Analytical interaction factor models for energy pile groups

Alessandro F. Rotta Loria[1] *, Lyesse Laloui[1]

[1] Swiss Federal Institute of Technology in Lausanne, EPFL, Lausanne, Switzerland
* alessandro.rottaloria@epfl.ch

Introduction

When pile foundations are located sufficiently close to each other, their individual responses differ from that of an isolated pile because of so-called "group effects". In the context of energy pile foundations, such group effects are caused by the mechanical and thermal loads applied to the piles as a consequence of their twofold role as a structural support and a geothermal heat exchanger. For example, these group effects result in an increased vertical displacement of the piles compared to situations where they may be located sufficiently far from each other (see, for example, Rotta Loria and Laloui, 2017c; Rotta Loria and Laloui, 2017b).

Over the last fifty years, the so-called interaction factor method proposed by Poulos (1968) has been proven to be a powerful tool for estimating in an expedient yet realistic way the group effects among piles subjected to mechanical loads and the related vertical displacement. Originally, the method has been formulated for floating and end-bearing conventional piles by Poulos (1968) and Poulos and Mattes (1974), respectively, with reference to design charts constructed via the results of boundary element analyses. Afterward, analytical models have been proposed for floating and end-bearing conventional piles by Randolph and Wroth (1979b) and Randolph and Wroth (1979a), respectively, to serve the considered method as an alternative to the charts. An additional formulation of these models by Chow (1986) and an improvement related to the definition of the interaction factor by Mylonakis and Gazetas (1998) have been later presented. The analytical models have been developed due to their capability of performing more comprehensively than the charts in the analysis of pile groups.

In recent years, the interaction factor method has been extended from the framework of conventional piles subjected to only mechanical loads to the framework of energy piles also subjected to thermal loads by Rotta Loria and Laloui (2016). In this context, the interaction factor method has been proven to be a suitable means for estimating the vertical displacement of energy piles subjected to thermal (and mechanical) loads. Design charts have been proposed via the finite element method for floating and end-bearing energy piles by Rotta Loria and Laloui (2016) and Rotta Loria and Laloui (2017a), 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.

To address this challenge, this study draws for the investigations of Rotta Loria et al. (2017) and discusses the capabilities of two interaction factor models that have been formulated for analysing the vertical displacement of energy pile groups subjected to thermal loads, based on the analysis of a single isolated energy pile.

Interaction factor analysis procedure and analytical models

According to the interaction factor analysis procedure for energy piles subjected to thermal loads (Rotta Loria and Laloui, 2016; Rotta Loria and Laloui, 2017a), the vertical head displacement of any pile k in a group of total number of piles n_{EP} subjected to a uniform temperature change with depth can be estimated by employing the elastic principle of superposition as

$$w_j(z) = w^1(z) \sum_{i=1}^{i=n_{EP}} \Delta T_i \, \Omega_{ij}(s,z) \tag{1}$$

where $w^1(z)$ is the vertical displacement of a single isolated pile per unit temperature change with depth z, ΔT_i is the applied temperature change to pile i and $\Omega_{ij}(s,z)$ is the interaction factor for two piles (i.e., the ratio between the additional displacement of a receiver pile due to the loading of an adjacent source pile in a pair and the displacement of a single pile subjected to the same loading, i.e., $\Omega_{ij}(s,z) = w_j(s,z)/w_i(z)$) corresponding to the centre-to-centre distance s between pile i and pile k. The same approach can be considered for the analysis of piles subjected to mechanical loads (Poulos, 1968; Poulos and Mattes, 1974).

The definition of $w^1(z)$ for piles subjected to thermal loads currently needs to resort to the results of numerical analyses. The definition of $\Omega_{ij}(s,z)$ can be achieved by applying two fully analytical models, i.e., a *layer* *model* and a *continuous model*, whose mathematical formulations have been modified and extended from those of Randolph and Wroth (1979b), Chow (1986) and Mylonakis and Gazetas (1998) for conventional piles to the framework of energy piles. The layer model assumes that the soil around the shaft of piles subjected to loads that induce vertical deformation may be idealised as consisting of concentric cylindrical elements, with shear stresses distributed on the surface of each element, and according to this hypothesis is formulated through a simplification of the indefinite equilibrium equations. The continuous model assumes that the distribution of the shear stresses at the pile shaft can be approximated as a distribution of point loads acting at the centre of the elements composing these piles as if they were linear entities, and according to this hypothesis is formulated through the equations of Mindlin (1936) for a point load acting in a semi-infinite space. While the hypotheses of these models are different in nature and their mathematical development is reported by Rotta Loria et al. (2017), both of them allow defining the interaction factor $\Omega_{ij}(s,z)$ for two piles in uniform or non-uniform soil.

Figure 1 presents the typical evolution of the displacement interaction factor predicted by the two analytical models with that obtained through three-dimensional thermo-mechanical finite element analyses. The results outline that the models can capture the interaction factor between the energy piles without the expense of a full rigorous analysis. This evidence, together with an extensive validation of the models proposed by Rotta Loria et al. (2017), makes the present analytical models useful tools for the geotechnical and structural analysis and design of energy piles under serviceability conditions.

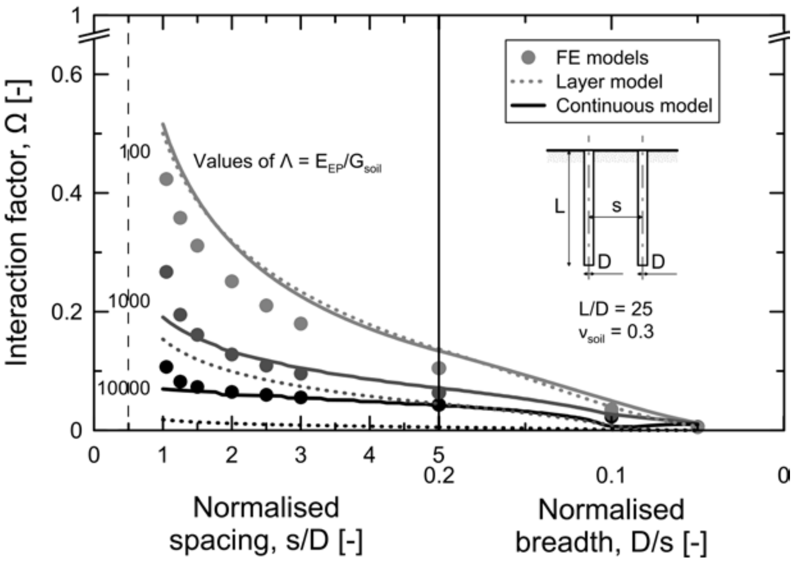

Fig. 1: Interaction factor relationship for energy piles subjected to thermal loads (L = pile length, D = pile diameter, E_{EP} = pile Young's modulus, G_{soil} = soil shear modulus and ν_{soil} = soil Poisson's ratio)

References

Chow, Y. (1986) Analysis of vertically loaded pile groups. *International journal for numerical and analytical methods in geomechanics* **10(1)**:59-72

Mindlin, R. D. (1936) Force at a point in the interior of a semi- infinite solid. *Journal of Applied Physics* **7(5)**:195-202

Mylonakis, G. & Gazetas, G. (1998) Settlement and additional internal forces of grouped piles in layered soil. *Geotechnique* **48(1)**:55-72

Poulos, H. G. (1968) Analysis of the settlement of pile groups. *Geotechnique* **18(4)**:449-471

Poulos, H. G. & Mattes, N. S. (1974) Settlement of pile groups bearing on stiffer strata. *Journal of geotechnical and geoenvironmental engineering* **100(GT2)**:185-190

Randolph, M. & Wroth, C. (1979a) A simple approach to pile design and the evaluation of pile tests. In *Behavior of Deep Foundations*.) ASTM International

Randolph, M. F. & Wroth, C. (1979b) An analysis of the vertical deformation of pile groups. *Geotechnique* **29(4)**:423-439

Rotta Loria, A. F. & Laloui, L. (2016) The interaction factor method for energy pile groups. *Computers and Geotechnics* **80**:121-137

Rotta Loria, A. F. & Laloui, L. (2017a) Displacement interaction among energy piles bearing on stiff soil strata. *Computers and Geotechnics* **90**:144-154

Rotta Loria, A. F. & Laloui, L. (2017b) Group action caused by various operating energy piles. *Geotechnique*:10.1680/jgeot.17.P.213

Rotta Loria, A. F. & Laloui, L. (2017c) Thermally induced group effects among energy piles. *Geotechnique* **67(5)**:374-393

Rotta Loria, A. F., Vadrot, A. & Laloui, L. (2017) Analysis of the vertical displacement of energy pile groups. *Geomechanics for Energy and the Environment*:10.1016/j.gete.2018.04.001