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Research Paper

The interaction factor method for energy pile groups

Alessandro F. Rotta Loria *, Lyesse Laloui

Swiss Federal Institute of Technology in Lausanne, EPFL, Laboratory of Soil Mechanics, LMS, Station 18, CH 1015 Lausanne, Switzerland

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ABSTRACT

Prior to this study, no simplified yet rational methods were available for estimating the vertical displacements of energy pile groups subjected to thermal loads. Observing such a challenge, the goal of this study has been threefold: (i) to extend the interaction factor concept from the framework of conventional pile groups to that of energy pile groups, (ii) to present charts for the analysis of the displacement interaction between two identical energy piles over a broad range of design conditions, and (iii) to propose, apply and validate the interaction factor method for the displacement analysis of energy pile groups.

1. Introduction

Over the last century, a substantial amount of research has been devoted to the analysis and design of conventional pile foundations because of their extensive application in the support of many structures and infrastructures. Classically, pile foundations have been applied to exploit adequate bearing capacities from soils of favourable strength and deformability characteristics, as well as to limit the use of surface area in densely built zones. In recent years, pile foundations have been increasingly used in an innovative form of energy piles to couple the aforementioned advantages associated with the structural support role of conventional deep foundations with the advantages associated with the role of the geothermal heat exchanger for satisfying the energy needs of building environments [1]. When addressing energy piles, a new challenge arises for civil engineers: the consideration of the mechanisms and phenomena induced by the application of thermal loads, in conjunction with those associated with the conventionally applied superstructure mechanical loads, on the mechanical behaviour of such foundations.

In the framework of the analysis and design of pile groups in which the piles are located sufficiently close to each other that their individual responses differ from that of an isolated pile because of the so-called "group effects" (i.e., closely spaced pile groups), two main aspects need to be considered (with reference to, e.g., the serviceability performance): (i) the vertical displacement – differential and average – of the piles in the group and (ii) the load redistribution among the piles in the group. The former aspect represents the subject matter of this paper.

To address the vertical displacement estimation of conventional pile groups subjected to mechanical loads, various numerical and analytical methods have been proposed. These methods include the finite element method [e.g., 2,3], the boundary element method [e.g., 4,5], the finite difference method [e.g., 6], the interaction factor method [e.g., 7,8–11], the equivalent pier and raft methods [e.g., 12–14], and the settlement ratio method [e.g., 15]. The finite element method, while providing the most rigorous and exhaustive representation of the pile group-related problem, is generally computationally expensive and considered mainly a research tool rather than a design tool. Conversely, the versatility of simplified (approximate) methods, such as the interaction factor approach that allows capturing the (e.g., vertical) displacements of any general pile group by the analysis of the displacement interaction between two identical piles and by the use of the elastic principle of superposition of effects, makes them attractive as design tools because they allow for the use of expedient parametric studies under various design conditions.

In contrast to the various approaches that have been used to estimate the vertical displacements of conventional pile groups subjected to mechanical loads, to date, only the finite element method [e.g., 16,17] has been applied for the same purpose for energy pile groups subjected to thermal loads and no detailed studies have been available on the analysis of the displacement behaviour of such foundations. This is because no simplified yet rational methods were available prior to this study for the vertical

* Corresponding author.
E-mail address: alessandro.rottaloria@epfl.ch (A.F. Rotta Loria).

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displacement estimation of energy pile groups subjected to thermal loads.

To address these challenges, the goal of this study has been threefold: (i) to extend the interaction factor concept from the framework of conventional pile groups to that of energy pile groups, (ii) to present charts for the analysis of the displacement interaction between two identical energy piles under a broad range of design conditions, and (iii) to propose and apply the interaction factor method for the analysis of the vertical displacement of energy pile groups subjected to thermal loads.

In addressing aspect (i), the key contributions concerning the displacement interaction between two identical semi-floating energy piles (i.e., the simplest system representing a pile group) subjected to a temperature change are described. In contrast to the description of the displacement interaction originally proposed by Poulos [7] for conventional piles subjected to mechanical loads, which was based on boundary element analyses, the description of the displacement interaction for energy piles subjected to thermal loads presented in this study is based on thermo-mechanical finite element analyses.

In addressing aspect (ii), the effects of many variables, including the pile spacing, the pile slenderness ratio, the pile-soil stiffness ratio, the Poisson's ratio of the soil, the depth of a finite layer, the non-uniform soil modulus and the soil-pile thermal expansion coefficient ratio, are investigated. According to the approach described by Poulos [18], although it is not possible to present theoretical solutions that cover all possible cases, those presented in this paper are considered to be sufficient to enable an approximation of the vertical displacement of energy pile groups to be made for most cases likely to be encountered in practice.

In addressing aspect (iii), the interaction factor concept defined for a group of two energy piles is first applied to the displacement analysis of symmetrical energy pile groups by exploiting the elastic principle of superposition of effects. This concept is next validated based on a comparison with results of 3-D thermo-mechanical finite element analyses. Then, a simplified (approximate) method for the displacement analysis of general energy pile groups with any configuration of piles in the group is formulated, although the solutions proposed in this paper refer to square groups of energy piles containing up to twenty-five piles. Finally, the interaction factor method is validated based on the comparison with results of 3-D thermo-mechanical finite element analyses on general energy pile groups subjected to thermal loads surrounded by soils with different thermal expansion coefficients.

2. The interaction factor concept

2.1. The problem: a group of two energy piles

The simplest system representing an energy pile group can be considered as consisting of two semi-floating energy piles in a deep soil layer. In the considered problem, the energy piles are (i) subjected to a thermal load, (ii) free of superstructure mechanical loads, and (iii) free to move vertically at their head.

The thermal load (i.e., aspect (i)) applied to the energy piles is a result of the geothermal operation of these elements. Cooling and/or thermal energy storage operations of energy piles can be associated to positive temperature changes applied to these elements. Heating operations of energy piles can be associated to negative temperature changes applied to these elements.

Reference to a situation in which no superstructure mechanical load is applied to the energy piles (i.e., aspect (ii)) allows focusing on the impact of the thermal load on the response of these elements.

The consideration of piles free to move at their head (i.e., aspect (iii)) has been generally accounted for in the analysis of conventional pile groups subjected to mechanical loads for estimates of the vertical displacement on the safety side. This approach appears to also be valuable for displacement analysis of energy pile groups and is considered in the following.

2.2. Idealisation

The previously described system is idealised considering the following assumptions. The energy piles are two identical isotropic, homogeneous and uniform cylindrical solids. The soil layer is a semi-infinite, isotropic, homogeneous and uniform mass. The same uniform temperature change is applied along the length of each of the energy piles. No mechanical load is applied to the energy piles. No head restraint is present (i.e., perfectly flexible slab). No slip or yielding occurs between each of the energy piles and the adjacent soil (perfect contact between the pile and soil is assumed). The energy piles are characterised by a linear thermo-elastic behaviour, whereas the soil is characterised by a linear elastic behaviour (i.e., the soil is an infinite heat reservoir that remains at a fixed constant temperature). Thus, reference is made to loading situations in which elastic (i.e., reversible) conditions prevail. Although not valid in situations where mechanical and thermal loads of significant magnitudes are applied to energy piles (especially if semi-floating) [19], these conditions have been demonstrated to characterise normal working situations based on the results of full-scale experimental tests [20–22] and numerical analyses [16,17].

The application of the temperature change to the energy piles involves a thermally induced deformation of these elements. An expansion of the energy piles is observed for cooling and/or thermal energy storage operations of these elements (positive temperature changes applied to the energy piles) whereas a contraction of the energy piles is observed for heating operations of these elements (negative temperature changes applied). In the former case, the upper portion of each energy pile displaces upwards, whereas the lower portion displaces downwards around a setting characterised by zero thermally induced displacements (defined as the null point referring to one-dimensional conditions [23]). In the latter case, the upper portion of each energy pile displaces downwards, whereas the lower portion displaces upwards[1]. The considered elastic assumption involves that the null point does not move depending on whether positive or negative temperature changes are applied to the energy piles. Hence, the displacement variation along the length of these elements for a unitary temperature change associated to their heating or cooling is the same in absolute value. The displacement field generated in each of the energy piles is transmitted in the adjacent soil. Interaction of the displacement fields generated by the thermally induced deformation of the energy piles thus occurs.

Assuming that the resulting deformation field of a group of two energy piles subjected to a temperature difference can be representatively decomposed through the elastic principle of superposition of effects, two (e.g., symmetrical) individual systems can be considered to describe the analysed problem. Fig. 1 provides an example of this decomposition for a situation in which a positive temperature change is applied to the energy piles. This decomposition approach has been widely proved to be suitable for

[1] It is worth noting that the phenomena characterising energy pile-related problems involve a remarkably different behaviour of the piles compared to that characterising most conventional pile-related problems in which a superstructure mechanical load (e.g., downward) is applied at the head of the piles inducing their overall settlement.