# Analysis of the interaction factor method for energy pile groups with slab

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## Abstract

The design of energy pile is hampered by the complex interaction between the piles and the slab subjected to thermal loads. Although finite element analysis is used to account explicitly for the interactions, this method is mainly considered as a research tool. A more practical approach for the routine design is the interaction factor method. However, to date no attention has been paid to address the pile-slab-soil interaction problem. This work investigates the energy pile-cap interaction and integrates the available formulation of the method. The method is compared with results from more rigorous finite element analyses to evaluate its performance.

**Keywords:** design; energy pile groups; soil-structure interaction; slab; displacement

## 1. Introduction

Energy pile foundations represent an increasingly important contribution to achieve energy performance targets and fulfilling nearly zero energy buildings requirements. As interest in this technology becomes more pronounced, engineers are progressively asked to plan and design these structures. Finite element numerical analyses are considered mainly as a research tool because of the computational resources required for foundations of practical proportions. In contrast, the flexibility of simplified procedures makes them attractive for the routine design of energy pile foundations.

Over the last decade, an increasing amount of research has been devoted to modifying and extending various approximate methods for the analysis of energy piles subjected to thermal loads, applied alone or in conjunction with mechanical loads that were originally developed for the analysis of conventional pile foundations subjected to only mechanical loads. This includes the formulation of a load-transfer approach [1-4] for the analysis of a single isolated energy pile and the interaction factor method based on design charts [5,6,7], the interaction factor method based on analytical models [8] and the equivalent pier method [9] for the analysis of energy pile groups.

The interaction factor method proposed by Poulos [10] is widely recognised as an approximate method for estimating the vertical displacement and increased deformation of conventional pile groups. Recent studies have been presented by Rotta Loria & Laloui [5,6,7], which provide design charts to address the vertical displacement of energy pile groups subjected to thermal loads. In the case of thermal load, to date, the proposed solutions refer to the displacement interaction for freestanding energy pile groups configuration. However, in practice, it is common to cast the cap of a pile group foundation directly on the ground [11]. Therefore, the goal of this study has been (i) to investigate the energy pile-cap interaction (ii) to extend the interaction factor method from that of freestanding energy pile groups to that of energy pile groups with a slab supported on soil (iii) to propose charts that can be completely integrated with the current available formulation (iv) to investigate the conditions of application of the simplified procedure proposed based on a comparison with results of 3D thermo-mechanical finite element analyses.

The analysis approach considered in this work draws on investigations by Poulos [12] for addressing the influence of a pile-cap on the behaviour of an axially loaded pile and Davis & Poulos [13] for the analysis of pile raft systems. In contrast to the approach originally proposed by Davis & Poulos [13], considering the limit of non-compatibility of the displacements, underlined by the authors themselves in the proposition of the method, a correction factor to consider the interaction between the slab and the piles is proposed. The study is based on thermo-mechanical finite element analyses.

## 2. Energy pile-soil-cap interaction: modelling and method

A rigorous analysis of pile foundations requires the study of the interaction between the foundation, the structure and the soil. The interaction of the pile-soil-structure assumes a character of not negligible complexity, whereby the search for the solution often requires the introduction of very marked simplifications. The greatest difficulties lie in the schematization of the ground response. Moreover, the correct representation of the stiffness of the structure is not without uncertainties either.

Early studies that consider the interaction between the pile-cap and conventional piles have been performed by Poulos [12] and Butterfield & Banerjee [14]. Butterfield & Banerjee [14] suggested that the loads carried by the individual piles in the groups with contacting caps differ from those occurring in similar floating cap systems and the contacting cap slightly increases the system stiffness depending upon the group size and pile spacing. This finding has been subsequently confirmed by experimental work [15]. Afterwards, for the analysis of pile raft foundations, approaches of varying complexity have been developed specifically by Davis & Poulos [13], Poulos & Davis [16], Randolph & Clancy [17], Randolph [18], Clancy & Randolph [11], Russo & Viggiani [19], Poulos [20], Viggiani et al. [21].

To date, with regards to energy pile group foundations, the current formulation of the interaction factor method allows the analysis of the displacement behaviour of such foundations where the cap does not make contact with the ground. Normal practice would rather be to rigidly attach the piles to a pile-cap which is supported on soil. Thermally induced mechanical interactions occur between the piles, the connecting slab and the surrounding soil which have been observed experimentally [22-25]. It is therefore considered important to have a thorough knowledge of the pile-soil-slab interaction and the availability of an approach to address the analysis of the vertical displacement.

### 2.1 The modelling approach

The simplest unit to be analysed to address the problem of interaction is formed of a pile-cap and an energy pile subjected to a thermal load as a result of the geothermal operation of this element. The geothermal operation of the energy piles entails thermally induced deformations of these elements. It turns out that two pile portions move in the opposite directions from the null point of the vertical displacement [22, 26]. Different from situations where no base or head restraints are present, when either a rigid soil layer below the toe or a cap is present, the location of the null point is shifted towards the region of the system characterised by the higher rigidity. The displacement field transmitted in the adjacent soil is thus affected by the presence of the cap.

Figure 1 provides a representation of the elementary unit composing the problem. The following assumptions and idealisation are considered. The energy pile and the pile-cap are an isotropic, homogeneous and uniform cylindrical solid and square prism respectively. The soil surrounding the shaft of the energy pile is a semi-infinite, isotropic, homogeneous and uniform mass. The application of the uniform temperature change concerns only the energy pile (i.e., only the pile is equipped as a heat exchanger). The analysis is conducted focusing on the response of these elements to a thermal load, thus reference is made to configurations in which no mechanical load from the superstructure is applied. This later hypothesis is justified by the elastic behaviour of the system allowing the use of the superposition principle. The pile is modelled as a perfectly jointed member with the cap (full moment connection). A perfect contact among the pile, the pile-cap and the soil is assumed, hence, no account has been taken of the possibility of slip or yielding at the interfaces. The pile-cap and the energy pile behave linear thermo-elastically, whereas the soil is considered as an infinite heat reservoir at a fixed constant temperature and is characterised by a linear elastic behaviour.

## 2.2 Method of analysis

Similarly, to the formulation of the method originally proposed by Rotta Loria & Laloui [5] for groups of energy piles in freestanding conditions, the description presented in this study for the interaction between energy piles subjected to thermal load and slab is based on thermo-mechanical finite element analyses.

### *2.2.1 Finite element analysis*

Thermo-mechanical finite element modelling is used in this study as an analysis and validation tool. Two types of simulations have been carried out: (i) steady state analyses to develop the simplified procedure and (ii) time dependent analyses to check the condition of validity of the method.

3D steady state finite element simulations are carried out with the software COMSOL Multiphysics version 5.3a [27] (i) to analyse the effect of interaction between the pile and the cap (ii) to propose a formulation of the interaction factor concept for energy pile groups with slab (iii) to present design charts for the analysis of the slab interaction fully compatible with the actual available method.

3D time dependent finite element simulations referring to problem closer to reality has been used to investigate the conditions of validity of the approach. Results obtained from the interaction analyses of the elementary unit, used in the simplified approach, are compared with results of interaction of general energy pile groups with slab.

Considering the symmetry of the problem only a quarter model is required. The model has a width and a breadth of $x = 50D$ and a height of $h = 25L$ in the analyses of the elementary unit. The model has a width and a breadth of $x = 50D + (n_{ep}-1)s$ and a height of $h = 25L$ in the analyses of the general energy pile group system, where $n_{ep}$ is the number of energy piles along a column or a row of the group in plain view in the considered direction and $s$ the spacing among the piles. For the mesh, an example regarding the elementary unit and the general energy pile group is illustrated in Figure 2. The energy pile, the pile-cap and soil domains are described through extremely fine tetrahedral elements. The distribution of the mesh is denser in the area around the piles and coarser towards the boundary of the models. Depending on the pile configuration the number of elements varies between 90000 and 140000.  The model was used in freestanding condition and the compatibility of the model has been verified in order to guarantee the integrity of the method with the current available formulation.

### *2.2.2 Mathematical formulation*

Steady state and time dependent thermo-mechanical finite element simulations have been performed.  The former refers to simplified analyses while the latter was used in the validation phase where the geometries and the responses of the ground and of the pile to temperature variations are closer to reality. The equilibrium equation refers to Equation (1)

$$\nabla \cdot \sigma_{ij} + \rho g_i = 0 \qquad (1)$$

and the stress tensor can be written as

$$\sigma_{ij} = D_{ijkl}[\varepsilon_{kl} + \alpha\delta_{kl}\Delta T] \tag{2}$$

where $D_{ijkl}$ is the elastic stiffness tensor, $\varepsilon_{kl}$ is the total strain tensor, $\alpha$ is the linear thermal expansion coefficient, $\delta_{kl}$ is Kronecker delta and $\Delta T$ is the temperature change.

The mathematical formulation employed in the finite element analyses refers to the heat transfer in porous materials theory. The heat transfer mode considered in this study is conduction. The energy conservation equation reads

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (\lambda \nabla T) = 0 \tag{3}$$

where $c_p$ is the specific heat, $t$ is the time, $\lambda$ is the thermal conductivity and $\nabla$ represents the gradient. The first term in Equation (3) disappear in steady state conditions. The thermal properties of the energy piles and the surrounding soil are temperature independent.

*2.2.3 Boundary and initial conditions*

Pinned boundary restrictions are applied ~~to~~ on the base of the model, hence, both vertical and horizontal displacements are prevented. Roller boundary restrictions are applied to the external sides of the soil mass that prevent horizontal displacements on the sides. Between the soil and the piles, a perfect contact is considered. No mechanical loads are prescribed at the top surfaces. The horizontal top boundary (i.e., soil surface and external boundaries of the cap/slab) is treated as adiabatic. Thermal loading was modelled by the application of an increment of temperature of $\Delta T = 10\ °C$ to all the nodes of the pile under steady state heat flow conditions. It is acknowledged that this is a simplification with respect to the actual temperature distribution in the pile cross-section and surrounding soil with time. However, this assumption is reasonable with respect to the temperature along the pile which has been found to be almost constant by Bourne-Webb et al. [28]. In the time dependent analyses, throughout these simulations, the temperature change is applied to all the nodes of the energy piles for a time of $t = 6$ months, representative of a seasonal cycle.

### *2.2.4 Material properties*

The soil properties have been successfully employed by Rotta Loria et al. [29] to model the behaviour of energy piles in dry Nevada sand with reference to physical observations. Table 1 summarises the material properties considered for the simulations. The analyses have been conducted considering a diameter of $D = 1$ m.

## 3. Single rigid pile-cap unit

This section presents the results of the analysis of a single rigid pile-cap unit, as a starting point for the analysis of general pile groups. The effects of contact between a single isolated pile subjected to a temperature change and a rigid cap are analysed in the following. The solutions refer to steady state finite element analyses.

The presence of a cap in contact with the ground results in a variation of rigidity of the system. Therefore, when a load is applied, variations of the displacement and stress fields, in comparison to the freestanding condition, are expected. The influence of a pile-cap on the displacement field is examined in this paper by comparing the displacement of the pile with the cap to the displacement of the corresponding freestanding pile. The ratio is expressed in terms of pile-cap displacement ratio, $R_c$.

$$R_C = \frac{displacement\ of\ pile\ with\ cap}{displacement\ of\ freestanding\ pile} \tag{4}$$

Figure 3 shows the evolution of the pile-cap displacement ratio $R_c$ against the pile-cap dimension ratio $D_c/D$. $R_c$ turned out to be dependent on pile slenderness and cap dimensions. The influence is more evident in the case of short piles or relatively wide cap. In terms of contribution to the total rigidity of the system Figure 4 shows how the stiffness of a single energy pile varies by the presence of a pile-cap in contact with the ground, depending upon the cap size and pile slenderness. The results are presented as ratio of rigidities based on the ratio of displacements under a unit force. For pile with a slenderness ratio of $L/D = 25$ with a pile-cap of $D_c/D = 5$ the system stiffness increase is 19%.

The presence of the cap at the head of the pile represents a further condition of restriction. This implies that due to the impeded deformations further stresses are developed along the length of the pile. Figure 5 shows, as an example, the maximum stress along the length of the pile normalized with respect to the maximum stress under freestanding conditions.

Figure 6 presents a comparison between two pile-cap unit in the case of thermal and mechanical loading. For small values of the size of the cap the trend is similar for both types of load while diverging for relatively large cap, showing a greater reduction in the mechanical case.

# 4. Analysis of energy pile groups with slab

## 4.1 Idealisation

The pile-cap unit may be seen as the simplest system representing an energy pile group with slab. The modelling approach is based on defining an equivalent value of $D_c$ such that the area occupied by the unit is the same as that occupied by a typical portion of the slab in the group. In this way, for regular and symmetrical geometries, it is possible to find a direct relationship between the dimensions of the cap and the centre to centre distance between two piles.

Figure 7, as an example, provides a representation of the modelling approach for regular and symmetrical pile groups in which the problem can be decomposed into several elementary units.

## 4.2 The modified interaction factor method

The interaction factor approach for the displacement analysis of energy pile groups in freestanding conditions has been formulated by Rotta Loria & Laloui [5]. The method is based on the principle of the superposition of effects and is to be considered as a simplified method, since it requires a degree of approximation to obtain solutions even in the case of ideal situations. The modified formulation presented in this study is an integration and extension of the approach for the conditions in which the slab is in contact with the ground.

The modified procedure for the displacement analysis of general energy pile groups with slab consists of 5 steps (cf., Figure 8). The first three summarise the original formulation and the last two evaluate the interaction of the slab through a simplified procedure.

1. An analysis of the displacement of an isolated pile subject to a temperature variation is done.
2. The interaction factor is defined for a pair of two piles at any given centre to centre distance. The design charts proposed by Rotta Loria & Laloui [5] can be used for this purpose.
3. The vertical head displacement of any pile *k* in the group in freestanding condition can be estimated by applying Equation (5)

$$w_k = w_i \sum_{i=1}^{i=n_{EP}} \Delta T_i \Omega_{ik} \tag{5}$$

4. The definition of the pile-cap displacement ratio can be achieved by referring to the design charts proposed in this paper.
5. The displacement determined in freestanding conditions can be corrected to consider the contacting slab by referring to Equation (6)

$$w_k = R_c w_i \sum_{i=1}^{i=n_{EP}} \Delta T_i \Omega_{ik} \tag{6}$$

The main hypothesis is to consider an area of influence of the slab, i.e. the definition of an equivalent area of interaction. It is therefore specified that the correction is independent of the position in the group. Differences in the correction factor, such it could be a different confinement in the centre compared to the edges, are not considered. Some inaccuracy may result from these approximations; however, an appropriate consideration would result in an excessive complexity of the method not commensurate with improvement in terms of accuracy. It should be kept in mind that the method is classified as a design method the goal of which is to provide preliminary information and orders of magnitude for the quantities studied.

### 4.3 Design charts

Interaction factors for varying design situations characterising a group of two energy piles have been presented by Rotta Loria & Laloui [5] and are shown as a function of 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, non-uniform soil moduli and the soil-pile thermal expansion coefficient ratio.

Following, the charts for the definition of the corrective factor ($R_c$) to be inserted at the step 4 of the procedure, as explained in section 4.2, are presented for the same conditions. They consider the presence of the slab in the determination of the displacements. The solutions have been obtained through steady state finite element analyses. The cap is rigid based on the definition of the relative flexural stiffness defined by Brown [30].

*4.3.1 Effect of pile spacing, pile slenderness ratio and pile-soil stiffness ratio*

The curves in Figs. 9 to 11 show~~s~~ the evolution of the pile-cap displacement ratio as a function of the dimensionless pile spacing *s/D* for several pile-soil stiffness ratios $\Lambda = E_{EP}/G_{soil}$ and slenderness ratio *L/D*.

The pile-cap displacement ratio decreases with the increase of the centre to centre distance. As the spacing increases the effectiveness of reducing the displacement is diminished with increasing pile compressibility. Compressible piles have little reduction effect on displacement, the effect is clearer in the case of short piles. The trends show the complex interplay of the relative stiffness of the elements of the system and how the relative stiffness of the elements influence the behaviour not in a univocal way. The effect of interaction results more marked for shorter pile, while for higher length the value is around 20% reduction.

*4.3.2 Effect of cap thickness*

The results showed above refers to a given value of the cap thickness. The influence of this parameter has been investigated and a correction factor $\xi_t$ to take it into consideration is proposed in Figure 12. The pile-cap displacement ratio for any value of *t* is given by

$$R_c = \xi_t R_{c,t=0.6\,m} \tag{7}$$

The reduction increases with the increase of the thickness of the cap. This effect becomes more marked as the dimensionless spacing *s/D* increases, corresponding to a larger cap.

*4.3.3 Effect of Poisson's ratio*

Correction factors $\xi_v$ to the pile-cap displacement ratio for different values of the Poisson's ratio, $v_{soil}$ are shown in Figure 13. The adjusted value reads

$$R_c = \xi_{v_{soil}} R_{c,\, v_{soil}=0.3} \tag{8}$$

The effect becomes more marked as the spacing increases, however in the whole range of the centre-to-centre distance the correction is less than 8%.

### *4.3.4 Effect of finite layer depth*

Solutions for the pile-cap displacement ratio for a unit where there is a finite layer are illustrated in Figure 14.

The actual pile-cap displacement ratio is then

$$R_c = \xi_h R_{c,h/L\to\infty} \tag{9}$$

Note that the presence of an infinitely rigid layer at the base results in a decrease of the restrictive effect of the cap in the head compared to the floating case. This is because since in the case of finite layer the restriction condition is lower in the head, there is a shift of the null point. Therefore, displacement in the head is greater compared to the floating case. Thus, the pile-cap displacement ratio is higher than that characterising floating piles.

### *4.3.5 Effect of non-uniform soil modulus and thermal expansion coefficient*

No correction values are presented for the interaction factor in the case of non-uniform soil modulus and soil-pile thermal expansion coefficient ratio. With regards to the first, analysis of its effect on the interaction showed a minor influence of 2% and therefore the use of the method in case of energy piles in homogeneous medium is considered conservative following the analyses carried out in freestanding conditions. With reference to the second, the assumption is to be considered satisfactory except in the case of values of the thermal expansion coefficient of soil greater than that of the pile [5]. In reference to the pile-cap displacement ratio, more detailed observations are discussed in the paragraph 5.2, with reference to the linear thermal expansion coefficient of the cap as a result of thermal interactions.

# 5. Discussion on the pile-cap displacement ratio concept

Analysis and design procedures can be divided into different categories depending on the level of sophistication and rigour [31]. The interaction factor method is proposed as a preliminary design method. It is characterised by a simplified procedure, but it has an appropriate theoretical basis. This type of procedures usually involves the use of simple computational methods or design charts with the aim of predicting the magnitude of vertical head displacements within the group with reasonable accuracy for most practical values of spacing between the energy piles.

To date, the interaction with the slab was not studied with this approach and a procedure to consider the effects were not presented. In this context, a simplified procedure has been described that can be coupled to current available classical interaction factor approach to estimate the displacement behaviour of pile groups with a contacting slab subjected to thermal loads. However, any simple approach must be first calibrated against a more rigorous numerical analysis.

The method is based on the correction of the displacement obtained in freestanding conditions by means of the pile-cap displacement ratio. The corrective factor was determined for several conditions, considered to be of practical engineering interest. It was defined in reference to the elementary unit, based on the hypothesis of an equivalent area representative of the portion of slab that influences the behaviour of the pile. It is therefore necessary to verify the accuracy of this factor in describing the interaction of the slab and the pile with reference to the values obtained by the finite element analysis, where the entire foundation is modelled and a more realistic behaviour of the soil is considered, i.e. thermally induced volumetric variations are considered.

Figs. 15 to 18 show the evolution of the pile-cap displacement ratio as a function of the normalised centre-to-centre distance. The analyses refer to the case of piles with slenderness ratio of $L/D = 25$, pile-soil stiffness ratio of $\Lambda = E_{EP}/G_{soil} = 1000$ and Poisson's ratio of soil of $v_{soil} = 0.3$. The results are presented in reference to four different thickness values of slab 0.6, 1, 2, 4 m. The values of $R_c$ derived from steady state simplified analyses, thus referring to the elementary unit, are compared with the values of $R_c$ obtained from time dependent thermo-mechanical finite element analyses of square groups of 4, 9, 16, 25 energy piles. A more accurate description of the problem is observed for small centre to centre distances between the piles, when the number of piles is limited and the thickness of the slab increases. When considering the two limiting cases in terms of slab thickness, the following considerations are valid: (i) thin slab: for small group of piles (i.e., 4 piles) the differences between rigorous and simplified analyses are between 2-7% and for groups with a large number of piles (i.e., 25) the differences reach 21%. It is also noted that in this last case there are configurations where there is no reduction of the displacement due to the presence of the slab compared to the freestanding case. (ii) thick slab: it is noted that in this case for groups of both small and large number of piles differences are minor and of the order at the maximum of 10%. The motivations of the inaccuracies found for large number of piles, large spacing and small thicknesses of the cap can be related to two aspects that are discussed in sections 5.1 and 5.2: the relative stiffness of the elements and the thermal interaction between the elements that turns out to be different from the mechanical load.

### 5.1 Effect of relative flexural stiffness

This section presents a more thorough discussion on the effects of slab stiffness and relative stiffness of the elements.

The relative flexural stiffness can be assessed with the formulation proposed by Brown [30]. This formulation refers to the relative stiffness between the raft and the ground, where the presence of piles and therefore its contribution to stiffness is not considered. Typical range is 0.001-10 [11]. Values above 0.1 refers to rigid behaviour while lower values refer to flexible behaviour [30]. Comparisons on the stiffness of the group and slab were presented by Randolph [32]. In the case of small pile groups, the pile group stiffness is significantly greater than the stiffness of a raft foundation. Therefore, even if the pile-cap rests directly on competent ground, it will contribute little to the response of the overall foundation. In the case of large rafts, the stiffness of a pile group occupying the full area of the raft will be quite similar to that of the raft alone. These statements are also reflected in the results of the analyses proposed in this article with reference to a thermal load (cf., Figs. 15 to 18). The flexibility of the pile-cap is governed by several factors including the thickness and the width. During all analyses, the behaviour of the elementary unit cap is rigid according to the definition of Brown [30]. For this reason, the estimates of the pile-cap displacement ratio of the elementary unit is to be considered as lower limit. In fact, considering groups of piles with the same thickness, the behaviour of the slab is more flexible as the numbers of piles and spacing increase, i.e. the overall increase of the size of the slab.

The representativeness of $R_c$ is therefore dependent on the relative flexural stiffness of the slab under examination (cf., Figure 19). If it has a rigid behaviour, then the fact of considering the interaction based on the areas of influence of the elementary unit is a good approximation. This does not appear to be accurate when the numbers of piles and spacing increase, for a slab of the same thickness. For the second conditions, the behaviour is flexible and therefore considering the slab as composed of many rigid elementary units is no longer a good representation. In these cases, however, it progressively approaches to the case of fully flexible slab configurations and the method can then be applied in its original formulation (i.e., freestanding piles).

### 5.2 Effect of thermal interactions

For conventional piles subjected to mechanical loads the presence of cap always implies a reduction in the displacement compared to the freestanding case. The present-day routine design practice for pile foundations neglects the contribution of the cap as a conservative assumption [21]. In the case of a thermal load this assumption is not always true. 3D finite element analyses show that the activation of the energy pile induces a variation in temperature around it and the heat is transferred mainly by conduction (in the absence of fluids in motion). Therefore, the surrounding soil and the cap undergo a variation in temperature and a consequent variation in volume. There are configurations (cf., Figs. 15, 16) where these thermal interactions are more pronounced. There may be cases in which the presence of the cap does not reduce the displacement in the head of the pile but on the contrary contributes to its increase ($R_c > 1$) because of its thermal expansion, albeit limited for practical case. Figure 20, shows the effect of the cap thermal expansion coefficient on the pile-cap displacement ratio. To highlight this effect in Figure 20, results for linear thermal expansion coefficient ratios of 0, 1, 2 are illustrated. While the values of 0 and 2 may be considered of limited practical importance, its purpose is to support the hypothesis of thermal interaction and to explain values of $R_c>1$.

## 6. Conclusions

This study carried out an analysis of the interaction between an energy pile and a rigidly attached rigid pile-cap resting on the soil surface. In addition, an improvement and extension have been made to the original formulation of the interaction factor method to consider the pile-slab-soil interaction. The method of analysis presented in this study falls within the category of procedures that have a proper theoretical basis, albeit simplified [31]. The usefulness of the development of this category of methods aims to enable complex practical problems to be examined in a systematic, albeit approximate, manner for the routine design. The growing demand for the use of renewable technologies, in order to meet international requirements, needs attention to the development of effective aid tools in the planning and design phases. However, simplifications and limitations of the presented theory should be acknowledged. As in the original formulation, the method suffers from some shortcomings and aspects such as potential construction imperfections, the residual stresses at the pile shaft, the order of the driving of the piles, the layering of the soil, nonlinear behaviour of the materials and cyclic aspects related to the operation of the geothermal system are not considered. This involves the exercise of judgement for assigning representative inputs in the method (e.g., the temperature variations).

From the study on the interaction for the single energy pile, the following conclusions can be drawn:

- The influence on the displacement due to the presence of the pile-cap is generally less than 20%. Larger influence is highlighted for short piles and relatively wide caps. Similar effect is shown by the presence of the contacting cap on the increase of the system stiffness depending upon the pile lengths and the cap width.
- Further stress is developed along the length of the pile due to the presence of the cap which represents a further condition of restriction. Maximum stress increases with decreasing length of the pile and increasing width of the cap.

For the analysis of general energy pile groups with slab some of the main conclusions that can be drawn from this work are as follows:

- An effective approach to integrate the pile-slab interaction in interaction factor method has been presented. The modelling approach is based on defining an equivalent area of influence and the pile-cap unit may be seen as the simplest system representing an energy pile group.
- This approach can be coupled with the current available formulation (e.g., [5]). The modified procedure for the displacement analysis of general pile groups is to correct the displacement determined in freestanding conditions through the pile-cap displacement ratio to consider the interaction with the contacting slab.
- The definition of $R_c$ can be accomplished employing design charts proposed in this work which cover a broad range of conditions of practical interest. The impact of 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 and the slab thickness has been investigated. The factor decreases with increasing of the spacing, the slab thickness and Poisson's ratio and with decreasing the pile slenderness ratio.
- Comparisons with results of 3D finite element analysis allowed to investigate the conditions of application of the simplified procedure. The comparison allows concluding that attention has to be paid mainly on two aspects: (i) the relative flexural stiffness and (ii) thermal interactions.

As a general conclusion, this method can be considered useful from an applicative point of view because it allows an estimation of the expected displacement that can be used as comparison and control tool for the results obtained through more sophisticated procedures in the advanced stages of the design process. Although the idealizations may seem relatively simplified in comparison to notoriously complex nature of the pile-soil-structure interactions, the proposed method is useful for several reasons considering the limited scientific development that address energy pile groups. (i) It facilitates understanding of the interactions between the piles, between the piles and the structure and the surrounding soil. (ii) It is a time- and cost-effective tool in the preliminary phases of the design to identify the parameters that affect the thermo-mechanical behaviour of the energy foundation. It therefore turns out to be a useful guidance tool for the engineer in the early stages of a project. (iii) It provides a reference for the analysis of more complex situations in which significant loading levels (i.e., irreversible conditions) cannot be neglected. In fact, these cases, at the engineering level, are still challenging for the difficulty of calibrating the parameters and the considerable computational effort required both in terms of time and cost. However, experimental evidence and a return of experience are necessary and fundamental for further validation of the method. To date, no absolute benchmarks for comparison are available.

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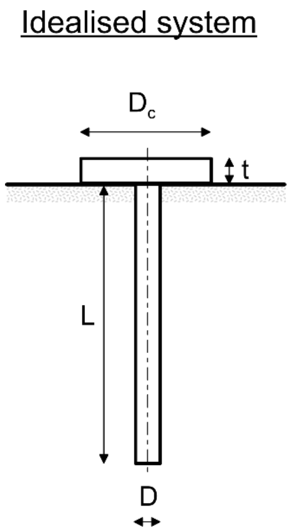


Figure 1. The elementary unit.

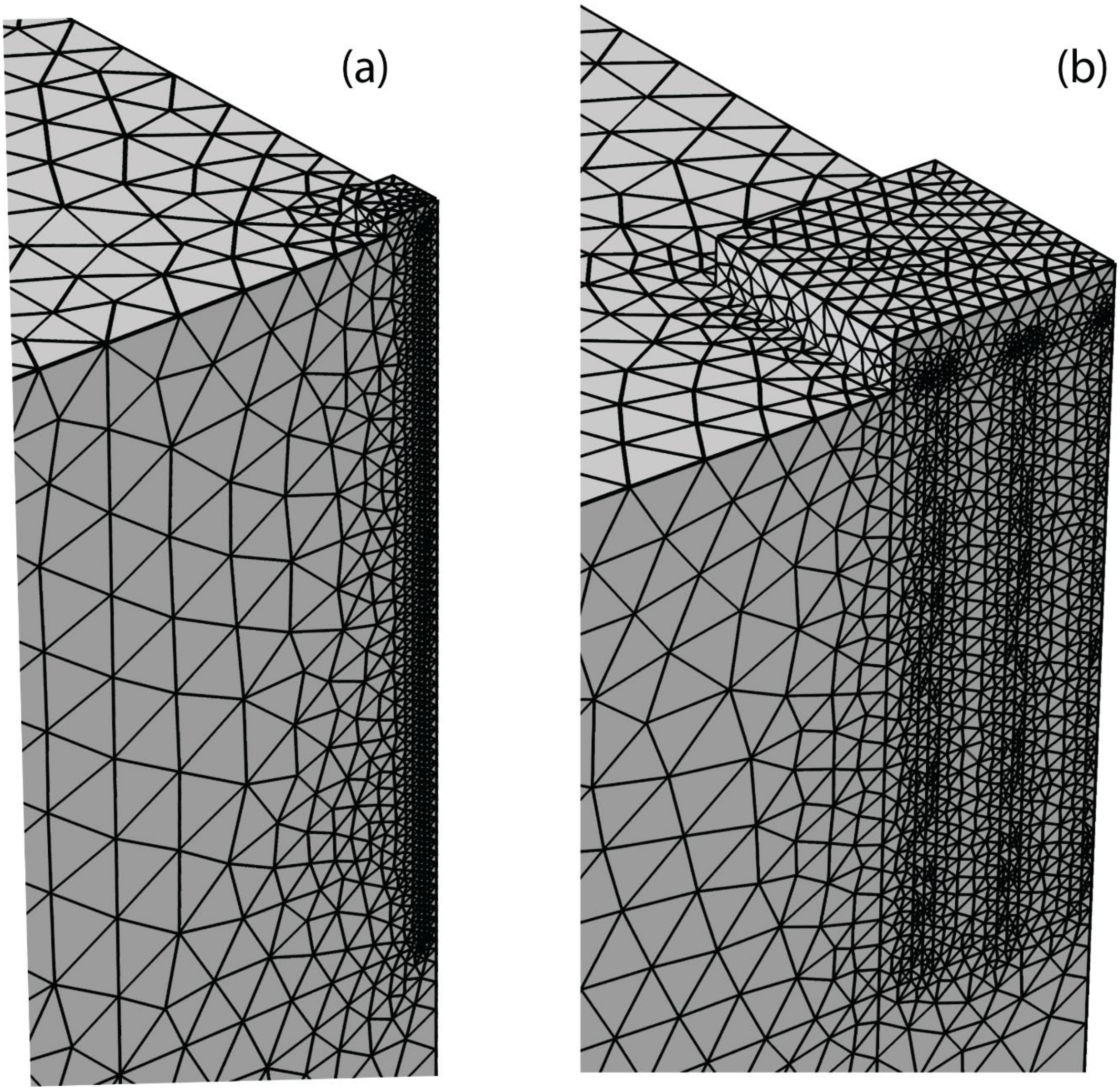


Figure 2. Example of the mesh for (a) the elementary unit and (b) the general energy pile group.

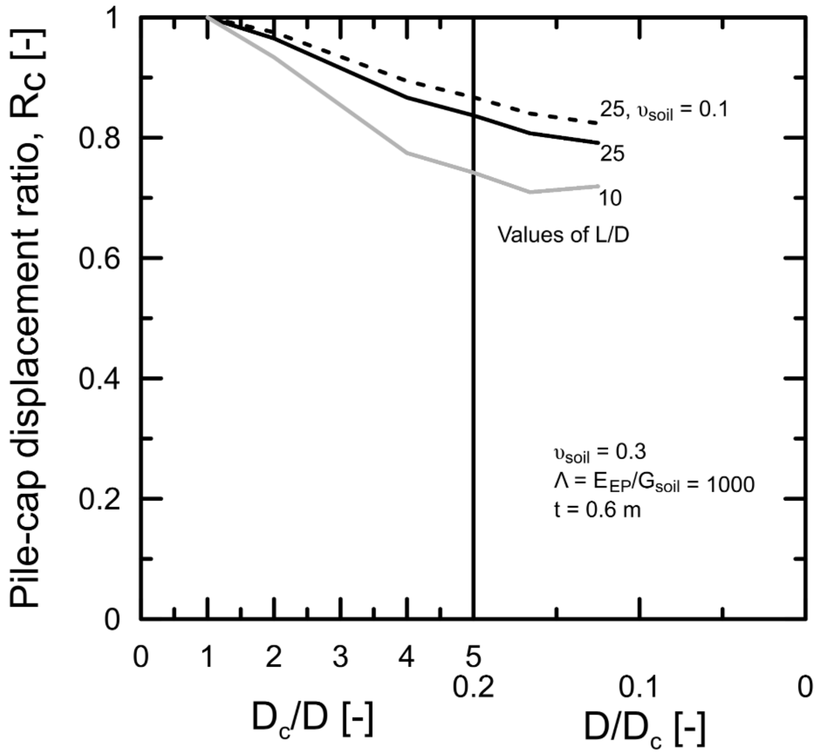


Figure 3. Influence of a pile-cap on displacements at the head of the pile in a deep soil layer.

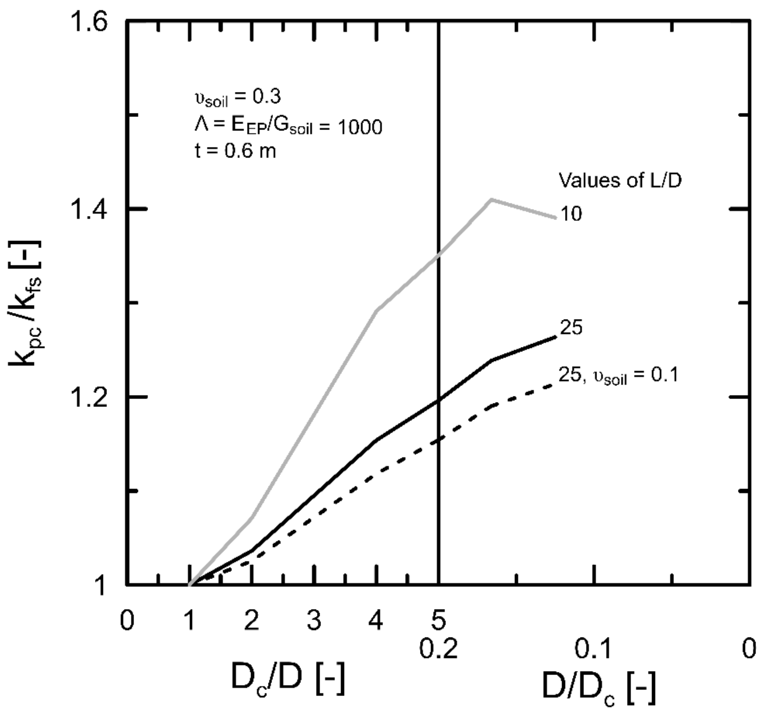


Figure 4. Effect of pile-cap on single pile stiffness.

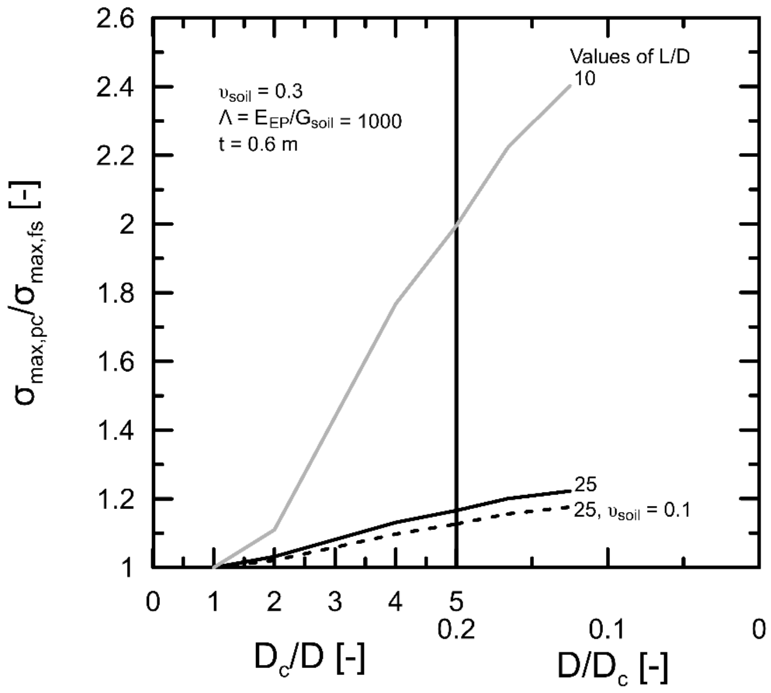


Figure 5. Influence of a pile-cap on maximum stress in a deep soil layer.

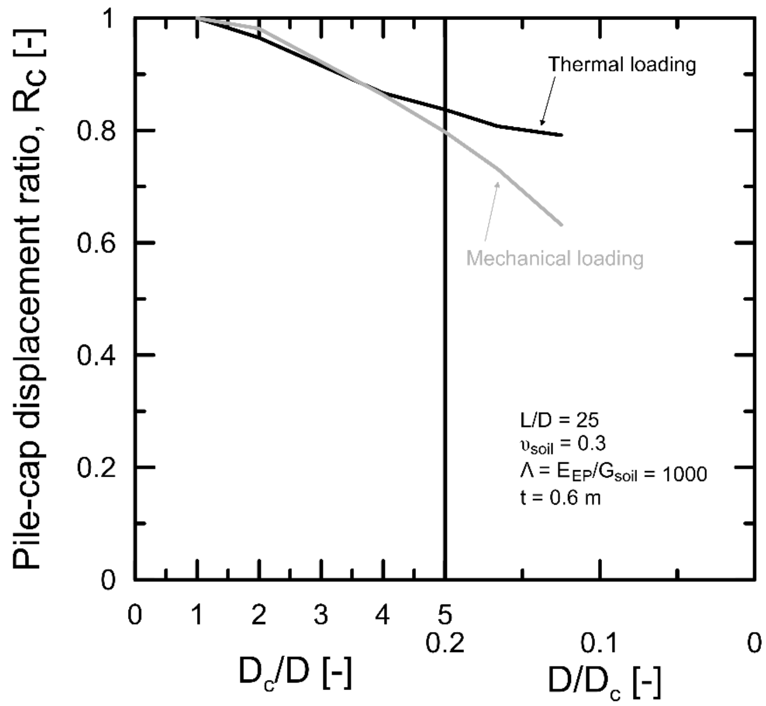


Figure 6. Comparison on the influence of pile-cap on displacements in the case of thermal and mechanical loading.

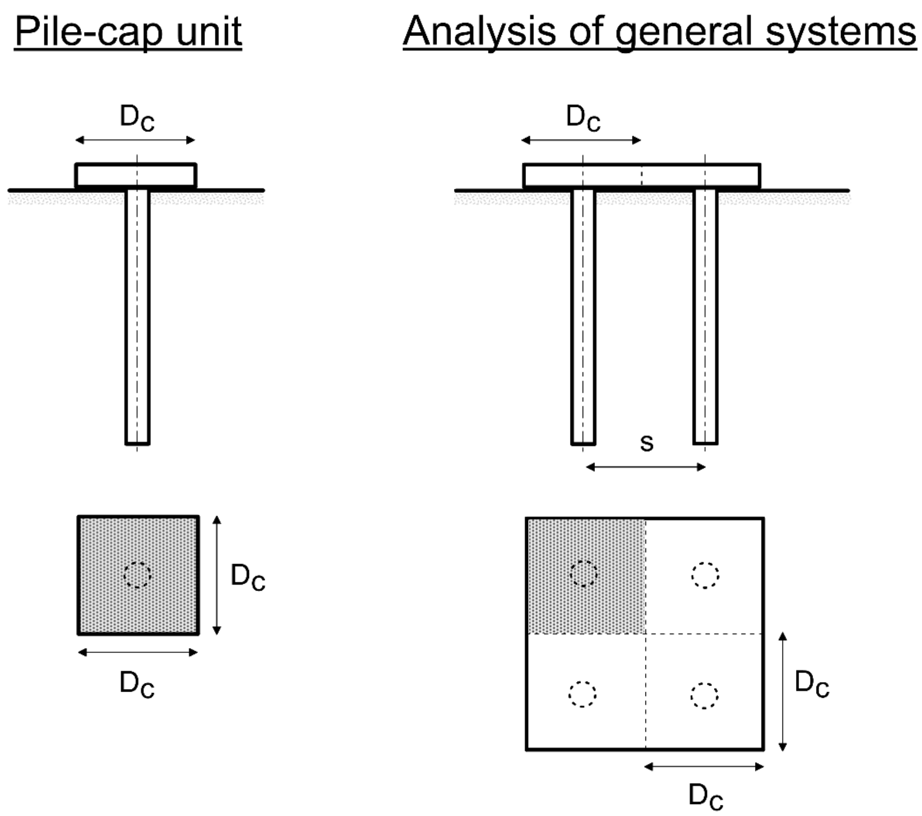


Figure 7. The modelling approach for the analysis of energy pile groups with contacting slab.

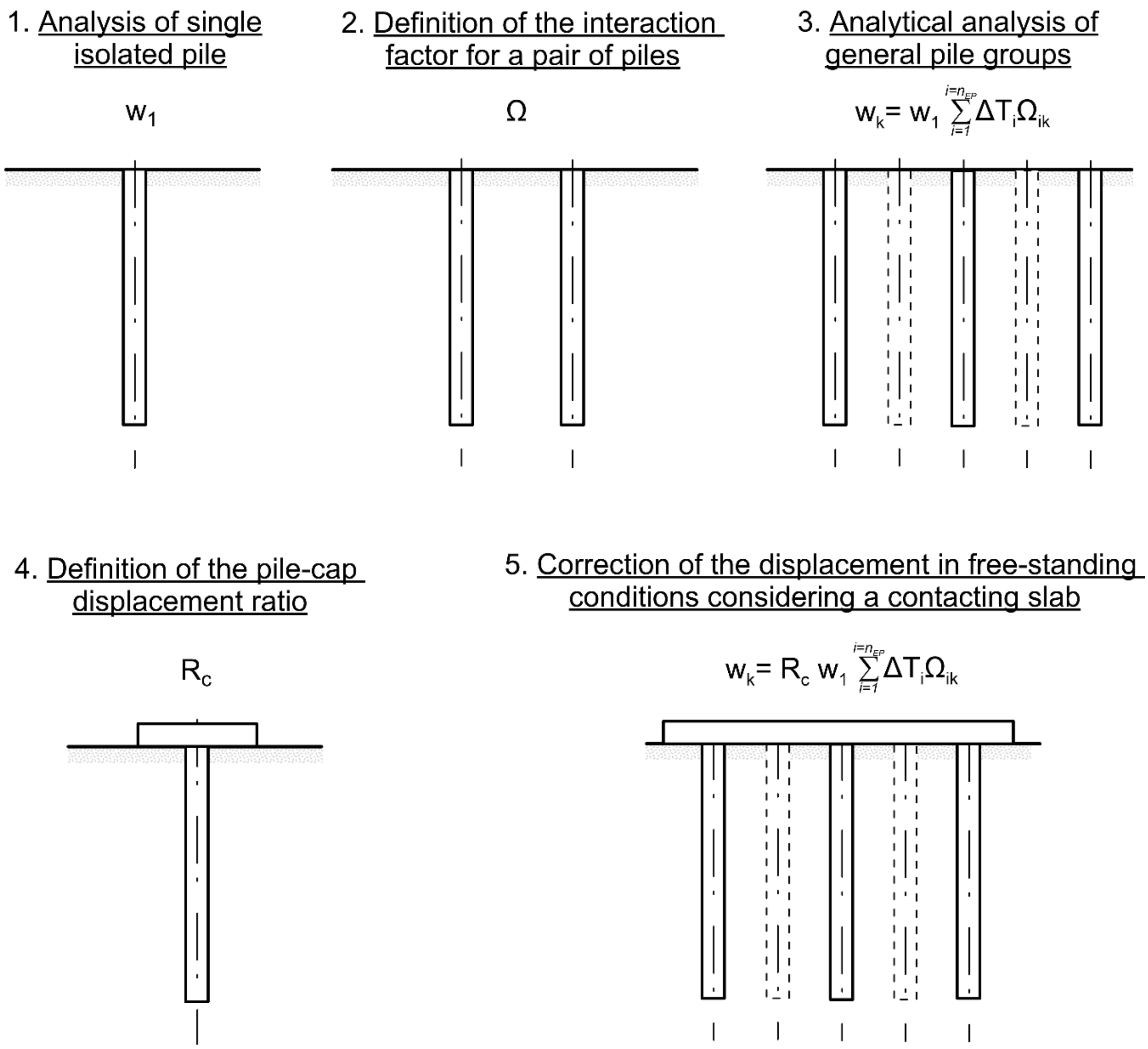


Figure 8. Key steps of the method for the analysis of energy pile groups with contacting slab.

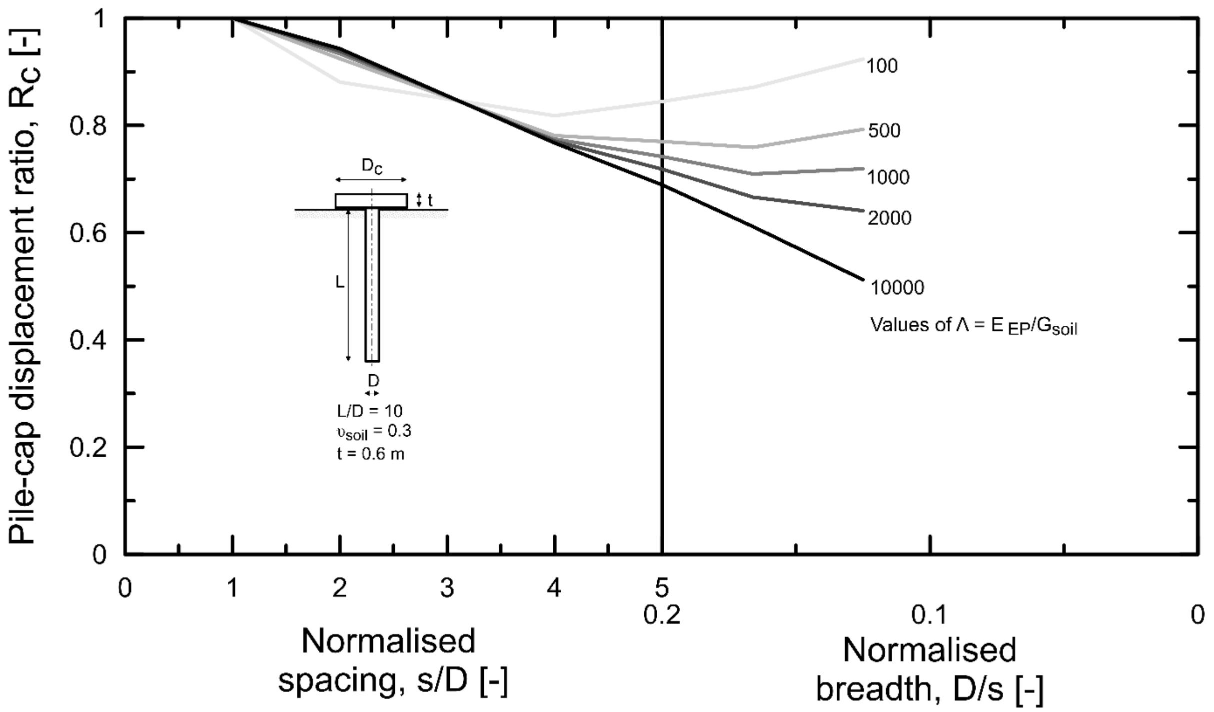


Figure 9. Pile-cap displacement ratio for L/D = 10.

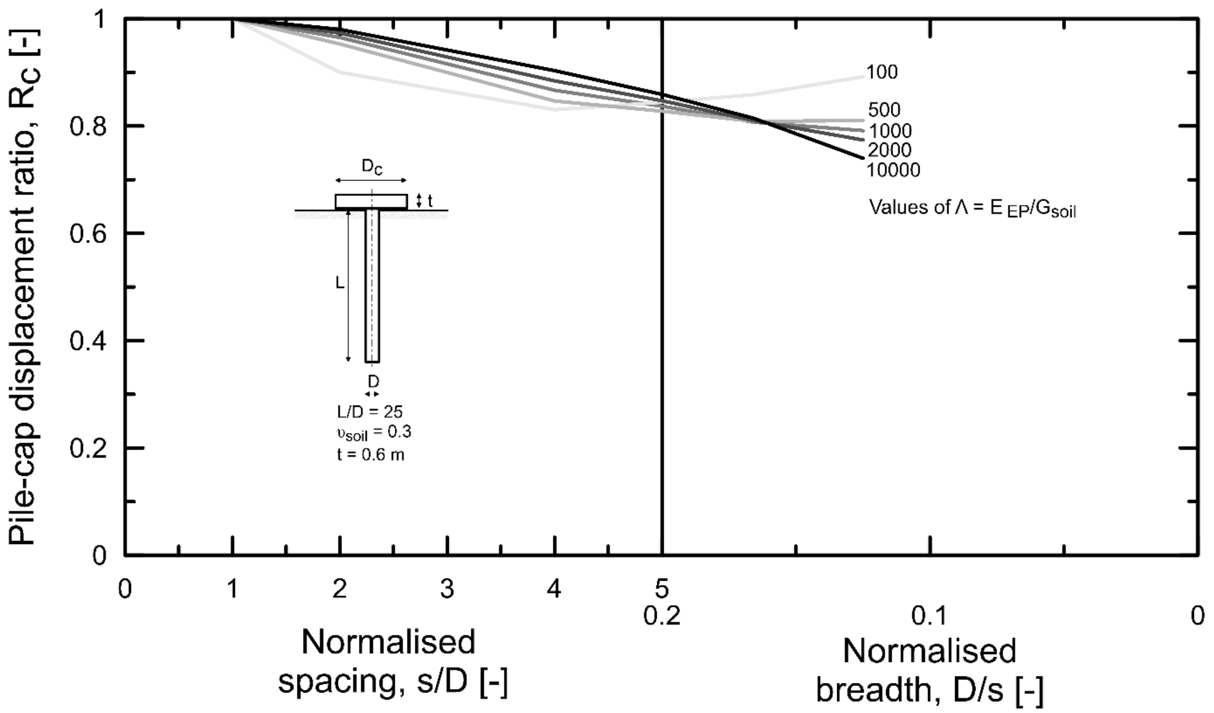


Figure 10. Pile-cap displacement ratio for L/D = 25.

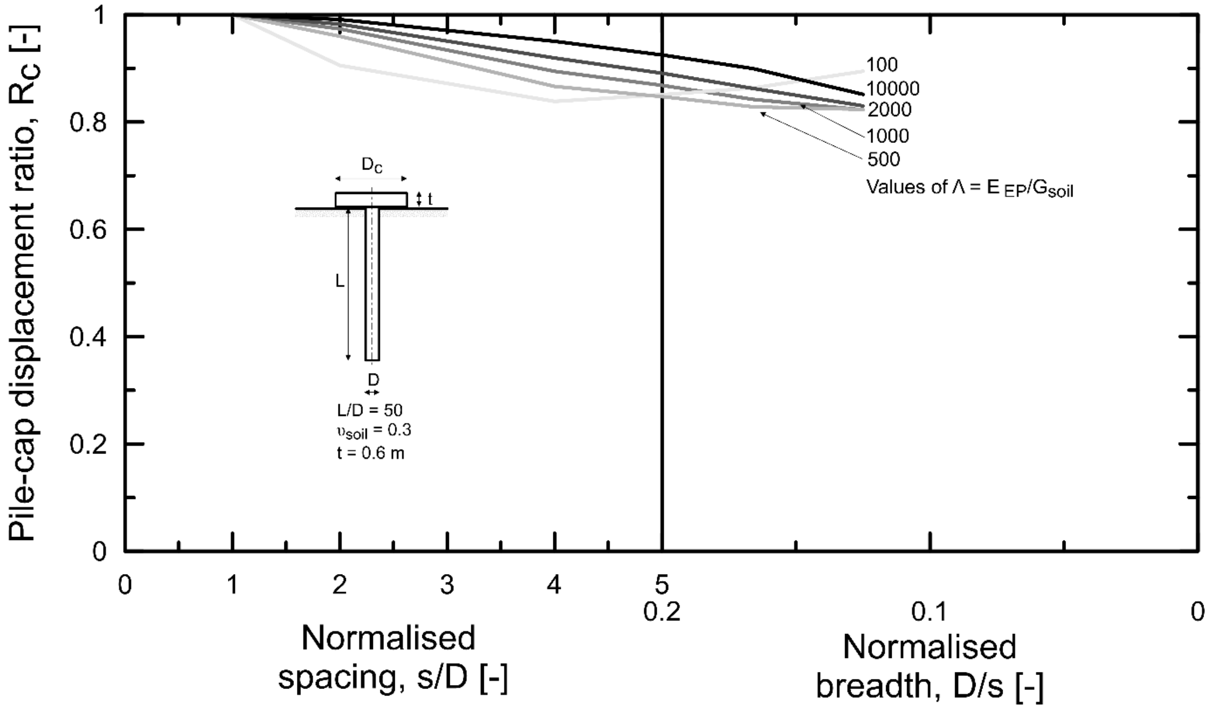


Figure 11. Pile-cap displacement ratio for L/D = 50.

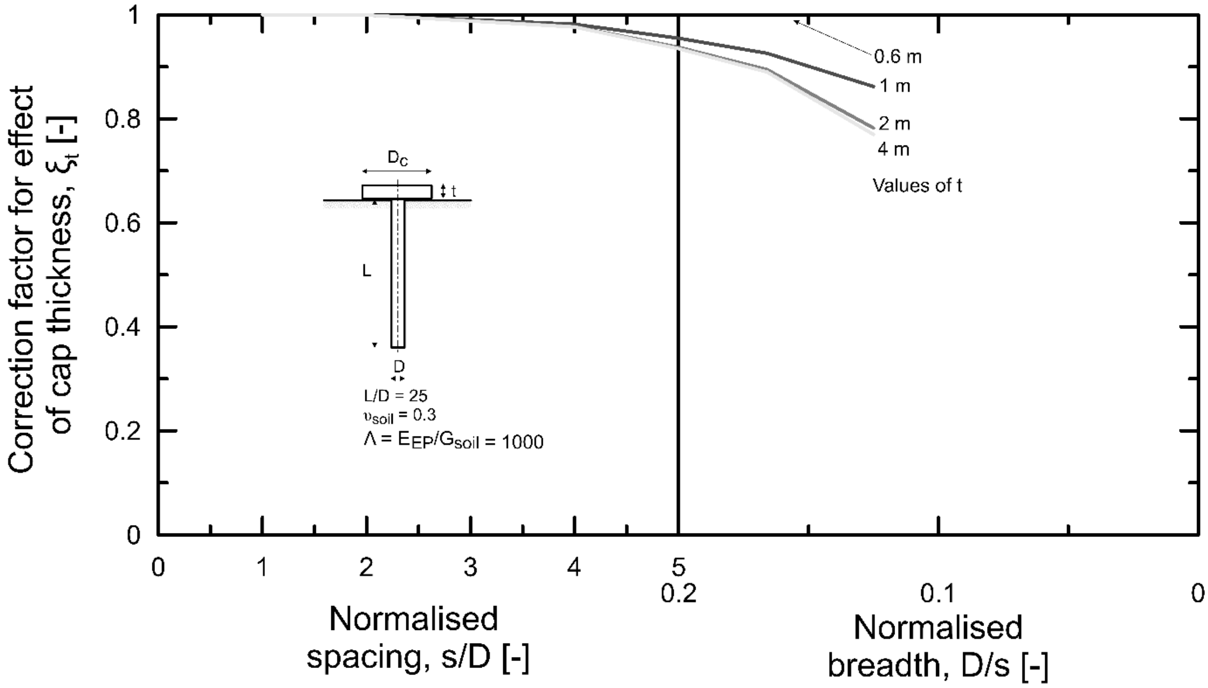


Figure 12. Correction factor $\xi_t$ for effect of cap thickness.

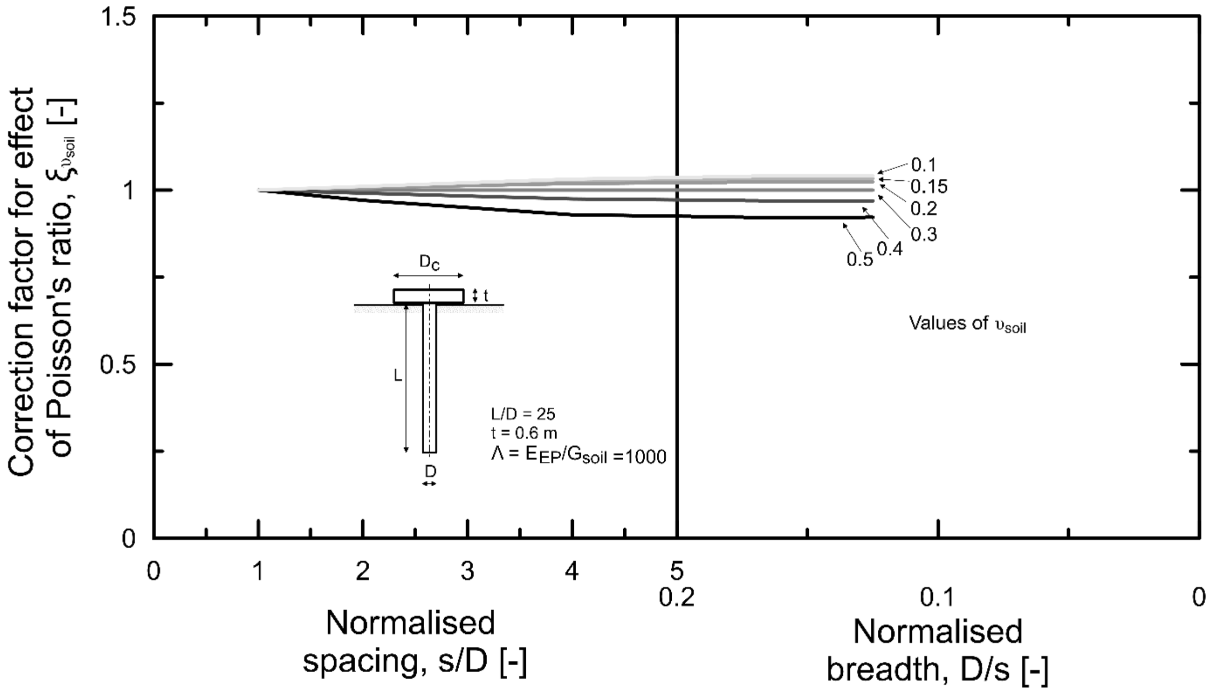


Figure 13. Correction factor $\xi_{vsoil}$ for effect of Poisson's ratio.

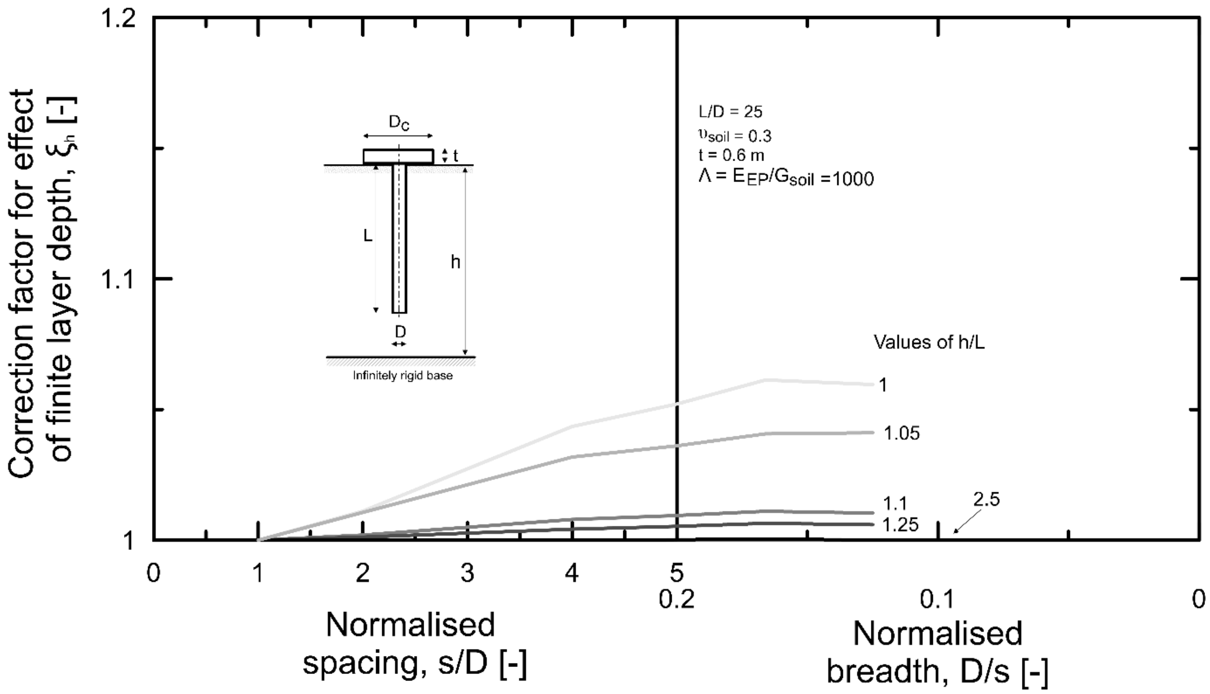


Figure 14. Correction factor $\xi_h$ for effect of finite layer depth.

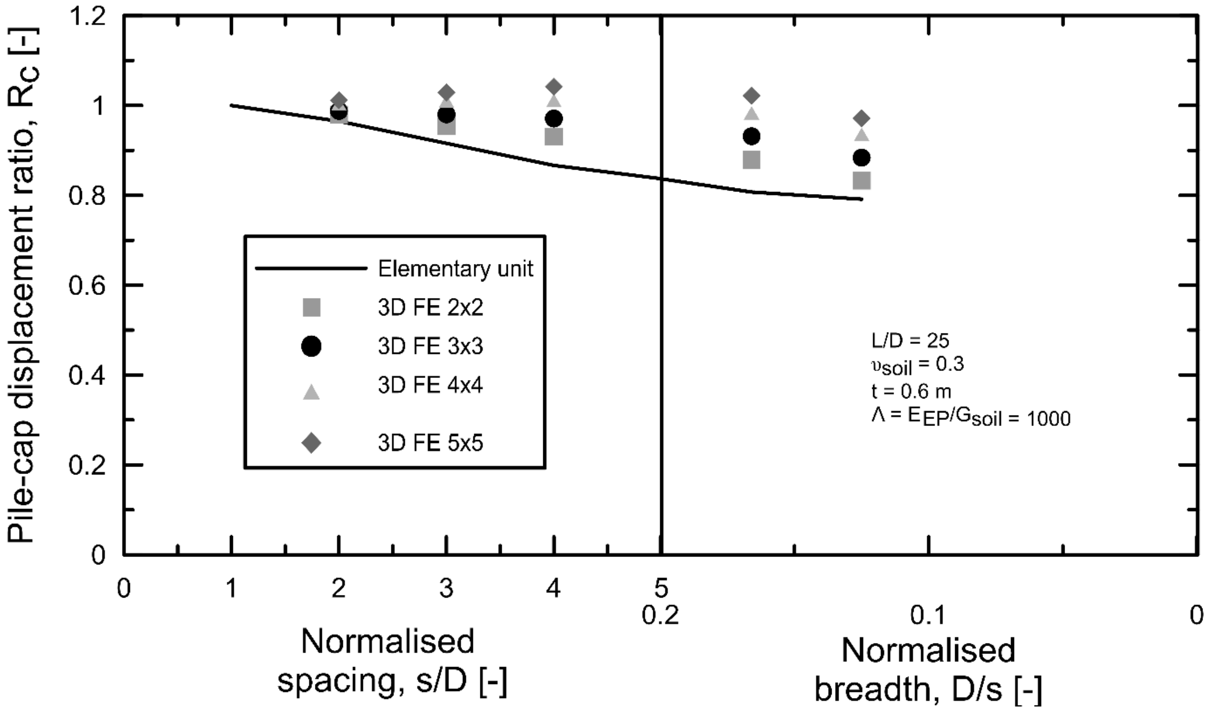


Figure 15. Comparison between the pile-cap displacement ratio obtained through steady state and time-dependent analyses for a thickness cap of 0.6 m.

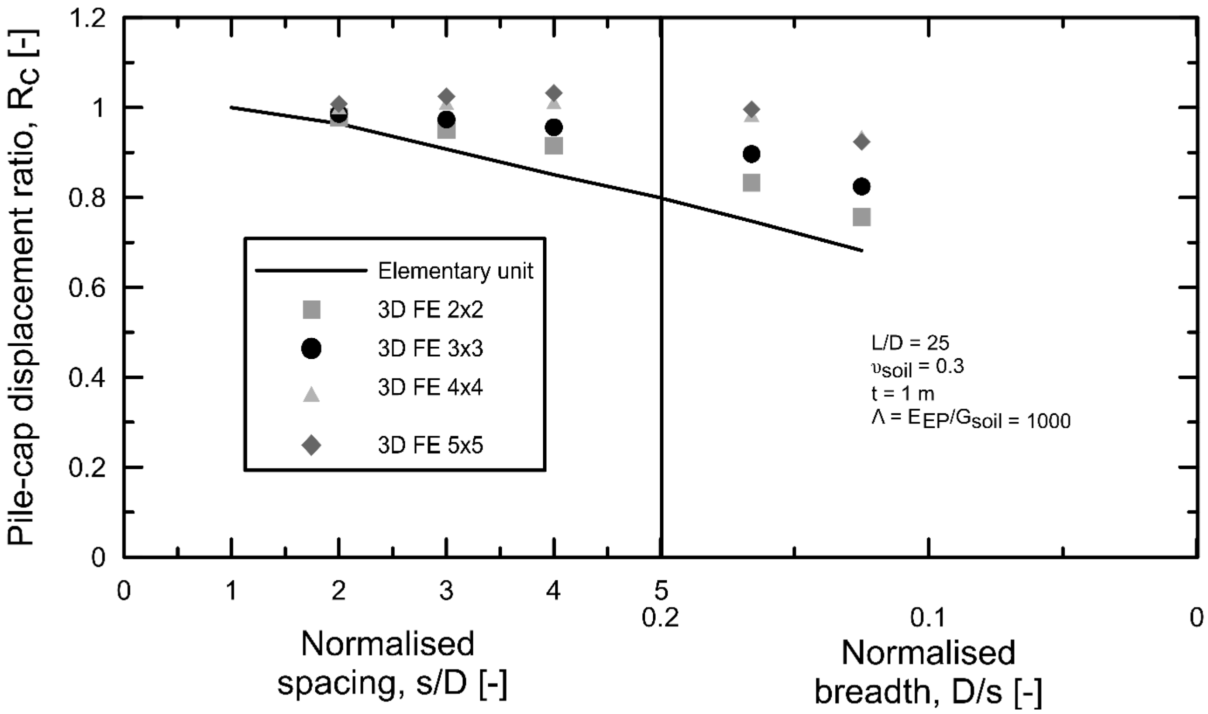


Figure 16. Comparison between the pile-cap displacement ratio obtained through steady state and time-dependent analyses for a thickness cap of 1 m.

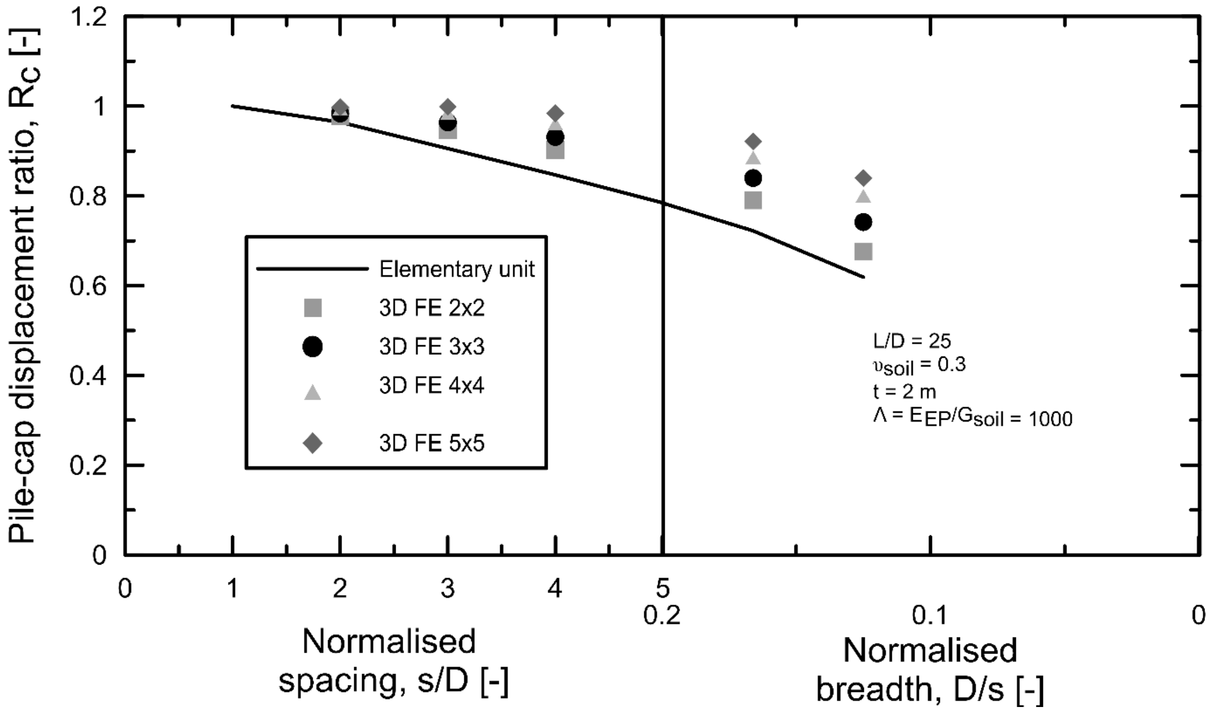


Figure 17. Comparison between the pile-cap displacement ratio obtained through steady state and time-dependent analyses for a thickness cap of 2 m.

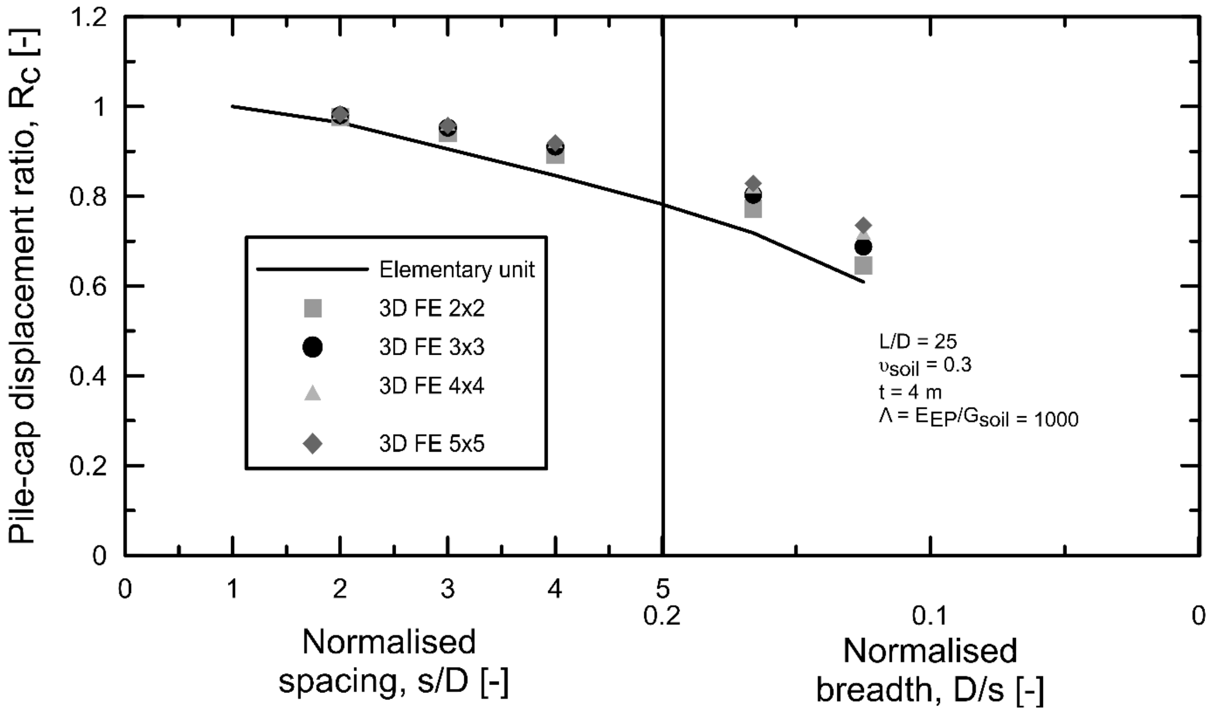


Figure 18. Comparison between the pile-cap displacement ratio obtained through steady state and time-dependent analyses for a thickness cap of 4 m.

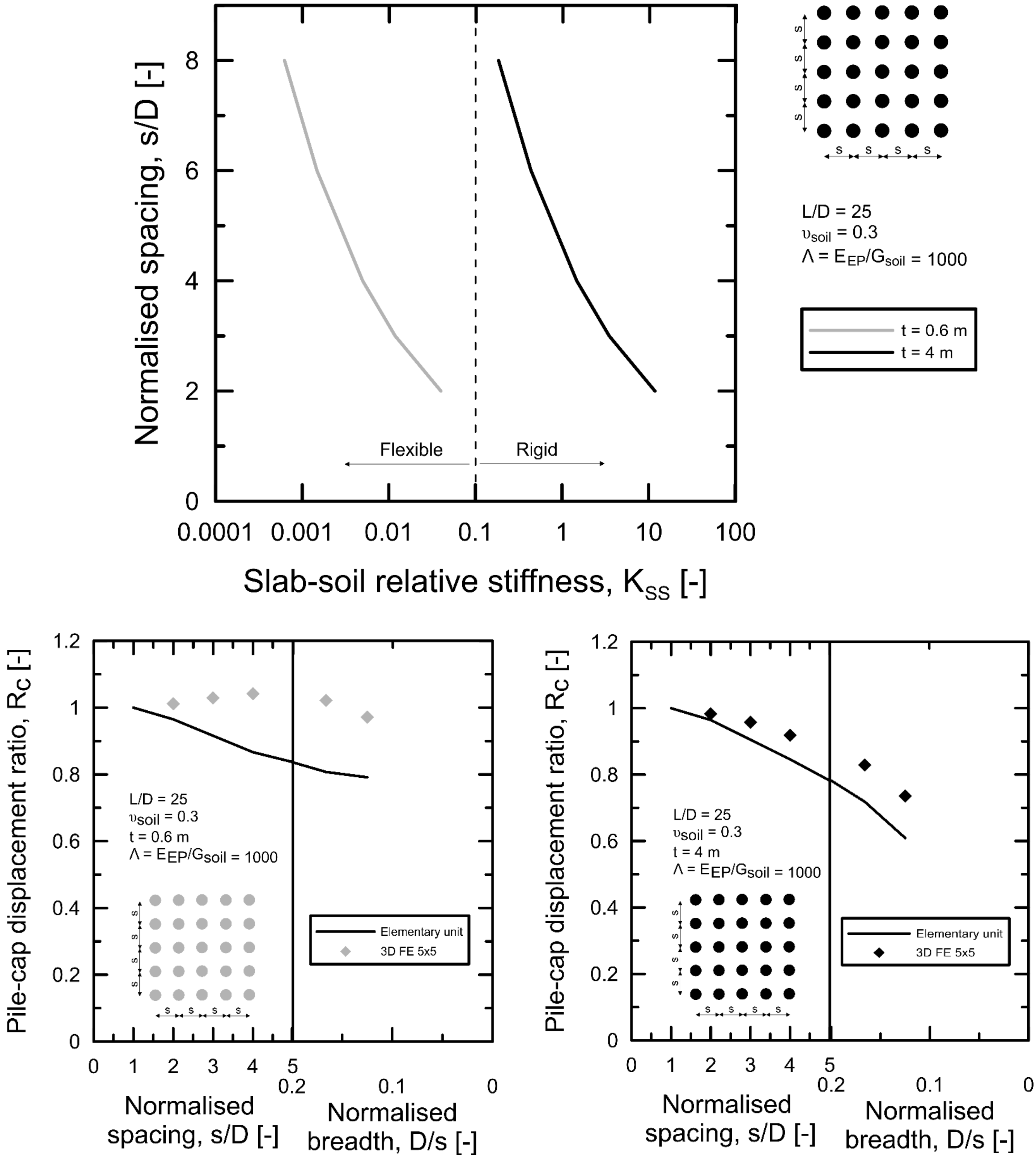


Figure 19. Effect of the relative flexural stiffness.

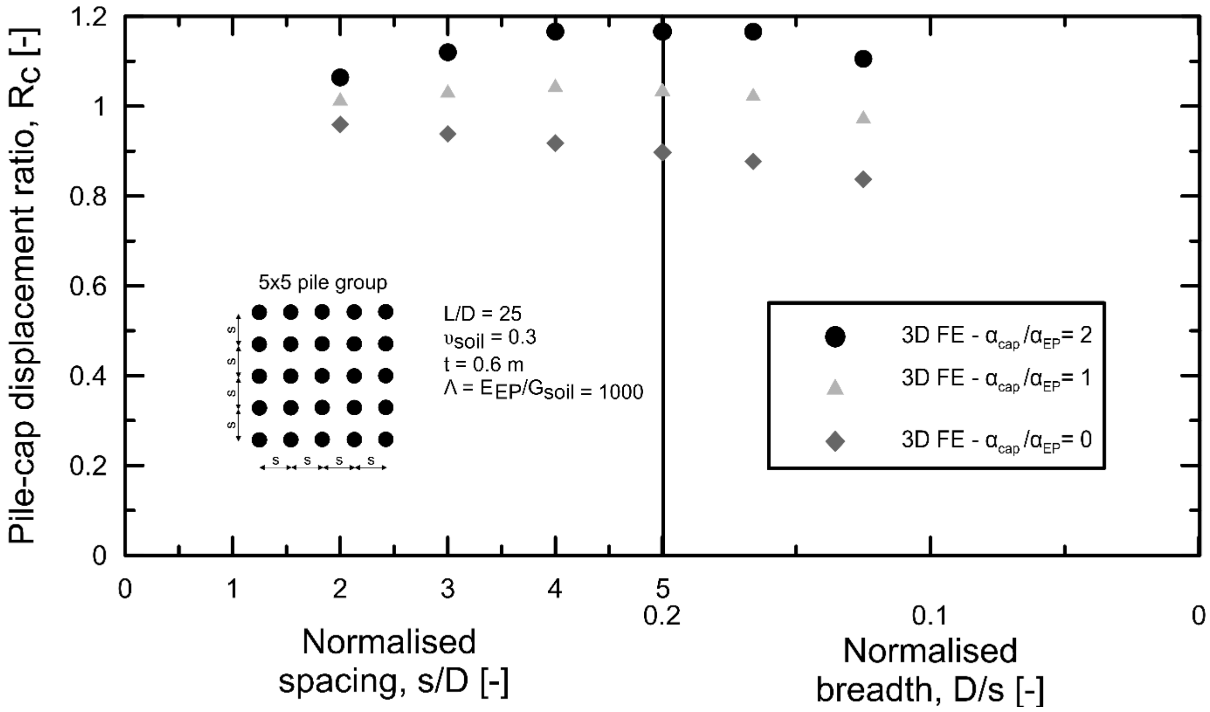


Figure 20. Effect of the linear thermal expansion coefficient.

Table 1. Material properties used for the 3D thermo-mechanical finite-element analyses of the comparative study. (Rotta Loria & Laloui, 2016)

| Reinforced concrete pile parameters | Value (thermo-elastic description) | Soil parameters | Value (thermo-elastic description) |
|---|---|---|---|
| $E_{EP}$ [MPa] | 30000 | $G_{soil}$ [MPa] | 30 |
| $\upsilon_{EP}$ [-] | 0.25 | $\upsilon_{soil}$ [-] | 0.3 |
| $\rho_{EP}$ [kg/m3] | 2450 | $\rho_{soil}$ [kg/m3] | 1537 |
| $\alpha_{EP}$ [1/°C] | $1 \cdot 10^{-5}$ | $\alpha_{soil}$ [1/°C] | $1 \cdot 10^{-5}$ |
| $\lambda_{Ep}$ [W/ (m °C)] | 1.47 | $\lambda_{soil}$ [W/ (m °C)] | 0.25 |
| $c_{p, EP}$ [W/ (m °C)] | 854 | $c_{p, soil}$ [W/ (m °C)] | 961 |