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Evaluation of pile group effect under axial loading on foundations for storage tanks using numerical modeling

Évaluation de l'effet de groupe de pieux sous charge axiale sur les fondations de réservoirs de stockage à l'aide de la modélisation numérique

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ABSTRACT: Within the petrochemical sector, there is a need to store liquid products. It is common for the density of liquids to be much higher than that of water, therefore, discharges are usually high. Recent cases of excessive settlement of tanks during hydrostatic tests made evident that the evaluation of the piles group effect is mandatory. The most basic way to predict this effect is to obtain the efficiency factor using simplified analysis; however, several methods exist to evaluate the behavior. In practice, the minimum center-to-center pile spacing (*s*) is about 3*D* to 3.5*D*. In this paper, load-displacement curves are presented in three soil profiles and two length to diameter ratios (*L/D*) of 15 and 30 for three diameters of pile and *s/D* ratios of 2, 3, 5 and 8 arranged in typical geometries of tank foundations. The impact of the use of an interface to simulate the skin friction is also evaluated. The data employed to construct the curves was taken from 90 load tests simulated by numerical modeling using the finite difference method and serve as a guide when evaluating the efficiency of group piles in foundations for tanks.

RÉSUMÉ : Dans le secteur pétrochimique, il est nécessaire de stocker des produits liquides. Il est courant que la densité des liquides soit beaucoup plus élevée que celle de l'eau, les rejets sont donc généralement importants. Des cas récents de tassement excessif de réservoirs lors d'essais hydrostatiques ont mis en évidence que l'évaluation de l'effet des pieux de groupe est obligatoire. La façon la plus simple de prédire cet effet est d'obtenir le facteur d'efficacité en utilisant une analyse simplifiée ; cependant, plusieurs méthodes existent pour évaluer le comportement. En pratique, l'espacement minimal entre les centres des pieux (*s*) est d'environ 3*D* à 3,5*D*. Dans cet article, les courbes charge-déplacement sont présentées dans trois profils de sol et deux rapports longueur-diamètre (*L/D*) de 15 et 30 pour trois diamètres de pieu et des rapports *s/D* de 2, 3, 5 et 8 disposés dans des géométries typiques de fondations de réservoirs. L'impact de l'utilisation d'une interface pour simuler le frottement surfacique est aussi estimé. Les données utilisées pour construire les courbes proviennent de 90 essais de charge simulés par modélisation numérique en utilisant la méthode des différences finies et servent de guide pour évaluer l'efficacité des pieux groupés dans les fondations de réservoirs.

KEYWORDS: axial bearing capacity, group efficiency, load test, finite difference method, liquid storage tanks.

1 INTRODUCTION

1.1 *Pile group effect*

In cases where a shallow foundation system is not feasible due to the subsoil conditions or because of restrictions within the engineering project itself, it is quite common to design deep foundations evaluating its axial bearing capacity using analytical methods or through *in situ* load testing depending on the significance of the project. In many cases, these systems are based on pile groups arranged in regular geometries consistent with the structural project or according to the designer experience.

The effect in closely spaced pile groups is based on the assumption that the transmitted stress of one pile overlaps the transmitted stress from a neighboring pile of the same group, reducing the axial bearing capacity due to the variations in the load-displacement behavior due to the pile-soil-pile interaction (see Figure 1); therefore, the axial bearing capacity of a pile group is related to the axial bearing capacity of a single pile by means of an efficiency factor η calculated through the following equation (Das, 2011):

$$\eta = \frac{Q_g}{nQ_s} \tag{1}$$

where η is the efficiency factor; Q_g is the axial bearing capacity of the pile group; n is the number of piles in the group; and Q_s is the axial bearing capacity of a single pile.

Several analytical methods are used in order to calculate de efficiency factor though equations where the main variables are *s* (center-to-center pile spacing) and *D* (diameter of the pile); however, Chellis (1962) performed a comparison between the empirical equations and found considerable variations.

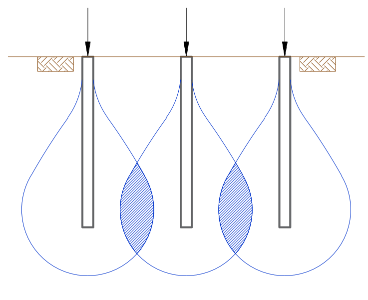

Figure 1. Transmitted stresses in a closely spaced pile group.

The common denominator between these analytical methods is that the efficiency factor is calculated for square or rectangular arrangements of pile groups, which is not a norm for circular foundations.

1.2 *Foundations for storage tanks*

Within the petrochemical sector, there is a need to store liquid products. It is common for the density of liquids to be much higher than that of water, therefore, discharges are usually high. Likewise, the tolerance of settlements is restrictive, so the use of pile groups is recurrent. Recent cases of excessive settlement of tanks during hydrostatic tests made evident that the evaluation of the piles group effect is mandatory.

The foundation of storage tanks is often designed in circular form (see Figure 2); therefore, the pile groups are arranged in this manner aiming to distribute the static and dynamic loads in the most uniform way possible. This geometrical arrangement is not fully compatible with the empirical equations; thus, the analytical method cannot be applied with safety.

This is the main purpose of this paper, where 90 three-dimensional numerical models were developed using the explicit finite difference method through FLAC3D software in order to obtain efficiency factors that might be used in practice during the design of deep foundations for liquid storage tanks.

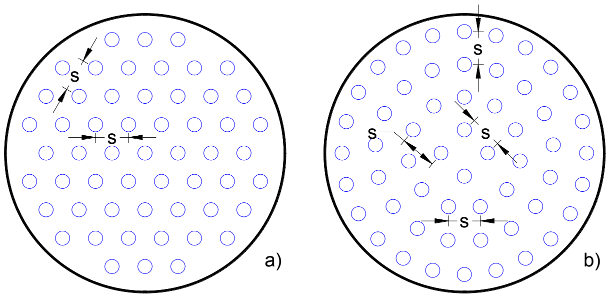

Figure 2. Typical arrangement of pile groups in circular foundations.

2 SIMULATION OF PILE LOAD TESTS

2.1 *Background*

Several authors have developed numerical models to simulate the load transfer mechanism of piles (Comodromos, *et al*., 2003; Mayoral, *et al.,* 2010; Paniagua, *et al.,* 2012; Pham 2012) and compared the results to *in situ* load tests. The comparison between the measured and the calculated results indicated that, when choosing the correct deformation and strength parameters, the load-displacement curve can be obtained with accuracy using a numerical model.

2.2 *Numerical modeling*

The technics based on numerical modeling consider the heterogeneity of soil layers through nonlinear constitutive laws in addition to initial states and boundary conditions that are very similar to the field conditions.

The explicit finite difference method in three dimensions is useful to study the mechanical behavior of continuous medium that reach equilibrium or a steady plastic flow; offering an ideal tool of analysis for the solution of three-dimensional problems within the broad field of geotechnical engineering.

2.3 *Constitutive model*

The constitutive law employed in this study is the Mohr-Coulomb model, which is considered a first-order approximation of the nonlinear behavior of soil. This perfect elasto-plastic model was developed from the Hooke´s law and the Mohr-Coulomb failure criteria. This formulation involves two general elements: the perfect elasticity and the plasticity associated to the development of plastic or permanent deformations. The input parameters of this model are Young modulus (E); Poisson ratio (v); cohesion (c); angle of internal friction (ϕ); and angle of dilation (ψ).

2.4 *Load tests*

Load tests in piles are generally performed to obtain the following:

1. Axial bearing capacity of the pile.
2. Behavior of the load-displacement plot.

The most common test is of compression, which is based on the application of staged vertical loads in order to obtain the load-displacement plot. Every load is maintained until the resulting settlement ceases before applying the next incremental load.

This methodology can be easily simulated through numerical models to obtain load-displacement plots and consequently, the axial bearing capacity of individual piles or a pile inside a group.

2.5 *Interface element in numerical models*

In practice, an interface element between the pile shaft and the soil is often implemented within the numerical models. The use of this element depends on the purpose of the analysis and the construction method of the piles.

This interface creates a preferred zone of displacement where the pile is detached from the elements representing soil; therefore, the axial bearing capacity when employing an interface is often inferior compared to models where this element is not used. Moreover, some experimental model tests (Noman, *et al.,* 2019) have shown that during load tests, soil is adhered to the pile shaft and later fails in a soil-soil contact. This phenomenon generates an increase in the pile perimeter producing higher axial bearing capacities.

In order to evaluate the effect of the interface element in the efficiency factor, a comparison will be performed between the results from models using an interface element and not using it at all.

2.6 *Pile cap*

It is well known that pile groups are normally connected to a pile cap, which distributes the loads of the structure into the piles. This distribution causes a differential settlement in piles depending on its location, where center piles in a group settle in more percentage than border or corner piles.

However, for simulation of load tests in pile groups using numerical models, the pile cap cannot be modeled because of two limitations:

1. The pile-cap itself produces a bearing capacity due to its contact with soil; therefore, the behavior of piles cannot be assessed correctly.
2. The axial loads would have to be applied on the pile cap and it is difficult to obtain the exact load that every pile is receiving, which is mandatory for the creation of load-displacement plots.

In order to evaluate the possible effect in the efficiency factor of the connection between the piles in the group caused by a pile-cap, a comparison will be performed between piles connected by rigid connections using beam elements and piles that are not connected at all.

3 THREE DIMENSIONAL NUMERICAL MODELS

3.1 *3D Meshes*

15 three-dimensional meshes of tetrahedron elements (see Figure 3) were generated using MIDAS GTS NX software and were later exported to FLAC3D using the proposed methodology by Flores and Ayez (2016). The characteristics of the meshes can be found in Table 1.

3.2 *Soil profiles*

Aiming to evaluate the results on different soil types, three soil profiles were generated. The geotechnical parameters employed can be found in Table 2.

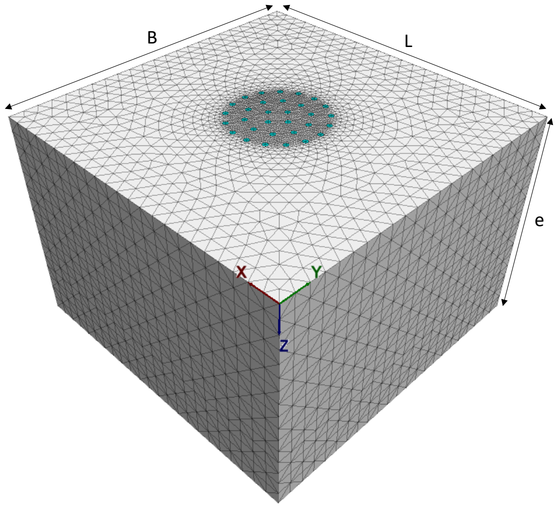

Figure 3. Generated mesh for D=1.0 m piles and s/D=3.

Table 1. Generated three-dimensional meshes.

D (m)	3D Model	No. of elements	No. of nodes	**B=L (m)	**e (m)
0.3	Single	331,692	59,571	30	40
	*s/D=2	225,632	39,006	12	40
	s/D=3	338,911	59,182	18	40
	s/D=5	506,055	87,487	27	40
	s/D=8	932,444	161,068	42	40
0.6	Single	197,132	35,489	30	40
	s/D=2	245,584	43,046	25	40
	s/D=3	386,425	68,020	35	40
	s/D=5	458,280	80,197	55	40
	s/D=8	887,143	154,481	84	40
1.0	Single	94,624	17,044	30	40
	s/D=2	214,307	37,354	42	40
	s/D=3	357,876	62,970	58	40
	s/D=5	574,852	101,981	130	40
	s/D=8	868,004	152,610	148	40

*s/D=center-to-center pile spacing to diameter of piles ratio
**see Figure 3

Table 2. Geotechnical parameters per soil profile.

Soil type	USCS	from (m)	to (m)	γ_m (kN/m³)	c (kPa)	ϕ (°)	ν (-)	E (MPa)
Clay	CH	0.0	5.0	11.5	15.0	0	0.45	2.30
	CH	5.0	10.0	13.0	12.0	0	0.45	1.30
	CH	10.0	15.0	13.5	20.0	0	0.45	4.55
	CH	15.0	20.0	13.5	40.0	0	0.45	5.81
	CH	20.0	30.0	13.0	50.0	0	0.45	8.44
	CH	30.0	40.0	13.5	65.0	0	0.45	18.87
Sand	SM	0.0	5.0	17.5	10.0	28	0.35	20.00
	SP	5.0	10.0	18.5	0.0	32	0.30	45.00
	SM	10.0	20.0	18.0	15.0	30	0.35	35.00
	SP	20.0	30.0	19.0	0.0	35	0.30	57.50
	SP	30.0	40.0	19.5	0.0	38	0.30	75.00
Stratified soil	SM	0.0	5.0	17.5	10.0	28	0.35	20.00
	CH	5.0	10.0	13.0	12.0	0	0.45	1.30
	SM	10.0	20.0	18.0	15.0	30	0.35	35.00
	CH	20.0	30.0	13.0	50.0	0	0.45	8.44
	SP	30.0	40.0	19.5	0.0	38	0.30	75.00

where: γ_m = unit weight; c = undrained cohesion; ϕ = angle of internal friction; ν = Poisson's ratio; E = static Young modulus.

3.3 *Pile properties*

The concrete of the piles is considered to have the properties shown in Table 3.

Table 3. Pile Properties.

f'c (MPa)	γ (kN/m³)	c (kPa)	ν (-)	E (MPa)
35	24	17,500	0.18	26,192

where: f'c = compressive strength; γ = unit weight; c = cohesion; ν = Poisson's ratio; E = Young modulus.

3.4 *Research considerations*

The following considerations were applied to the numerical models:

a. Three soil profiles (clay, sand and stratified soil).
b. Three pile diameters (*D*=0.3 m, 0.6 m, and 1.0 m).
c. Two length to diameter ratios (*L/D*= 15 and 30).
d. 3D models of single pile and pile groups with four center-to-center separations (*s/D*=2, 3, 5 and 8).
e. Three rings of piles (center, intermediate and border piles) in a circular geometry for pile groups.
f. Bored cast-in-place concrete piles.
g. Directly applied loads on pile head. No pile cap considered.
h. Load controlled tests in piles to reach a displacement of 0.3D (*D*=diameter) of the pile head.
i. Axial bearing capacity taken at 0.1*D* settlement of the pile head from the load-displacement plots (Terzaghi 1942).
j. The changes in pile capacity with time are not evaluated.
k. The effect of an interface element will be evaluated on the clay profile for piles of 1.0 m diameter and *s/D*=15.
l. The effect of a rigid connection between piles will be evaluated on the three soil profiles for piles of 1.0 m diameter and *s/D*=15.

4 EFFICIENCY FACTORS

The results from the 90 load test simulated through the three-dimensional explicit finite difference method were plotted to obtain the load-displacement behavior (see Figure 4), where the axial bearing capacity was taken at a displacement of the pile head of 0.10*D*. The load-displacement plot observed in Figure 4 is normalized at the horizontal axis as settlement of the pile head (S_{ph}) to pile diameter (D) and at the vertical axis as axial bearing capacity of a center pile in the group (Q_g) to axial bearing capacity of a single pile (Q_s).

Using the data from the load-displacement plots, the efficiency factors were calculated employing Equation 1. The calculated values are tabulated in Table 4 and Table 5 and plotted versus the *s/D* ratio in Figure 5.

Table 4. Axial bearing capacity and efficiency factors calculated for L/D=15.

D (m)	s/D	Clay		Sand		Stratified soil	
		[1]η	[2]Q_g (kN)	η	Q_g (kN)	η	Q_g (kN)
0.3	2	0.03	25	0.14	165	0.06	59
	3	0.04	30	0.22	255	0.09	83
	5	0.05	37	0.36	430	0.12	115
	8	0.11	82	0.55	650	0.16	150
0.6	2	0.12	135	0.25	950	0.26	660
	3	0.17	1,395	0.39	1,470	0.34	850
	5	0.26	295	0.63	2,400	0.42	1,060
	8	0.43	485	0.86	3,270	0.62	1,550
1.0	2	0.23	620	0.32	3,700	0.20	1,800
	3	0.34	930	0.47	5,425	0.27	2,400
	5	0.50	1,350	0.80	9,150	0.49	4,400
	8	0.87	2,350	1.01	11,550	0.78	7,000

[1]efficiency factor
[2]axial bearing capacity of an intermediate pile in the group

Table 5. Axial bearing capacity and efficiency factors calculated for L/D=30.

D (m)	s/D	Clay		Sand		Stratified soil	
		η[1]	Q_g (kN) [2]	η	Q_g (kN)	η	Q_g (kN)
0.3	2	0.05	47	0.14	250	0.11	145
	3	0.07	63	0.23	400	0.17	220
	5	0.09	83	0.34	600	0.23	310
	8	0.14	125	0.63	1,100	0.31	410
0.6	2	0.17	440	0.24	2,100	0.17	1,050
	3	0.22	570	0.36	3,100	0.22	1,350
	5	0.32	820	0.52	4,500	0.28	1,680
	8	0.52	1,350	0.73	6,350	0.42	2,550
1.0	2	0.25	2,090	0.33	9,400	0.34	7,300
	3	0.34	2,900	0.48	13,600	0.45	9,550
	5	0.59	5,000	0.76	21,500	0.63	13,400
	8	0.95	8,050	1.00	28,200	0.84	18,000

[1]efficiency factor
[2]axial bearing capacity of an intermediate pile in the group

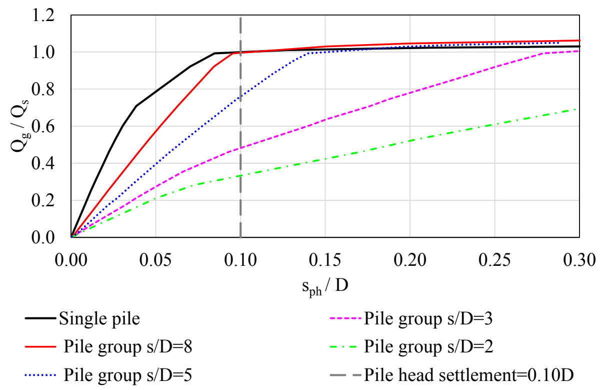

Figure 4. Load-displacement plot for piles in the sand profile, D=1.0 m and L/D=30.

5 ANALYSIS OF RESULTS

The effects on the efficiency factor of the considerations that were studied are presented in the following paragraphs.

5.1 *Soil type*

The associated behavior due to the stiffness and the strength of a soil profile was analyzed with plots of weighted average values of Young modulus, undrained cohesion and angle of internal friction (see Figure 6) versus the calculated efficiency factors.

The stiffness is represented by the Young modulus in Figure 6a; it can be observed that the group effect has a major impact on the clay profile, i.e. the efficiency group decreases as the stiffness decreases. It is important to highlight, that efficiency factors for Young modulus in the range of the stratified soil profile lies between the behavior of the clay and the sand profile.

Figure 6b represents the undrained cohesion of the clay profile versus the efficiency factor, where it is evident that this parameter does not directly provide an increase in the efficiency factors and it depends on the diameter of the pile and the *s/D* ratio.

The case of the angle of internal friction for the sand profile is plotted in Figure 6c versus the efficiency factors. It can be deduced that an increase in this parameter represents an increment of the efficiency factors.

An interesting observation of the calculated efficiency factor is that in stratified soils, the behavior of the pile group will depend in a great percentage of the type of soil where the pile tip is resting, as can be observed in Figure 5c and Figure 5d.

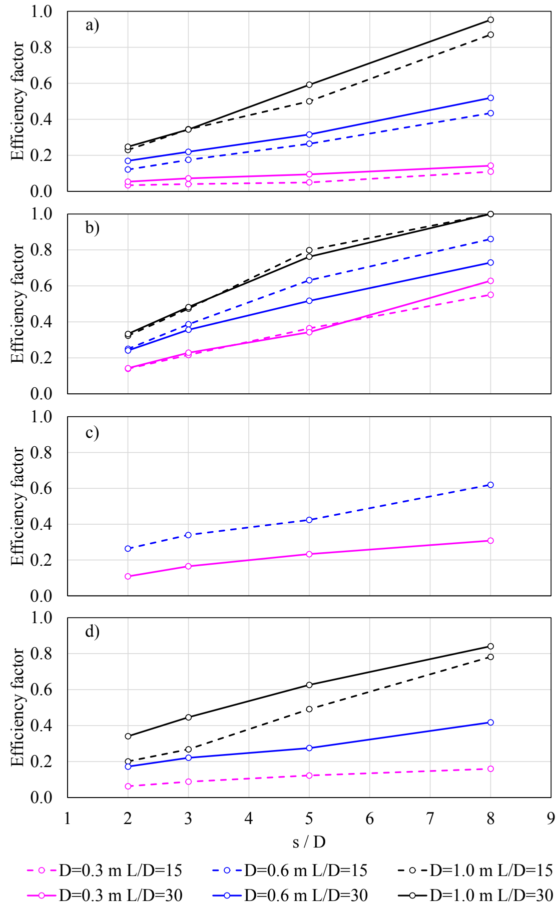

Figure 5. Efficiency factors calculated for a) Clay profile; b) Sand profile; c) Stratified soil and pile tip resting in clay; d) Stratified soil and pile tip resting in sand.

5.2 *Center-to-center pile spacing*

As previously mentioned, this parameter is the main variable of the empirical methods that exist to calculate the efficiency factor of a pile group.

In practice, the center-to-center pile spacing is considered of at least 2.5*D*, although is close to 3*D* and 3.5*D* in ordinary conditions for the axial bearing capacity of the pile group to be no lower than the sum of the axial bearing capacity of a single pile (Das, 2011), or in other words, to obtain an efficiency factor equal or almost equal to 1.

The results of the developed numerical models of this investigation (see Figure 5) showed an increment of the efficiency factor as the *s/D* ratio increases; however, the separation of 3*D* showed efficiency factors with values lower than 1 in all the studied cases as can be seen in Table 4 and Table 5, with efficiency factors from 0.04 to 0.34 in the clay profile; from 0.22 to 0.48 in the sand profile: and 0.09 to 0.45 in the stratified soil profile. Therefore, the commonly center-to-center spacing of 3*D* used in practice to increase the efficiency factors should be taken with some reservation for circular geometries in pile groups as the results from this paper indicated.

5.3 *Piles diameter*

It was observed that the diameter of piles plays an important role in the behavior of the efficiency factor, showing an increment as the diameter increases (see Figure 5); i.e. the group effect is diminished for larger diameters, which is not a regular variable of the analytical methods to calculate the efficiency factor.

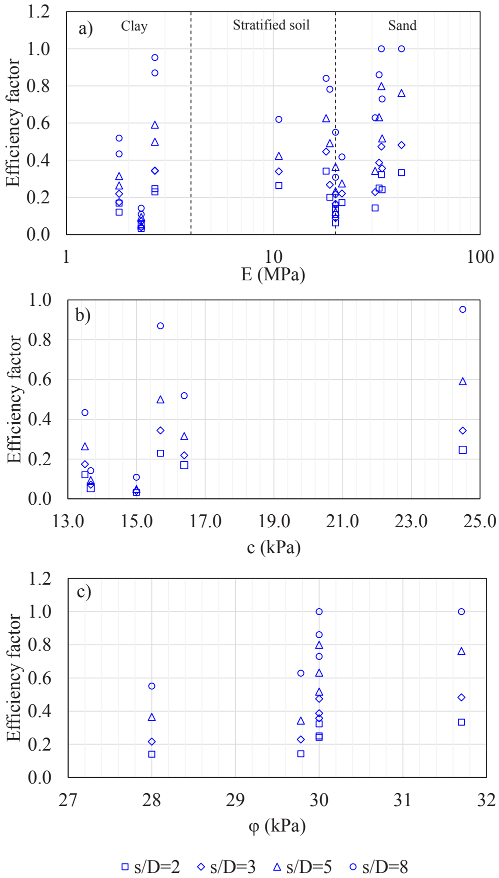

Figure 6. Weighted average parameters versus efficiency factor a) Young modulus; b) Undrained cohesion; c) Angle of internal friction.

5.4 *Soil displacement surrounding the pile group*

An interesting effect was observed in the soil that surrounds the pile group through the rendering of IsoSurfaces of the same value. These surfaces represent the vertical displacement for a defined value in the model.

In Figure 7, the IsoSurfaces corresponding to a vertical displacement of 0.10*D* (axial bearing capacity according to Terzaghi, 1942) of the pile tip in an intermediate pile were plotted for the sand profile and *L/D*=15 developed models. As can be observed, in the case of a single pile (see Figure 7a), only the soil directly attached to the pile shaft displaces; however, in the case of the lowest *s/D* ratio of 2 (see Figure 7b) an interaction of soil between the piles in the group appears, acting as a whole, involving an important group effect which is directly seen in the efficiency factor of this particular model (η =0.32, see Table 4). As the s/D ratio increases, the interaction of the soil is lowered and reaches a single pile behavior for the larger *s/D* ratio of 8 (see Figure 7e) reaching an efficiency factor of 1.01 (see Table 4).

5.5 *Pile cap effect*

The possible effects of a pile cap were represented in the model as rigid beams connecting the piles in the group. This evaluation was performed for the three soil profiles and the pile groups of 1 m in diameter. The efficiency factors that were calculated for comparison with the results from the models with piles that are not connected by any means are plotted in Figure 8. In the case of the clay profile (see Figure 8a) the factors calculated using a rigid connection between piles in the group displayed a slight improvement; the efficiency factors derived from the analysis on the sand profile (see Figure 8b) did not indicate a modification, except for the *s/D* ratio of 8, where the efficiency factor increased from 1 to 1.29; and in the case of the stratified soil profile, where the pile tips are resting in sand, the efficiency factors did not show a major modification.

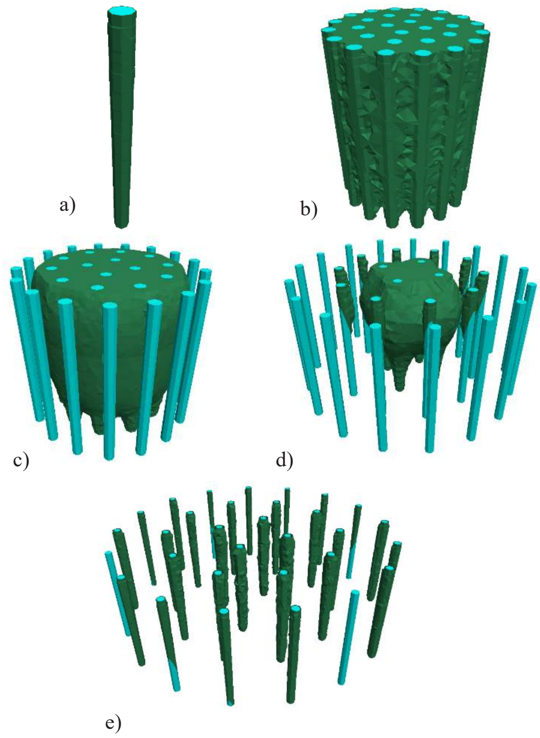

Figure 7. IsoSurfaces of vertical displacement at 0.10D of the pile tip in an intermediate pile for the sand profile and L/D=15. a) Single pile; b) s/D=2; c) s/D=3; d) s/D=5; and e) s/D=8.

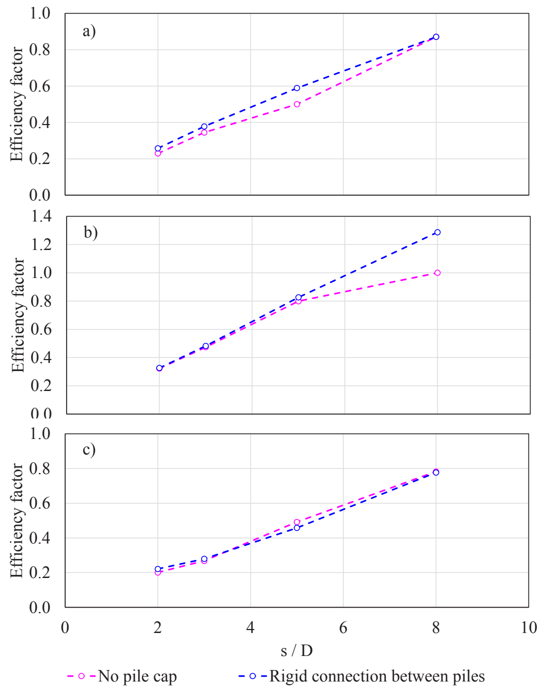

Figure 8. Comparison of efficiency factors calculated for pile groups without pile cap and pile groups connected by rigid elements in piles of D=1.0 m and L/D=15. a) Clay profile; b) Sand profile; and c) Stratified soil profile.

5.6 *Interface element*

The evaluation of the efficiency factors using and interface element between the pile shaft and the soil was performed for the models of piles groups with 1 m in diameter in the clay profile. Different shear strength parameters for the interface were used in the analysis (S_u values ranging from 0.7S_u o 1.0S_u of foundation soil); this sensibility analysis did not indicate a strong modification of the efficiency factors; however, when comparing these values with the ones calculated for the models where an interface was not analyzed (see Figure 9), an increase of the efficiency factors is observed for the models considering an interface; although, this effect decreases as the *s/D* ratio increases.

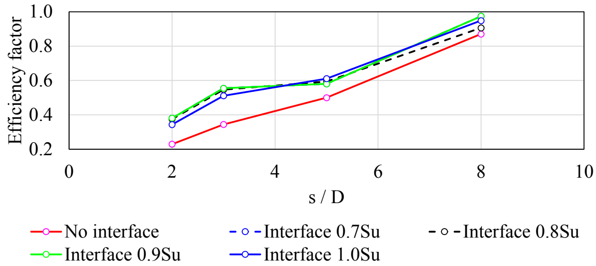

Figure 9. Comparison of efficiency factors calculated for pile groups without interface and pile groups considering an interface between the pile shaft and the soil in piles of D=1.0 m and L/D=15 in the clay profile.

5.7 *Length to diameter ratio*

The efficiency factors calculated for two length to diameter ratios (*L/D*=15 and 30, see Figure 5) indicated a slight modification between them and it depends on the soil type in analysis. In the case of the clay profile (see Figure 5a) the efficiency factor for the larger *L/D* ratio of 30 improved; however, for the sand profile (see Figure 5b), the effect is the opposite; finally, as already stated, the behavior of the efficiency factors in the stratified soil strongly depends on where the tip is resting (see Figure 5c and Figure 5d).

6 CONCLUSIONS

In this paper, 90 pile load tests were simulated using the three-dimensional explicit finite difference element method according to the considerations stated in Section 3.4 in order to obtain efficiency factors for circular geometries of pile groups.

Among the most important findings was that the commonly used in practice center-to-center pile spacing of 3 diameters to decrease the group effect, still represents a strong reduction of the efficiency factors for all the studied cases.

At the same time, the analytic methods that exist to estimate this factor are based mostly on the variable center-to-center pile spacing; however, in this research it was found that there are several parameters involved in the group effect that directly affect the efficiency factor. The detailed impact of the analyzed parameters reported in Table 6 can be found in Section 5 of this study.

In the cases of the clay and sand profile, the efficiency factors presented a similar almost linear behavior that increases as the pile diameter and the center-to-center pile spacing is increased. The efficiency factors on the stratified soil profile indicated an intermediate behavior between the clay and the sand profile, getting close to the soil behavior where the pile tip is resting.

The impact of a connection between piles in a group as a consequence of being connected to a pile cap was also evaluated, fixing the piles through rigid elements for some models to later compared them with models where a connection of the piles in a group was not considered. The comparison indicated minor modifications of the efficiency factors, except for one case where the *s/D* ratio was of 8.

Table 6. Parameters that directly affects the efficiency factors.

s	center-to-center pile spacing
D	diameter of pile
ϕ	angle of internal friction
E	Young modulus
L/D	length to diameter ratio

The implication of an interface element between the pile shaft and the soil was also investigated. A modification of the shear strength of the interface did not show a major difference on the calculated efficiency factors. However, when comparing these factors with the obtained values from the models without an interface, an improvement was observed when applying this element and it reduces as the *s/D* ratio increases. Therefore, the use of an interface when evaluating the group effect through numerical model will depend strongly on what the researcher is searching to obtain using this type of element.

The efficiency factors (see Figure 5) obtained in this investigation can be applied during the foundation design for storage tanks using four variables that are simple to obtain from an engineering project:

a. Diameter of piles.
b. Center-to-center pile spacing.
c. Type of foundation soil.
d. Length to diameter ratio.

Nevertheless, further investigation is needed in order to obtain efficiency factors that apply for the wide variables involving the behavior of deep foundations such as the changes in pile capacity with time or the installation method.

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