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Analysis of the vertical displacement of energy pile groups

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HIGHLIGHTS

- Two analytical performance models are presented for interaction factor analyses.
- The lower and upper boundaries of pile interaction are given by their application.
- The displacement of energy piles in uniform and non-uniform soil is captured.
- Expedient analyses and designs of even large energy pile groups can be performed.

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ABSTRACT

Over the last fifty years, the interaction factor method has been widely used to address the vertical displacement and the increased deformation of conventional pile groups subjected to mechanical loads when group effects and interactions occur among the piles. Design charts and analytical models have been proposed to serve the considered analysis method. In recent years, the interaction factor method has been extended to address energy pile groups subjected to thermal loads. Design charts have been proposed. However, prior to this study, no analytical models capable of analysing the vertical displacement and the increased deformation of energy piles subjected to thermal loads in a more comprehensive and flexible way than through design charts have been available. To address this challenge, this study presents two analytical models for analysing the vertical displacement of energy pile groups subjected to thermal loads, based on the analysis of a single isolated energy pile. Comparisons with three-dimensional finite element analyses outline that the models can accurately capture the displacement of energy piles without the expense of a full rigorous analysis. This evidence makes the present models useful tools for the analysis and design of energy piles under serviceability conditions.

1. Introduction

Over the last fifty years, the interaction factor method proposed by Poulos[1] has been widely used for the analysis of the vertical displacement and increased deformation of pile groups caused by mechanical loads when group effects and interactions are present. This method assumes that the vertical displacement of any pile group, e.g., under serviceability conditions, may be estimated through elastic theory and the superposition principle by knowing (i) the displacement interaction relationship – quantified by an interaction factor – among two representative piles of the group considered in an isolated pair, (ii) the vertical displacement of a single pile under unit load and (iii) the loads applied to the piles. The expediency and capability of this method to model the problem previously described, which is often considered for design purposes although being an approximation of reality, have played a major role for its diffusion.

Numerical analysis approaches, such as the finite element method, can provide a more rigorous and comprehensive understanding of the response of pile groups than analyses performed via the interaction factor method (e.g., with reference to problems of load redistribution between the piles, interaction between the piles and the slab, etc.). However, these approaches generally require more remarkable computational efforts and expertise than the interaction factor method, which can be applied analytically. For this reason, when the primary purpose of the analysis and design is to estimate the vertical displacement and deformation of pile groups, the interaction factor method can be a very effective alternative to numerical methods.

Originally, design charts for floating and end-bearing conventional piles have been proposed via the boundary element method by Poulos[1] and Poulos and Mattes[2], respectively, to serve the interaction factor method in estimating the interaction factor. Afterward, analytical models have been proposed for floating and end-bearing conventional piles by Randolph and Wroth[3] and Randolph and Wroth[4], respectively. An alternative formulation of these models by Chow[5] and an improvement related to the definition of

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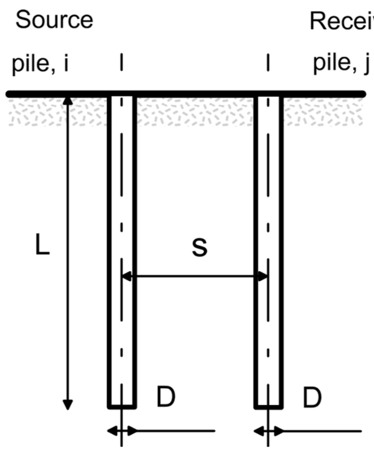

Fig. 1. The source and receiver pile constituting the considered problem.

the interaction factor by Mylonakis and Gazetas[6] have been later presented. The analytical models have been developed due to their capability of estimating the interaction factor in a broader range of conditions and performing more comprehensively and flexibly than the charts in the analysis of pile groups.

In recent years, the interaction factor method has been extended and proven to be a suitable means for estimating the vertical displacement of energy piles subjected to thermal loads[7]. Design charts have been proposed via the finite element method for floating and end-bearing energy piles by Rotta Loria and Laloui[7] and Rotta Loria and Laloui[8], respectively. Despite the aforementioned developments, prior to this study no analytical models capable of estimating the vertical displacement of energy pile groups subjected to thermal loads and accounting for group effects and interactions have been available.

Observing such a challenge, the present paper addresses the development of two analytical models, i.e., a *layer model* and a *continuous model*, capable of the following: (i) estimating the vertical displacement with depth of a thermally loaded pile and neighbouring pile in a pair starting from the analysis of a single isolated pile; (ii) defining the interaction factor with depth between these piles; and (iii) analysing the vertical displacement with depth of any energy pile groups using the interaction factor method.

2. Problem definition and solution approach

2.1. The problem

The interaction factor method addresses the displacement analysis of general pile groups by considering the displacement response of a pair of piles constituted by a loaded "source" pile and a "receiver" neighbouring pile, with reference to the response of a source pile in an isolated case subjected to the same loading of the source pile in the pair [see for further details, e.g., Refs. 3, 6, 7]. The piles are identical cylindrical solids characterised by a length, L, and a diameter, D. When considered in a pair, the piles are located at a centre-to-centre distance (i.e., spacing), s, apart from each other (cf., Fig. 1).

When accounting for the effects caused by thermal loads, the source pile is assumed to be subjected to a (positive or negative) temperature change, ΔT. The influence of vertical mechanical loads may be considered as well by assuming that the source pile is subjected to a vertical mechanical load applied at its head, P. The piles are assumed to be free to move vertically at their head.

The loading of the source pile in the pair results in a deformation of this element that modifies the displacement field along its length, influences the surrounding soil and changes the displacement field of the neighbouring receiver pile. Thermal loads involve one portion of the pile (and surroundings) that moves upwards while the other portion that moves downwards around the so-called null point of the vertical displacement[9]. Mechanical loads induce a movement of the pile (and surroundings) in the same direction of the applied load along the entire pile length.

In principle, a complete description of the interaction between the source pile and the receiver pile in the pair would require three-dimensional (3-D) time-dependent numerical analyses because of its three-dimensional and time-dependent character. For example, the vertical displacement field is generally not homogeneous in the three-dimensional space because of the stiffness and presence of the piles. Bending moments occur in the piles and in the soil due to the compatibility and continuity of the displacement field. The heat exchange involves temperature variations with time that cause thermally induced deformations of the soil and potentially of the receiver pile. In practice, an approximate yet realistic analytical description of the considered problem can be performed based on a number of simplifying hypotheses and considerations presented below.

2.2. Idealisation, hypotheses and considerations

In the following, the idealisation of the problem described above and a number of hypotheses and considerations that have been widely used in seminal developments of the interaction factor method for piles subjected to mechanical loads[10,11] are extended to piles subjected to thermal loads based on previous studies[7,8].

The piles are identical, isotropic, homogeneous and uniform cylindrical solids. The soil is a semi-infinite isotropic mass assumed to be composed of a unique homogeneous layer or different horizontal layers. The aforementioned assumptions represent typical approximations of reality employed in engineering theory. When applied with judgement, however, they can adequately represent real problems[10].

A uniform temperature change is applied to the source pile. A vertical mechanical load may be applied at the pile head as well. The temperature variations observed within energy piles are not uniform[12,13] but can be considered uniform by choosing representative values of the temperature field within the cross-section and along the length of the pile[14,15].

No head restraint is present (i.e., infinitely flexible slab). This assumption conservatively analyses the vertical (e.g., head) displacement of piles according to the widely used assumption of a negligible contribution of the uppermost slabs or other shallow foundations in the deformation of piles, at least for preliminary analyses and designs[10,11,16].

No slip or yielding occurs between the piles and the adjacent soil (i.e., perfect contact between the pile and soil is assumed). Although not valid in situations where mechanical and thermal loads of significant magnitudes may be applied to energy piles (especially if predominantly floating)[17], these conditions have been shown through full-scale experimental tests and numerical analyses[13] to characterise serviceability conditions targeted by the interaction factor method.

The piles are characterised by a linear thermo-elastic behaviour. The soil is characterised by a linear elastic behaviour. Loading situations in which reversible conditions prevail are thus assumed, according to the hypothesis of no slip or yielding between the piles and the adjacent soil. The present hypothesis involves that the effect of thermal and mechanical loads can be superimposed at any time, based on the superposition principle via separate analyses addressing thermal and mechanical loads.

Considering the soil to be characterised by an elastic behaviour involves assuming it is an infinite heat reservoir that remains at

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