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Numerical analysis of seasonal heat storage in an energy pile foundation

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ABSTRACT

The use of concrete geostructures for energy extraction and storage in the ground is an environmentally friendly and easy way of cooling and heating buildings. With such energy geostructures, it is possible to transfer energy from the ground to buildings by means of fluid-filled pipes cast in concrete. By injecting thermal energy in summer and extracting it in winter, the ground in the area of a building's piles can be used for seasonal energy storage, as long as the underground water flow in the storage remains low. This paper is a contribution to the improvement of the knowledge in the field of energy geostructures. The behaviour of a multi-pile seasonal storage system subjected to thermo-mechanical loading is examined numerically from both thermal and mechanical perspectives. The purpose of this paper is (i) to propose a thermo-hydro-mechanical 2D solution to the 3D problem, (ii) to explore the thermal behaviour of this type of storage and (iii) to evaluate its structural consequences. Coupled multi-physical finite element modelling is conducted. The efficiency of the storage is not dramatically affected by an increase in the annual mean temperature of the storage. It is shown that induced mechanical loads are less important when considering a wholly heated pile structure than when considering a single heated pile in a foundation. The evolution of stresses in the piles and in the soil during heating–cooling cycles also reveals possible critical phenomena.

1. Introduction

The management of energy resources is one of the main challenges of the 21st century. Following the global trend of population increase and improvement of living standards, primary energy consumption also continues to increase. In this context, energy geostructures represent a way to achieve environmentally friendly heating and cooling of buildings at low cost. The purpose of energy geostructures is to take advantage of the thermal storage capacity of the ground as an energy storage system using the foundation of buildings and to base the efficiency of the system on the invariability of ground temperature at depths below 10 m [1,2].

The use of ground energy from the near surface through a heat pump is a relatively common technology that has evolved to adapt to new constraints, such as required space and cost. These two constraints led to the initial development of vertical borehole heat exchangers and then to the integration of heat-exchanger pipes in structural piles by the Nägele Bau company in the early 1980s. These energy piles were then used directly in foundations assuming that temperature influence was negligible in the considered range. This technique, combined with the use of reversible heat pumps, has become an important element of low-energy building design, allowing both heating and cooling of the building by heat exchange with the ground with good efficiency, without air conditioning [3,4]. Several aspects of this technology, such as the thermal and thermo-mechanical behaviour of various soils and the interaction between energy piles and soils, are being investigated. One recent development is the departure from current heating and cooling technologies, which primarily make use of the natural thermal reload of the ground. Seasonal energy storage systems that can input summer thermal energy to the ground for extraction in winter are now preferred. However, their optimisation is constrained by structural stability uncertainties associated with the foundation. While small and conservative temperature changes are commonly used in practice (less than 5 °C deviation), greater deviations from the natural temperature of the soil are considered in this paper to study the optimisation of the structure and its stability.

The behaviour of a single vertical borehole heat exchanger is relatively well known due to the symmetry of its configuration and the existence of analytical solutions. From a thermal point of view, the case of a single pile is similar to that of a borehole heat exchanger, and it has also been studied [5], as has (more recently) a group of piles [6]. However, research addressing the

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mechanical aspects of such systems and their interaction with temperature variations is limited to studies by Laloui et al. [7] and Bourne-Webb et al. [8] on test sites and summarised by Amatya et al. [9] and extended to design recommendations by Knellwolf et al. [10].

This paper addresses a multi-pile seasonal storage area subjected to thermo-mechanical loading through a thermo-hydro-mechanical simulation of such a foundation. The purpose of this study is to identify good engineering practices, from both energy and structural points of view, through coupled simulation. Storage efficiency needs to be evaluated depending on extraction and injection rates. The problems that may be linked with high temperatures cycles in a foundation, and ways to monitor them, also need to be identified. This paper is organised as follows: The first section justifies the treatment of the 3D problem using a 2D simulation and the parametres that are used. The second section addresses the determination of the general thermal behaviour of the storage (i.e., thermal losses and storage efficiency for various rates of injection and extraction). In the third section, the hydro-mechanical consequences of thermal loading are discussed. A comparison is made between a configuration where only one pile is heated and cooled and a configuration where all piles of the foundation are heated and cooled. The positive effect of heating the whole foundation on thermally induced stresses is highlighted.

2. Description of the model study

2.1. The considered structure

To take into account the necessary elements for such a study (i.e., they must be generic while retaining some specific attributes of energy geostructures), the dimensions of the foundation were fixed. For satisfactory seasonal storage performance, a large reservoir is required (greater than 30,000 m^3, according to Pahud [11]). For a conventional building in dense overconsolidated clayey soil, the typical pile length is 20 m. Because the system is analysed in 2D, the volume is "infinite", but for the purpose of using realistic numbers, it has been decided to use a theoretical storage volume of 104,000 m^3. This foundation, shown in Fig. 1, would be made of 105 piles (on a 7 $\times$ 15 grid), each with a diameter of 80 cm, a length of 20 m and spaced 7 m apart, giving the raft dimensions of 51.6 $\times$ 117 m. The foundation is considered to function as a piled raft and is located on deep, low-permeability, clayey soil, which is presumed to be homogeneous. This clayey soil is assumed to behave thermo-elastically.

Interactions between thermal, mechanical and hydraulic responses are the main source of uncertainty in the design of a thermal energy storage geostructure. Heat exchange is the driving physical factor in this problem, and it creates thermal strains and thermal diffusion. As such, heat exchange also has hydraulic and mechanical consequences.

2.2. Concepts for the transition from a 3D to a 2D configuration

From a mechanical point of view, the transition from 3D to 2D for a piled raft foundation can be considered by modifying the Young's modulus of the piles, as indicated by Prakoso and Kulhawy's work [12]. The responses of vertically loaded pile foundations are controlled primarily by the axial stiffness of the piles. Because the piles are simplified into strips in a plane, a row of piles has to be simplified into an equivalent plane strain pile with the following modified Young's modulus:

$$E_{eq} = \frac{n_{p,row} A_p}{L_r B} E_p = e_{eq} E_p \tag{1}$$

where E_{eq} is the equivalent elastic modulus, E_p is the concrete elastic modulus, A_p is the pile section, B is the pile diameter, L_r is the out-of-plane raft length, $n_{p\text{-}row}$ is the number of piles in a row, and e_{eq} is the 3D–2D coefficient, as defined in Eq. (1).

This paper proposes in this section an extension of the approach developed by Prakoso and Kulhawy [12] to the more complex thermo-hydro-mechanical (THM) problem. The introduction of effective stresses and thermal deformation induces new stress–strain relationships. The basis of the approach is that the evolution of stresses in the piles is not governed by their real modulus, but by the equivalent modulus that results in similar deformations and thus realistic displacements of the foundation. In the linear elastic framework and with a strictly mechanical approach, the stress–strain relationship for the pile becomes the following:

$$\boldsymbol{\sigma}_{\mathbf{eq}} = E_{eq}\boldsymbol{\varepsilon}^{\mathbf{e}} \text{ and } \boldsymbol{\sigma}_{\mathbf{p}} = \frac{\boldsymbol{\sigma}_{\mathbf{eq}}}{e_{eq}} \tag{2}$$

where $\boldsymbol{\sigma}_{\mathbf{eq}}$ is the equivalent evaluated stress tensor in the pile, $\boldsymbol{\sigma}_{\mathbf{p}}$ is the real stress tensor, and $\boldsymbol{\varepsilon}^{\mathbf{e}}$ is the elastic strain tensor.

The extension being introduced in this work concerns the use of effective stresses under the same assumption. If effective stresses are now considered, using traditional soil mechanics sign conventions (positive values in compression), the effect of water pressure on actual stresses should be written as follows:

$$\boldsymbol{\sigma}'_{\mathbf{p}} = \boldsymbol{\sigma}_{\mathbf{p}} - p_w\mathbf{I} = \frac{E_{eq}\boldsymbol{\varepsilon}^{\mathbf{e}}}{e_{eq}} \tag{3}$$

where p_w is the pore water pressure and $\boldsymbol{\sigma}'_{\mathbf{p}}$ is the real effective stress in the pile. On the other hand, the assumption of equal strains in both configurations remains, which implies the following:

$$\boldsymbol{\varepsilon}^{\mathbf{e}} = \frac{\boldsymbol{\sigma}'_{\mathbf{eq}}}{E_{eq}} = \frac{e_{eq}\boldsymbol{\sigma}_{\mathbf{p}'}}{E_{eq}} \tag{4}$$

Eq. (3) can also be written as the first line of the pair shown in Eq. (5), where the general form of the definition of effective and total stresses is shown in the second line, and c and $\boldsymbol{\sigma}_{\mathbf{eq}}$ are unknowns:

$$\begin{cases} \mathbf{e_{eq}}\boldsymbol{\sigma}'_p = \mathbf{e_{eq}}\boldsymbol{\sigma}_p - e_{eq} \times p_w\mathbf{I} \\ \boldsymbol{\sigma}'_{\mathbf{eq}} = \boldsymbol{\sigma}_{\mathbf{eq}} - c \times p_w\mathbf{I} \end{cases} \tag{5}$$

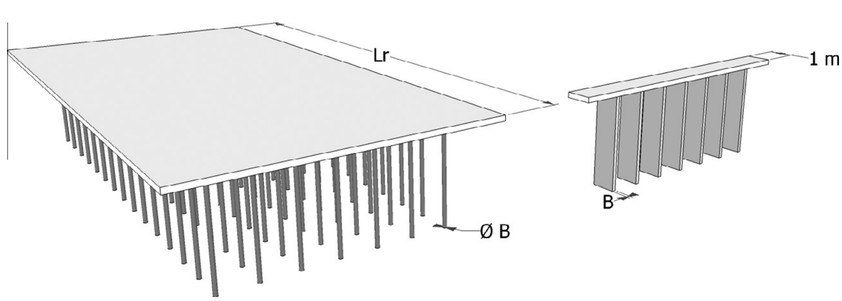

Fig. 1. 3D foundation and representation of the equivalent 2D foundation.