Interaction Factor Between Piles: Limits on Using the Conventional Elastic Approach in Pile Group Analysis

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Abstract. Analyses of load settlement behavior for pile groups must consider the interaction of nearby piles. In small pile groups, the key factor for evaluating load-settlement behavior is single-pile stiffness, but when analyzing large pile groups and piled rafts, the importance of induced settlements due to neighboring piles increases. This paper reviews the most commonly used approaches that consider the interaction between piles and notes some aspects that can result in important differences in foundation settlement predictions. Topics including soil heterogeneity, the presence of other piles, and large pile groups are presented using both the conventional approach and finite element method analysis, showing that for large piled foundations, such aspects can result in considerable differences.

Keywords: pile group, piled raft, pile-to-pile interaction factor, settlement analysis.

1. Introduction

Currently, most piled foundation designs are based only on the load capacity of the pile group, and the main challenge in a project is the definition of how many piles would be necessary to support the applied load. Since the emblematic paper of Burland *et al.* (1977), who primarily noted the use of piles as settlement reducers, many authors have reinforced this idea (Randolph, 1994; Mandolini & Viggiani, 1997; Poulos 2001; and others). Randolph (2003) stated that the trend towards design based on allowable deformations may be appropriate for both large and small pile groups, such as those used to support bridge piers.

The load settlement behavior of a pile group results from the individual characteristics and the piles arrangement. Each pile in a group, regardless of its similarity to the neighboring piles, has its individual stiffness (relation between load and settlement of the pile) influenced by the presence of other piles. Mandolini (2003) noted that in large pile groups, in which different piles would be in different stages of mobilized loads, the nonlinear pile behavior should be considered. Moreover, at some distance from a loaded pile, the elastic displacements would prevail.

The additional settlement suffered by one pile near another pile has been studied by many authors. Poulos (1968) and Cooke *et al.* (1980), in a very similar way, labeled the relation between the induced settlement to a nearby pile and the self-settlement of a loaded pile the “interaction factor”.

The focus of the present paper is to evaluate how the interaction factor α can be calculated, the similarities of the available theories, and how they affect the final prediction of piled foundations.

2. Existing Theories

Poulos (1968) considered soil to be an elastic continuum and developed a solution based on a boundary element method to evaluate the two-pile interaction factor, as defined in Eq. 1. Some of the charts presented in that paper allowed a “manual prediction”, in which the final interaction factor α would be estimated by Eq. 2. This method was well detailed by Poulos & Davis (1980).

$$\alpha_{ji} = \frac{w_{ji}}{w_i} \quad (1)$$

where α_{ji} is the interaction factor between loaded pile “i” and its neighboring pile “j”; w_{ji} is the induced settlement on the pile “j” due to the loaded pile “i”; and w_i is the settlement of pile “i” due to its own load.

$$\alpha = \alpha_f \cdot N_h \cdot N_b \cdot N_v \quad (2)$$

where α is the final two-pile interaction factor; α_f is the interaction factor for a semi-infinite soil using “0.5” for Poisson’s ratio (the presented curves are for specific values of K_p and relative spacing - S/D); N_h is the correction for the finite soil layer; N_b is the correction for the presence of a stiffer soil layer below the pile tip; N_v is the correction for other Poisson’s ratios; K_p is the pile stiffness (P/w = load/top settlement); S is the center-to-center distance between piles; and D is the pile diameter.

Poulos (1989) highlighted that α decreases with increasing pile-to-pile distance, or as the distribution of the Young’s modulus of the soil becomes less uniform with depth. Considering K to be the relative stiffness of a pile ($= E_p/E_s$ = pile Young’s modulus/soil Young’s modulus),

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for floating piles, the interaction factor α increases with increasing relative stiffness; in contrast, α decreases with increasing relative stiffness for end-bearing piles.

Randolph & Wroth (1979) presented a simpler approach based on Winkler approximation. The resulting analytical solutions consider that shear stresses around the pile would decay inversely with radius, leading to a logarithmic decay in vertical displacements, all limited to a maximum radius of influence (r_m). The interaction between two piles is calculated separately in terms of shaft and base induced displacements. Eqs. 3 and 4 present the final shaft and base settlements of two similar rigid neighboring piles. Adding the effects of shaft and base displacements, the overall load-settlement ratio could be expressed as Eq. 5. Thus, the interaction factor α can be obtained from Eq. 6.

$$w_s = w_1 + w_2 = \frac{\tau_0 r_0}{G_{l/2}} \left[\ln \left(\frac{r_m}{r_0} \right) + \ln \left(\frac{r_m}{S} \right) \right] \quad (3)$$

$$w_b = w_1 + w_2 = \frac{Pb(1-\nu)}{4r_0 G_1} \left(1 + \frac{cr_0}{S} \right) \quad (4)$$

$$\left(\frac{P_i}{G_l r_0 w_i} \right) = \frac{4}{1-\nu} \frac{S}{r_0 c + S} + \frac{2\pi\rho}{\zeta + \ln \left(\frac{r_m}{S} \right)} \frac{L}{r_0} \quad (5)$$

$$\left(\frac{G_l r_0 w_i}{P_i} \right)_2 = (1 + \alpha) \left(\frac{G_l r_0 w_i}{P_i} \right)_1 \quad (6)$$

where w_s , w_b and w_i are the shaft, base and total settlements, respectively; w_1 and w_2 are the settlements of Piles 1 and 2, respectively; τ_0 is the shear stress at the pile shaft; $G_{l/2}$ and G_l are the values of the shear modulus at the pile mid-depth and pile base, respectively; r_0 is the pile radius; r_m is the limiting radius of influence of the pile; S is the center-to-center distance between piles; P_b and P_i are the base and total loads acting on the pile, respectively; ν is the Poisson's ratio of the soil; c is a constant ($= 2/\pi$); L is the pile length; ρ is the degree of homogeneity ($= G_{l/2}/G_l$); and ζ is calculated as $\ln(r_m/r_0)$.

El Sharnouby & Novak (1990) presented a method based on boundary element analysis. The authors noted that the longer the pile, the larger the number of discretized points at the pile-soil interface should be. They suggested at least 30 points for shorter piles (relative length $L/D < 50$) and 50 points for longer piles ($L/D > 50$). El Sharnouby & Novak (1990) recalled that the charts presented by Poulos & Davis (1980) featured only 10 points at the pile-soil interface, so discrepancies could arise when applying the method for longer piles. Another interesting point of the same paper is that the influence of intermediary piles was mentioned for the first time. Figure 1 shows one particular example ($K = 1000$, $L/D = 50$, $\nu = 0.5$) for 3-in-line piles with the tips resting on a much stiffer layer. The curves in

Fig. 1 represent the effect of the presence of Pile 2 or the lack thereof between Piles 1 and 3. When Pile 2 is considered, Pile 3 suffers a lower influence from Pile 1, resulting in a lower interaction factor. The authors also explored an example for a 5-in-line pile group, and presented results in a dimensionless format. In this situation, α_{21} is the interaction factor on Pile 2 due to the load on Pile 1 but considers the presence of all five piles and so on for α_{31} , α_{41} , and α_{51} .

Southcott & Small (1996) presented some analyses based on the finite layer method that can solve three-dimensional (3D) problems but in a much easier way (computational effort). The authors mentioned that for a floating pile, the interaction factor of many two-pile theories are in reasonable agreement but that for non-uniform soils, the differences can be relevant. The paper explained the method and revisited some examples from previous theories.

Mylonakis & Gazetas (1998) developed a general analytical formulation based on the Winkler model of soil reaction to study the two-pile interaction problem, especially for piles embedded in multilayered soils. In addition to the induced displacements on neighboring piles, the authors presented an approach to consider the generated stresses along the shaft on nearby piles. The paper shows that a loaded pile will induce a soil displacement field around itself. However, if there is another pile inside this free-displacement field, the axial stiffness of that pile tends to reduce the settlement of any other neighboring piles. To incorporate this physical behavior an attenuation function was suggested for the original free-displacement field, as in the following equation.

$$\alpha = \psi(S) \cdot \zeta(h\lambda, \Omega) \quad (7)$$

$$\psi(S) = \frac{\ln \left(\frac{r_m}{S} \right)}{\ln \left(\frac{r_m}{r_0} \right)} \quad (8)$$

Figure 1 - Interaction factor for two piles with the presence or lack of another pile between them. $K = 1000$, $L/D = 50$ (El Sharnouby & Novak, 1990).

$$\zeta(h\lambda, \Omega) = \frac{2h\lambda + \sinh(2h\lambda) + \Omega^2 [\sinh(2h\lambda) - 2h\lambda] + 2\Omega [\cosh(2h\lambda) - 1]}{2 \sinh(2h\lambda) + 2\Omega^2 \sinh(2h\lambda) + 4\Omega \cosh(2h\lambda)} \quad (9)$$

where α is the final interaction factor; $\psi(S)$ is the free displacement field (as presented by Randolph & Wroth, 1979); $\zeta(h\lambda, \Omega)$ is the attenuation factor due to the self-stiffness of the neighboring pile; h is the layer thickness crossed by the pile (in a homogeneous soil, $h = L$); λ is the

Winkler load transfer parameter ($= \sqrt{\frac{\delta G_s}{E_p A_p}}$); Ω is the

dimensionless pile base stiffness ($= \frac{K_b}{E_p A_p \lambda}$); δ is the rela-

tion between spring stiffness and soil shear modulus in the Winkler model proposed by Randolph & Wroth (1978); G_s is the soil shear modulus; E_p is the pile Young's modulus; A_p is the pile cross-sectional area; and K_b is the pile load/settlement relation at the pile base.

Mylonakis & Gazetas (1998) reported that the attenuation process occurs mainly along the pile shaft and the parcel due to the pile base interaction could be disregarded. Therefore, the total value of $\zeta(h\lambda, W)$ could be presented as shown in Fig. 2.

Cao & Chen (2008) presented an interesting analytical method for calculating the interaction factor between two identical piles subjected to vertical loads. The solution starts from the point at which the continuum medium (original loaded piles) is decomposed into two parts (Fig. 3): an

“extended soil” mass and “two fictitious piles”. The former is the soil, which is considered a three-dimensional elastic material (E_s and ν) loaded with the difference of stresses, defined as the total applied stress minus the stresses on the piles ($\sigma = (P_0 - P^*)/\text{pile area}$), at the positions where the piles should be. The “two fictitious piles” consist of one-dimensional material for which the Young's modulus (E') would be the difference between the pile material Young's modulus (E_p) and soil Young's modulus (E_s). The pile should be discretized in parts to solve the equations and the authors claimed that four or more segments would be sufficient. Plotted data with the interaction factors are presented for different values of relative spacing (S/D), the relation of the base soil and shaft soil Young's modulus (E_b/E_s) and different relative lengths (L/D).

In all presented methods, once the interactions between two piles are estimated, the total settlement of any pile situated in a pile group can be calculated as the sum of every two-by-two induced settlements, as expressed in the following equation.

$$w_j = \sum_i^n w_{ji} = \sum_i^n \alpha_{ji} w_i \quad (10)$$

where w_j and w_i are the settlements of piles j and i , respectively; w_{ji} is the induced settlement in pile j due to the loaded pile i ; and α_{ji} is the interaction factor between piles i and j .

The presented analysis of the aforementioned methods indicate that the original and most commonly used method presented by Poulos (1968) had an important role in stating a mathematical and logical way to predict the settlement of pile groups and that the simple two-pile interaction factor would be more effective for homogeneous soil and small pile groups, but divergences could emerge in other contexts. The following items will attempt to focus on the last points.

3. Comparing the Different Theories

To discuss the similarities of the presented theories, an analysis was performed using the finite element method (FEM) to establish a benchmark for what should be the “reference value”. Despite the importance of nonlinear analysis for pile settlement predictions, the interaction factors between two piles using a simple elastic approach are widely accepted (Mandolini, 2003). The soils used in all of the following examples were considered a continuous elastic medium, and the piled foundations were subjected to “project loads” (serviceability limit state - SLS).

The chosen program for FEM Analyses was DIANA (TNO, 2012), which has already been described in Hemada *et al.* (2014), Tradigo *et al.* (2015), and many other papers.

Figure 2 - Attenuation factor $\zeta(h\lambda, W)$, after Mylonakis & Gazetas (1998).

Figure 3 - Cao & Chen's (2008) hypothesis of foundation decomposition in: (a) original problem; (b) fictitious piles; (c) extended soil.

A typical mesh used in the following examples is presented in Fig. 4. Lateral and vertical boundary limits of $3L$ and $5L$ (L is the pile length), starting from the superficial center load point, were considered. Three different solid isoparametric elements (4faces/10nodes, 5faces/15nodes or 6faces/20nodes) were applied to better represent different geometries, always with a quadratic interpolation.

Figures 5 and 6 present comparisons of a two-pile interaction factor predicted from the different described theories. The example piles had relative lengths (L/D) of 25 and 50 with a relative stiffness (K) of 1000. For the methods of El Sharnouby & Novak (1990), Mylonakis & Gazetas (1998), Cao & Chen (2008), the presented values were taken from the original papers on each theory. Poulos &

Figure 4 - Example of FEM analysis. (a) general view, (b) zoom close to the pile, (c) zoom of the more refined mesh near the pile.

Figure 5 - Two-pile interaction factor predictions from different theories. Piles with $L/D = 25$ and $K = 1000$.

Figure 6 - Two-pile interaction factor predictions from different theories. Piles with $L/D = 50$ and $K = 1000$.

Davis (1980) interaction values were calculated using the DEFPIG software application (Poulos, 1980), which is the original program used to prepare the book charts, but with more than 20 elements to discretize the pile. The values for Randolph & Wroth's (1979) method were obtained by using Eq. 3 through 6. In a general view, all results are in reasonable agreement.

The presented results are in general agreement with many other analyses presented by Curado (2015) and demonstrate that the solution of El Sharnouby & Novak (1990) tends to produce higher values of α . The results of Randolph & Wroth's (1979) theory present marginally higher values for longer piles ($L/D = 100$). It must be noted that in these examples, homogeneous soil was assumed.

4. Stiffness of the Neighboring Piles

Almost all theories define the interaction factor α_{21} based on the induced settlement on Pile 2 due to the loading on Pile 1, generally considering similar piles. In other words, the induced settlement is calculated using only the material properties of Pile 1 and the soil characteristics where this pile is embedded. The real stiffness of Pile 2 is not considered. Figure 7 presents the results of FEM analysis for two hypothetical limits of Pile 2 stiffness. The Young's modulus for the Pile 2 material was varied from a very low value (same as the soil) up to the same value of Pile 1 modulus (similar concrete piles). The Pile 2 settlement is not the same if its stiffness changes. The longer the piles are, the larger the difference in induced settlement is. Figure 8 highlights that for end-bearing piles, the differences would be even larger. In these examples, E_b represents the Young's modulus of a stiffer soil layer below the pile tip. Based on these figures, it is possible to note that the interaction problem depends on the behavior of both piles. Poulos & Davis (1980) and Wong & Poulos (2005) have studied the interaction-factor problem for dissimilar piles and presented simplified approaches in attempts to incorporate correction factors into the original value of α for similar piles.

5. Interference of Other Piles

Some examples are presented to evaluate the effect of the presence or lack of other piles between the two analyzed piles. Figures 9 and 10 compare the interaction factor

Figure 7 - Interaction factors behavior under different pile materials for the affected pile (Pile 2). Piles embedded in a homogeneous soil.

Figure 8 - Interaction factors behavior under different pile materials for the affected pile (Pile 2). Piles resting on a stiffer layer with Young's modulus E_b .

among piles 1-2 and 1-4, respectively. Figure 9 presents the factor α_{21} , which represents the interaction of two neighboring piles, with a separation of $S = x$, a relative length (L/D) of 25 and a relative stiffness (K) of 1000. For Poulos & Davis's (1980) method, this is the two-pile inter-

action factor; *i.e.*, only these two piles exist. The El Sharnouby & Novak (1990) curve was obtained from the problem of the 5-in-line pile group, where Piles 1 and 2 are the two leftmost piles, separated by a distance of x , but now with the presence of three piles at the right-hand side of Pile 2. Four different values of x were considered ($S/D = 2.5, 3, 4$ and 5) along with different relations for the base and shaft soil Young's modulus ($E_b/E_s = 1, 10, 100$ and 1000).

Figure 10 presents a similar analysis for α_{41} . For Poulos & Davis's (1980) theory, the piles were a distance of $3x$ apart, but only the two piles existed. For El Sharnouby & Novak (1990), α_{41} is the interaction between the first and fourth piles in a group of five piles. For this figure, the interaction factors were calculated for center-to-center spacings of 7.5, 9, 12 and 15 diameters. In both figures, Poulos & Davis's (1980) theory achieved better predictions for homogeneous soils ($E_b/E_s = 1$), whereas for end-bearing piles, the interaction factors from ElSharnouby & Novak (1990) were similar to the FEM analysis.

Figure 9 - Interaction factor α_{21} for two piles in groups of two and five piles ($L/D=25, K=1000$).

Figure 10 - Interaction factor α_{41} for two piles in groups of two and five piles ($L/D=25$, $K = 1000$).

Mylonakis & Gazetas (1998) mentioned that intermediate piles would provoke a reduction in the induced settlement to a neighboring pile, this direct correlation was not confirmed by the results, as could be inferred from the presented data in Fig. 10 for the homogeneous soil case. Values of α_{41} (with two other piles between the loaded and the analyzed piles) from El Sharnouby & Novak (1990) were higher than the factors predicted by Poulos & Davis's (1980) theory. To further examine this result, four different pile groups were studied using FEM. Figure 11 presents the results for groups with 2, 3, 5, 9 and 25 piles. The only loaded pile is represented with an arrow, and all other piles were unloaded. No cap was considered in these cases, and the interaction factor was calculated for the pile represented by a hatched area (target pile). These examples are not found in practice, but this is the manner to exclude all other factors that affect the pile settlement prediction. Therefore, in all groups with three or more piles, there was always one pile between the loaded and the studied piles. A relative stiffness (K) of 1000 and different spacings were consid-

ered in this analysis. Figures 11a and 11b show the results for piles with relative lengths of 25 and 50, respectively.

Some remarks can be drawn from Fig. 11:

- By comparing the groups with 3 and 5 piles, we can observe that not only did the pile placed between the studied piles result in lower values of α , but the other piles in the same line still contributed to reduce the settlement in the target pile;
- Other nearby piles also contributed to reduce the interaction factor between the two studied piles, as seen for the 9- and 25-pile groups.

With all of these comments, we can see that the interaction factor is not simply a two-pile problem. The presence of other nearby piles can interfere in the total pile stiffness. Thus, the nearby piles would hamper the soil movement around the pile that is receiving the influence of the loaded pile.

6. Pile Position in the Foundation

Returning to Fig. 11, one point stands out. Comparing the groups with 5 and 9 piles, the 9-pile group has a lower

Figure 11 - Interaction factor for two piles with another intermediate pile in groups of 3, 5, 9 and 25 piles. (a) piles with $L/D = 25$, (b) piles with $L/D = 50$.

interaction factor for all spacings and both pile lengths, except when $S/D = 4$ (distance from loaded and studied piles, recalling that another pile was between them). For some reason, the trends were reversed at this point. To explore this fact, a 25-pile group was analyzed with a finite element software program DIANA (TNO, 2012), and Fig. 12 presents the interaction factor between 2 piles. Two different relative pile lengths were explored: $L/D = 25$ (Fig. 12a) and $L/D = 50$ (Fig. 12b), changing the spacings between piles (S/D). In this group, only one pile was loaded, and the settlement was evaluated in other pile (filled circle). In Case A, the loaded pile was in the center, and the studied pile (target pile) was the leftmost lateral one. Conversely, in Case B, the loaded pile was in the lateral position, and the central pile was receiving settlement influence. As shown in Fig. 12, for all situations, Case A resulted in the higher settlement of the neighboring pile because the settlement receiving pile was in the lateral position; thus, the less confined situation allowed this pile to experience a higher movement. In contrast, when the target pile (filled circle)

Figure 12 - Comparing the interaction factor α_{31} inside a 25-pile group with different loaded pile positions. (a) $L/D = 25$, (b) $L/D = 50$.

was in the center (Case B), the most confined position, the induced settlement was lower.

This example shows that a two-pile interaction is not a reciprocal problem. Despite all similarities between piles, the interaction factors were different ($\alpha_{21} \neq \alpha_{12}$), showing that pile position and group geometry do matter.

For the reason mentioned previously, the studied pile in the 9-pile group (Fig. 11 with $S/D = 4$) was “less confined” than the corresponding 5-pile group, so the influenced pile had a higher settlement. When the pile spacing increased, the confinement started to change, and the interaction factor gradually decreased.

7. Large Pile Groups and Piled Rafts

All previous comparisons presented differences that could be classified as “not so relevant”. This is partially true for groups with only a few piles. For a large piled foundation (pile groups or piled rafts), as used in an increasing number of tall building foundations, the cumulative differences due to lower interaction factors can result in a considerable difference in the final elastic settlement prediction.

Figure 13 compares the predictions for three different pile groups with different approaches: one calculated as a full three-dimensional (3D) pile group problem (ρ_{FEM}) and the other using a theoretical method based on the superposi-

Figure 13 - Influence of different concepts for interaction factors in a homogeneous soil for groups with different numbers of piles.

tion of interaction factors (ρ_{Theory}). In the theoretical case, the individual two-pile interaction was also pre-calculated with the same software (as in Fig. 5). Square pile groups with 9(3×3), 25(5×5) and 49(7×7) piles are presented, and the reduction factor is defined here as the relation between the settlement difference (true 3D FEM analysis minus the conventional superposition of interaction factors) and the considered more realistic approach (3D FEM analysis). In this example, the soil was considered as a homogeneous profile with $K = 1000$ and $L/D = 25$, all piles had the same load, and the spacing of three diameters between the piles (center-to-center) was considered for all of these groups. The figure shows an increasing difference becoming more than 15% for the largest group. The reduction ratio is non-linear because the number of interactions increases with increasing pile number, which results in lower interaction factors for even more distant piles. For heterogeneous soils, the differences can be even larger.

To exemplify this situation, the problem proposed by TC-18 in 1998 (Matsumoto *et al.*, 1998) of a 16-pile group resting in a heterogeneous profile is presented here. The elastic soil modulus distribution was considered to be similar to Frankfurt clay, as suggested by Amman (1975) and explored in Sales *et al.* (2010). Some authors were invited

to present predictions of the settlement and distribution of pile loads. Figure 14 presents the soil, piles and raft data, and a total load of 80MN was uniformly spread over the raft. Table1 compares some returned predictions and a new 3D FEM analysis using the software application DIANA (TNO, 2012). We clearly have two different sets of predictions: the first group (Horikoshi & Randolph, 1998; Matsumoto, 1998 and Sales, 2000) contains the predictions based on hybrid methods using the two-pile interaction concept (not considering the other piles when calculating the pile interactions), and the second group uses 3D FEM software. Inside each group of predictions, the results are very similar; however, the difference between the average values for the predicted settlements (42 mm and 28.7 mm, respectively) is greater than 30%. The procedure of considering all sets of piles in a 3D analysis resulted in a lower foundation settlement than using the conventional superposing two-pile process. The presented example indicates that for a heterogeneous soil, the difference in pile group settlement predictions can still be higher than the values shown in Fig. 13. Considering the remarks of Fig. 13 and Table1, it should be pointed out that for large pile groups (more than 9 piles) and piled rafts, especially for a heterogeneous soil, a more rigorous analysis on settlement predictions would be necessary.

Figure 14 - 16-pile group in a heterogeneous soil proposed by TC-18.

Table 1 - Settlement Predictions for the 16-piled raft of TC-18.

Author	Software	Interaction Method	Maximum Settlement (mm)
Horikoshi and Randolph(1998)	HyPR (HM [*])	Two-piles	41-43
Matsumoto (1998)	KURP (HM [*])	Two-piles	42
Sales (2000)	GARP (HM [*])	Two-piles	42
Yamashita (1998)	NA (FEM)	Full Interaction	29
Sales (2000)	ALLFINE (FEM)	Full Interaction	27
This Paper	DIANA (FEM)	Full Interaction	30

^{*}HM = Hybrid Method, FEM = Finite Element Method, NA = name not available.

Conclusions

This paper discussed methods used to evaluate the interaction between piles in a piled foundation under a vertical load. The conventional process of superposing interaction factors, which is a consequence of induced settlements of two neighboring piles, was compared with a three-dimensional finite element analysis in foundations with different pile configurations; and the following aspects can be noted:

1) The factor α , proposed by Poulos (1968) to evaluate the interaction between two piles, is the basis of many other theories. The superposing principle of two-pile interaction to study pile group settlements achieves good results mainly for small pile groups and homogeneous soils;

2) Some theories, including El Sharnouby & Novak (1990) and Mylonakis & Gazetas (1998), note that if another pile is between the other two considered piles, the settlement field and the interaction factor will be affected;

3) The presented examples showed that, in a pile group, the position of all other piles will interfere with the induced settlements. Thus, the two-pile interaction is not a perfect “reciprocal problem” because the pile position and group geometry change the factor α .

4) When comparing a complete 3D FEM analysis with the conventional approach of superposing interaction factors, a smaller pile group settlement is found. This difference can exceed 15% for homogeneous soils but can be much larger for heterogeneous soils and a large number of piles (over 9-pile groups).

5) This paper analyzed the process of induced settlements on nearby piles. Only elastic examples were presented to clarify and simplify the comparisons. The authors, however, recognize that many other aspects can contribute to pile interaction factors, including nonlinear behavior, and pile installation method.

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List of Symbols

- A_p : pile cross-sectional area
 c : a constant
 D : pile diameter
 E^* : "fictitious pile" Young's modulus
 E_b : Young's modulus of a stiffer soil layer below the pile tip
 E_p : pile Young's modulus
 E_r : raft Young's modulus
 E_s : soil Young's modulus
 FEM : Finite Element Method
 $G_{1/2}, G_i$: values of the shear modulus at the pile mid-depth and pile base, respectively
 G_s : soil shear modulus
 h : layer thickness crossed by the pile
 K : relative stiffness of a pile
 K_b : pile load/settlement relation at the pile base
 K_p : pile stiffness
 L : pile length
 n : number of piles
 N_b : correction for the presence of a stiffer soil layer below the pile tip
 N_h : correction for the finite soil layer
 N_v : correction for other Poisson's ratios
 P : load
 P^* : applied load on the "fictitious piles"
 P_o : total applied load on the original piles
 P_b, P_t : base and total loads acting on the pile, respectively
 P_{ult} : ultimate load
 r_o : pile radius
 r_m : limiting radius of influence of the pile
 S : center-to-center distance between piles
 w : top settlement
 w_1, w_2 : settlements of Piles 1 and 2, respectively
 w_b : base settlement
 w_{ji} : induced settlement on the pile "j" due to the loaded pile "i"
 w_j : settlement of pile "j" due to its own load
 w_s : shaft settlement
 w_t : total settlement
 x : center-to-center distance between piles, in 5-in-line pile group
 α : two-pile interaction factor
 $\alpha_{21}, \alpha_{31}, \alpha_{41}, \alpha_{51}$: interaction factor on pile number "n" due to the load on Pile 1 but considers the presence of all five piles

α_f : interaction factor for a semi-infinite soil using “0.5” for Poisson’s ratio	ρ_{Theory} : predictions for pile groups using a theoretical method based on the superposition of interaction factors
α_{ji} : interaction factor between loaded pile “ i ” and its neighboring pile “ j ”	σ : soil stress load
δ : relation between spring stiffness and soil shear modulus in the Winkler model	τ_0 : shear stress at the pile shaft
λ : Winkler load transfer parameter	ν : Poisson’s ratio of the soil
ρ : degree of homogeneity	ν_p : Poisson’s ratio of the pile
ρ_{FEM} : predictions for pile groups calculated as a full three-dimensional (3D) pile group problem	ν_r : Poisson’s ratio of the raft
	Ω : dimensionless pile base stiffness
	$\psi(S)$: free displacement field
	ζ : calculated as $\ln(r_m/r_0)$
	$\zeta(h\lambda, W)$: attenuation factor due to the self-stiffness of the neighboring pile