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Research Paper

Displacement interaction among energy piles bearing on stiff soil strata

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ABSTRACT

This study presents an analysis of the displacement interaction among general configurations of energy piles bearing on stiff soil strata that are subjected to thermal loads. This work integrates recent analyses investigating the displacement interaction among predominantly floating energy piles subjected to thermal loads in deep uniform soil deposits. To address this challenge, design charts for energy piles resting on either infinitely or finitely rigid soil strata are presented, applied and validated for the analysis of the vertical displacement of predominantly end-bearing energy pile groups subjected to thermal loads using the interaction factor method.

1. Introduction

In recent years, an increasing amount of research has been performed to address the thermally induced mechanical behaviour of energy pile groups, by means of both experimental [1–4] and numerical [5–9] analyses. Attention has been particularly devoted to the analysis of the vertical displacement of energy piles caused by the action of thermal (and mechanical) loads involved with the geothermal (and structural support) operation of such ground structures [10,11]. The reason for this is that, in situations where energy piles are located sufficiently close to each other, interactions caused by the presence of and loading on the neighbouring piles occur and involve group effects. For example, such group effects include a greater vertical displacement of the energy piles compared to situations where the piles may be located sufficiently far from each other and behave as single isolated elements.

The interaction factor method has recently been proven to be an effective means for estimating the vertical displacement of general configurations of energy piles subjected to thermal loads based on the consideration of the displacement interaction occurring among the piles [10]. At the present time, an analysis of the vertical displacement of and interaction between predominantly floating (i.e., friction) energy piles subjected to thermal loads in deep uniform soil deposits and design charts for the expedient consideration of this problem have been proposed [10]. However, neither an analysis of the vertical displacement of and interaction between predominantly end-bearing energy piles subjected to thermal loads resting on stiff soil strata nor design charts for the expedient consideration of this problem have yet been presented.

The displacement interaction among predominantly floating energy pile groups subjected to thermal loads has been proven to merit consideration in the analysis and design of such foundations [10,11]. Therefore, the expanded knowledge of the displacement interaction among predominantly end-bearing energy pile groups subjected to thermal loads and the availability of design charts for the analysis of the vertical displacement of such foundations using the interaction factor method are considered of importance.

To address this challenge, this paper expands on the displacement interaction among predominantly end-bearing energy pile groups subjected to thermal loads resting on stiff soil strata and presents design charts for the analysis of the vertical displacement of such foundations using the interaction factor method.

The analysis approach considered in this work draws on investigations by Poulos and Mattes [12] for addressing the displacement interaction among predominantly end-bearing conventional pile groups subjected to mechanical loads resting on stiff soil strata.

In this study, the interaction factor concept is first expanded with reference to the analysis of energy piles bearing on stiff soil strata. Then, design charts that can be used to determine the interaction factor characterising energy pile groups bearing on stiff soil strata are presented. Finally, the proposed charts are applied for estimating the vertical displacement of energy pile groups subjected to thermal loads in various design situations using the interaction factor method and are validated based on a comparison with results of 3-D thermo-mechanical finite element analyses.

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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 energy piles in a deep soil deposit. In the original analysis presented by Rotta Loria and Laloui [10], the energy piles were considered to be predominantly floating and socketed in a uniform soil layer. In this study, the energy piles are considered to be predominantly end-bearing, to be surrounded by a shallower uniform soil layer and to rest on a deeper uniform soil stratum. 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.

2.2. Idealisation

The previously described system is idealised considering the following assumptions, which are justified by Rotta Loria and Laloui [10]. The energy piles are two identical isotropic, homogeneous and uniform cylindrical solids. The soil deposit is a semi-infinite mass characterised by a layer surrounding the shaft of the energy piles and a layer located below the toe of the energy piles. Each of these soil layers is isotropic, homogeneous and uniform. 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).

The application of the temperature change associated to the geothermal operation of the energy piles involves a thermally induced deformation of these elements. Under the application of the temperature change, there is a setting characterised by zero thermally induced displacement, i.e., the null point (of the vertical displacement), around which the upper and lower portions of the energy piles displace in opposite directions to ensure vertical equilibrium [13]. The upper and lower portions of the energy piles displace upward and downward, respectively, when positive temperature changes are applied to the piles, and vice versa when the temperature changes applied to the piles are negative. In general, the more rigid the soil layer below the toe of the energy piles is, the lower the location of the null point is for the boundary conditions characterising the considered problem. The null point coincides with the toe of the energy piles when the underlying soil layer is infinitely rigid (i.e., the energy piles entirely expand upward and contract downward above their toe under positive and negative temperature changes applied to the pile, respectively). The displacement field generated in each of the energy piles is transmitted to 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 using the elastic principle of superposition of effects, two (e.g., symmetrical) individual systems can be considered to describe the problem. Fig. 1 provides an example of this decomposition for a situation in which a positive temperature change is applied to a pair of energy piles that are surrounded by a finitely rigid, i.e., compressible, soil layer and rest on an infinitely rigid soil stratum. This decomposition approach has been widely proved to be suitable for describing the displacement interaction between conventional piles subjected to mechanical loads [14,15] and recently for describing that between energy piles subjected to thermal loads [10].

The elementary unit (cf., Fig. 2) composing the problem described above involves a source pile i subjected to a temperature change ΔT (i.e., thermally loaded) and a receiver pile j located at a certain spacing (i.e., centre-to-centre distance between the piles) s in the soil. As previously specified, the energy piles have the same length L and shaft diameter D.

2.3. Finite element analysis

2.3.1. Numerical models

Finite element modelling with the software COMSOL Multiphysics [16] is used in this paper as an analysis and validation tool.

3-D and axisymmetric finite element simulations are used as the analysis tool (i) to propose a description of the displacement field characterising the elementary unit described above and a

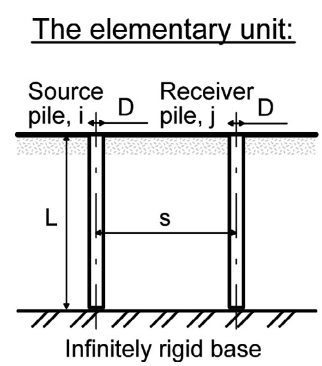

Fig. 2. The source and receiver piles constituting the elementary unit.

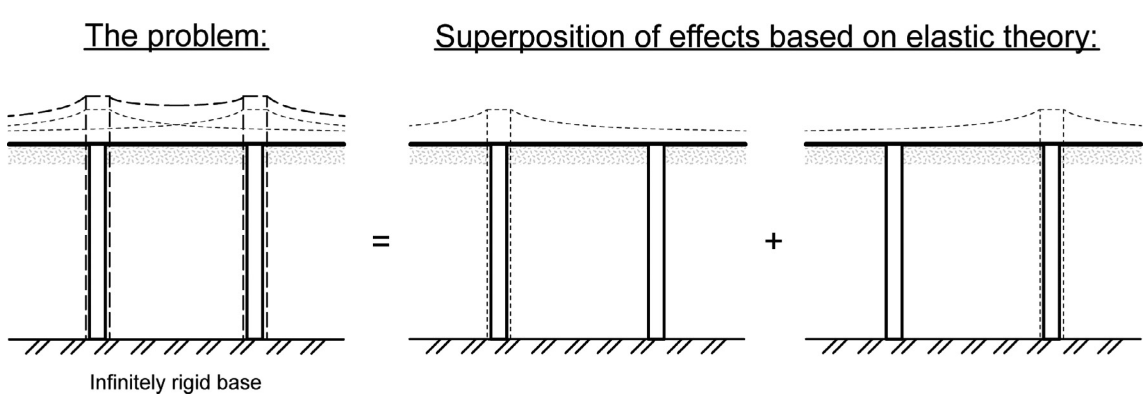

Fig. 1. The modelling approach.