in the pile. Gashti et al. [6] find higher stresses at the pile toe resulting from higher temperature variations caused by the thermal fluctuation around the U-tubes, and Rotta Loria et al. [7] present non-linear response of the foundation due to increasing thermal loads. Bourne-Webb et al. [8] assured through conducted numerical

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simulations that the contribution of the affected surrounding soil should not be ignored in the design of energy piles especially in the case of moderately to highly over-consolidated clays. This work confirms the importance of considering and analysing the temporal and spatial distribution of temperature for energy pile design in order to propose an appropriate way to design energy piles.

This paper aims to focus on the influence of the thermal solicitations on the design of energy piles through analysing their thermo-mechanical behaviour. For this objective, the study of a single energy pile installed in saturated sandy soil affected by coupled thermo-mechanical loads is proposed. Three dimensional finite element analyses of energy piles are conducted using the finite difference software FLAC3D. The data are issued from the results of experimental tests carried out in the North of France [9]. Several forms of thermal solicitations are examined to assess their influence on the pile reaction with the aim to provide some insights regarding the choice of the appropriate thermal solicitation for a precise project. Specifically, the influence of the rest period is considered as well as real continuous sinusoidal temperature variations. These different alternatives in terms of thermal solicitations can account for the difference between the seasons or even for passive cooling. Through studying the vertical displacements and the distribution of normal axial stresses in the pile, the behaviour of energy piles is analysed. Some recommendations are provided at the end of the paper to help the designer to choose the most appropriate thermal solicitation in order to ensure the robustness and the reliability of the energy piles under design.

## 2. Mechanical behaviour of the energy pile

In order to develop appropriate concepts related to the choice of the thermal solicitations for the design of energy piles, it is needed to consider the behaviour of a typical pile and the first step is to account for the main mechanical nonlinearities observed on the load-settlement curve. This step is fundamental since the variations of temperature in the energy pile lead to thermal contractions and expansions that are constrained by the friction conditions at the soil-pile interface and by the ground close to the energy pile. These thermal contractions and expansions induce some variations in terms of settlement and axial force distribution from an initial equilibrium state due the dead-load applied on the pile head.

### 2.1. Model geometry and boundary conditions

The pile geometry and the soil mechanical properties are adapted from the full scale loading tests carried by Szymkiewicz et al. [9] near Dunkirk, northern France (among the three tested piles, two are energy piles). The considered pile is a continuous flight auger (CFA) pile of 12 m length and 52 cm in diameter.

Concerning the ground, at the top, the 2.7 m are silty soil, and the rest are clean and very homogeneous sandy soil. The water table is 1.5 m deep of a hydrostatic regime and the soil is supposed to be saturated from this depth. In the numerical model, the soil is considered as saturated sandy soil since the unit weights of silt and sand are almost the same.

The behaviour of energy piles under only mechanical then thermo-mechanical loading is studied through numerical modelling via the finite difference code FLAC3D [10]. The modelled pile has a square section with equivalent width of 41 cm and of 12 m length. Due to symmetry, only one quarter of the domain is modelled. Concerning the mechanical boundaries, the lateral sides are normally fixed whereas the model is fully fixed at the bottom as shown in Fig. 1.

### 2.2. Comparison between numerical and experimental results

The pile is supposed to be wished in place and the initial stress state is obtained by applying gravity forces in the mesh. The constitutive laws considered to simulate the ground behaviour are simple and include an isotropic elastic part, a conventional Mohr-Coulomb failure criterion and a non-associated flow rule. The pile is supposed to have an isotropic linear elastic behaviour. The main objective of these assumptions is not to study in details the mechanical behaviour of the pile but only to capture the main features of the load-settlement curve in order to have a good assessment of the energy pile stiffness taking into account the surrounding ground and the loading level.

The mechanical properties for the soil including the cohesion, friction angle, and density are those measured at the experimental site [9]. The elastic modulus can be obtained by correlations with pressure meter tests or the cone resistance tests. No information is known about the dilation angle; consequently, several parametric studies have been performed in order to determine the dilation angle of the soil best fitting the experimental data. Table 1 presents the mechanical properties of soil and pile. Fig. 2 shows the results of the experimental and numerical static load tests where the soil with a Young modulus E equal to 73 MPa, and a dilation angle $\psi$ equal to 6° are found to have a good agreement with the load-settlement curve.

The difference between numerical results and experimental data is not negligible but can be assumed to be sufficiently low for the following of the study, as the mechanical load applied is around 33% of the pile bearing capacity. It is important to note that perfect contact is considered between the pile and the soil, therefore no interface elements are modelled. No cyclic parameters are also considered in the constitutive law of the soil since the loading level is low and should not lead to mechanical cyclic accumulation of displacements or strains.

It is worth mentioning that in all of the presented figures, negative axial forces represent tensile forces, and positive axial forces represent compressive forces.

## 3. Thermal solicitations under consideration

A sequential transient thermo-mechanical analysis is carried out to examine the impact of applied mechanical and imposed thermal load on the behaviour of an energy pile installed in saturated sandy soil. A mechanical load equivalent to 33% of the pile bearing capacity is applied at the head of the pile prior to the imposed thermal cycles. This loading level corresponds to the serviceability limit state in many pile design codes. The pile head is supposed to move without any fixity (free conditions).

The initial thermal conditions are defined as following:

- An initial temperature of 14 °C is imposed in the entire model, corresponding to the soil constant temperature at a depth 10–12 m in Europe and the soil mass has a volumetric heat rate of 0.001 W/$m^3$.
- The surface boundary is exposed to external air temperature, while a constant or sinusoidal variable temperature is imposed into the pile. At the surface, the equation used for the boundary condition is the following:

  $$T(t) = T_{ave} + A_0 \sin(wt)$$

  where $T_{ave}$ and $A_0$ are the average soil temperature and the annual amplitude of soil temperature, respectively, and w is the annual radial frequency.
- At the bottom frontier, a terrestrial surface flux of 0.0544 W/$m^2$ is imposed and on the four lateral boundaries, adiabatic conditions are considered.

These thermal conditions ensure an initial ground temperature profile in accordance with [11].

Concerning the thermal properties of the pile and soil, they are those used for concrete and saturated sandy soil (Table 2).

Regarding the imposed thermal solicitations into the pile, ten consecutive periodic thermal cycles corresponding to ten years are