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# COMPUTATIONAL MODELING AND PARAMETRIC STUDY OF PILE GROUPS

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**Abstract**

Geotechnics and the study of the behavior of soil with the construction inserted in it is of extrema importance. This study aims at the computational analysis of a group of three reinforced concrete piles with axial and horizontal loads. The piles were inserted in non-cohesive soil (medium and dense sand). The geometric parameters of the piles (diameter, distance between them, and length) and physical parameters of the soil (stratification and angle of friction between them) were varied. The GEO5 "Pile Group" program, the NAVFAC DM 7.2 method was used to determine the bearing capacity. The Poulos & Davis (1980) and FEM methods for settlement, and the p-y method (FEM) to determine the internal forces distribution. The efficiency of the piles is more sensitive the more the distance between them varies. For settlement, Poulos & Davis values are sensitive to distance and diameter, and in FEM they are more sensitive to diameter and length variation.

**Keywords:** Pile group. Computational analysis. Axial load capacity. Horizontal load capacity. Settlement. Group efficiency. Horizontal displacements. Seismic activity.


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## 1 INTRODUCTION

Knowing the soil and its movements is essential for structural design. Predicting soil behavior is a difficult task due to the heterogeneity of the rock or earth mass, which prevents precise and consistent characteristics. However, it must be ensured that there are no construction failures without over-design.

This study uses deep foundations, which dissipate the loads of the construction into deep soil beds. The objective is to determine the sensitivity of the bearing capacity (with the NAVFAC DM 7.2 method), settlement (Poulos & Davis (1980) and FEM methods), and group efficiency to variations in the piles and soil using the geotechnical analysis software GEO5 version 2020.

Soil has always occupied an important position in human evolution and engineering. The study of soil and its movement is known as geotechnics and dynamics. This knowledge helps to determine the physical and mechanical characteristics of soil, and thus to design its behavior under loads.

Usually, soil studies using empirical methods are found in the academy, which project local results for total volume. Even though they are close to the real ones, the results do not accurately describe soil behavior, which allows design errors. In deep foundations, the error can be even greater because they are inserted in numerous soil layers with different properties. Thus, the construction may encounter unexpected conditions and cause problems in the dispersion of loads.

Finally, studies such as this computer simulation are very important, enabling a range of information from different methods, soils, foundation solutions, and soil stratifications.

## 2 BIBLIOGRAPHIC REVIEW

Deep foundations are necessary when the uppermost soil layers are not strong enough for the building. Therefore, the foundation must reach deep into the soil. The pile group consists of elongated cylindrical or prismatic pieces, which can be precast or cast in the field, joined by a pile cap.

### 2.1 Load capacity

The distribution of structure loads through the piles is carried out in two components. The lateral frictional mobilization along the vertical axis, also called shear, is the $R_{sk}$ component. The tip or base resistance is the $R_{bk}$ component. All foundations use both components to transfer their loads. If more than 80% occurs through lateral resistance, the pile is called a floating pile. If 80% of the total occurs through tip resistance, the pile is called a tip pile. The sum of the two components results in the total load capacity of the pile ($R_k$).

For non-cohesive soils, the method of foundation execution must be considered. This is done using the coefficient $N_q$, which depends on the angle of internal friction of the soil. For stratified soil, the value corresponding to the greatest angle of friction should be used. The equations determine how the forces are calculated, and the tables show the fixed values.

$$q_{bk} = \gamma D N_q = \sigma'_{vb} N_q \tag{1}$$

$$q_{sk} = \sigma'_n \tan\delta = K \sigma'_v \tan\delta \tag{2}$$

Where: $\sigma'_{vb}$ Effective vertical stress at the base of the pile [kN/m$^2$]

$\sigma'_{v}$: Effective vertical stress in the pile vertical axis [kN/m$^2$]

$K$: Lateral thrust coefficient

$\delta$: angle of friction between soil and pile (¾ of angle of internal friction)

For the bearing capacity it should also be said that the greater the depth in the soil, the greater the limit capacity of the pile. The critical depth is the quota that determines constant capacity values and is determined by the figure below [5].

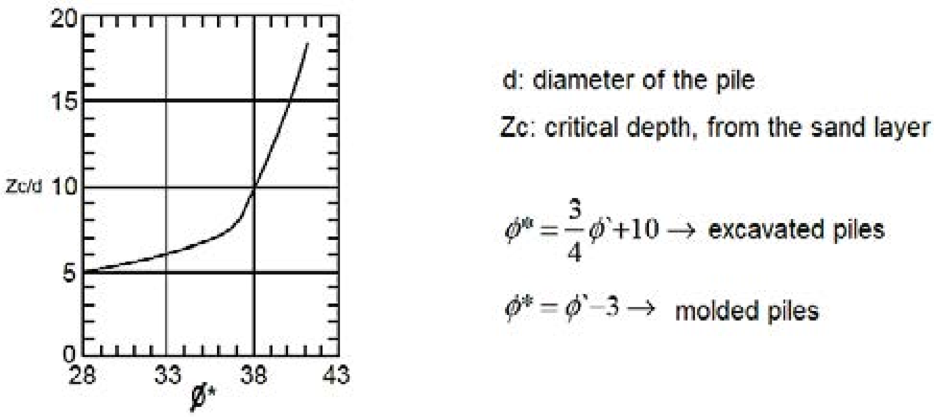



Figure 1: Abacus used for the calculation of the critical depth. [5]

### 2.2 Group load capacity

For a group of piles, Prakash & Sharma (1989) determine that the minimum value of distance between elements should be three times the value of the diameter. If this heat is not placed, the group may behave as a single block.

When piles are placed in a group, there is an influence on the distribution of stresses and soil movement between them, called the group effect. This effect causes the piles not to perform at 100% of their capacity.

The expression that calculates the actual load capacity value is shown below.

$$R_{k;G} = \eta * n * R_k \tag{3}$$

Where: $R_{k;G}$: Pile group load capacity [kN]

$\eta$: Group Efficiency Factor [-]

$n$: Number of piles in the group

$R_k$: Pile load capacity [kN]

To calculate the efficiency factor, there are numerous methods. But none of them is completely reliable, the most widely used being that of Converse-LaBarré (1941), whose equation is shown below.

$$\eta_g = 1 - \psi \left[\frac{(n_x-1)n_y+(n_y-1)n_x}{90 n_x n_y}\right] \tag{4}$$

Where: $\eta_g$: Efficiency of the pile group

$\psi$: Angle with tangent expressed in degrees $tg\psi = \frac{d}{s}$, where s is the axial spacing between piles and d is the diameter of the piles.

$n_x$: Number of piles in the x direction.

$n_y$: Number of piles in the y direction.

### 2.3 Horizontal load capacity and displacements

Besides axial loads, structures can suffer horizontal loads, generating displacements, rotations, and bending moments. These loads can occur due to structural requests or, mainly, due to internal soil actions (seismic activities).

For the construction to be safe regarding these loads, it must present materials and strength that avoid rupture and control deformations along the pile [1].

There are many possible methods for structural behavior analysis, but the one that stands out as to its simplicity and coherence with reality is the p-y method, based on the finite element method and Winkler's model (spring method) [2].

#### 2.3.1. Winkler Model (Spring Method)

This method was proposed in 1867, it considers the soil as a set of independent springs of elastic and linear behavior. The stiffness of these springs is numerically equal to the unit reaction coefficient of the soil ($k_h$). These values vary with the soil composition and vary according to the following table [2].

| Soil | k [MN/m3] |
|---|---|
| Dense sand | 155 – 300 |
| Medium Sand | 110 – 280 |

Table 1: Unit reaction coefficient of soils according to Bowles [2] (adapted).

The final equation of the model follows Hooke's Law, and relates the modulus of elasticity of the pile and the moment of inertia with the soil and its respective displacement.

To determine the resulting values, the pile is considered as floating, in addition to considering the soil characteristics and the type of connection that the pile makes with the heading massif (fixed or with joints).

The GEO5 software determines that you should reduce the stiffness of a unit pile according to the position it is in the group. For horizontal stiffness, the value is reduced by 50% for external positions and 25% for internal ones. As for vertical springs, the reduction is 50% and 10% for exterior and interior positions.

### 2.3.1. P-y method

The p-y curve is a solution of the equation from the previous method. The vertical axis represents the applied load P and the horizontal axis represents the displacement y of the structure. This curve is a non-linear relationship, but it is common to consider it as linear for simplification of the calculations. [2]

The main advantage of this method is that it does not depend on the geometry nor the stiffness of the piles, and it can be used for numerous practical cases [11].

As a disadvantage, Budhu (2013) points out that the method does not consider the soil continuity effect and does not consider the shear strength of the soil, which can generate differences between the calculations and what happens. [10]

## 2.4 Settlement

The settlement of a structure is the displacement of the soil around it, causing vertical displacement. The values can vary for each element of the structure, with the total value being the sum of each. The total value for a group of piles is many times greater than that of an isolated pile, since one element generates the influence over the other as already explained in the group effect. [10]

There are many possible methods to use to estimate settlement, and it is necessary to analyze which one best suit the needs of the project in question. These values are difficult to estimate, they depend directly on the history of stresses over the years in the soil, the way the loads dissipate, the construction method used, among many other factors. [11]

The two types of methods used in this study are that of Poulos & Davis 1980 (theoretical analytical) and that in the finite element method (empirical).

### 2.4.1. Finite element method (FEM)

The finite element method subdivides the pile into small segments, thus determining the displacement for each of them. The total settlement value is the sum of these results. The method also takes into consideration analysis points at the interface between the pile and the soil, promoting values more consistent with reality.

This method also uses the endometric modulus, which determines the compression that occurs in the soil when the foundation is inserted. The equation that determines the settlement of each layer is presented below.

$$s_i = \sum \frac{\sigma_{z,i} h_i}{\frac{E_{def}}{\beta}} \quad (5)$$

Where: $h_i$: Layer thickness i.

$\sigma_{z,i}$: Vertical component of the stress increase at the center of layer i.

$E_{def}$: Soil deformation modulus.

$\beta$ : Ground scattering angle.

### 2.4.2. Poulos & Davis (1980)

This method is based on the theory of elasticity and considers the soil to have constant and unchanging characteristics, so the soil is homogeneous, isotropic, and elastic. In addition, the authors consider the distribution of stresses along the shaft to also be uniform, and that the resulting settlement values are proportionally linear to the requesting loads.

To determine the maximum settlement of a unit pile, the method uses the equation below.

$$S_{máx} = \frac{R_{bk}}{\alpha d E_s} + \left[R_{bk} - \frac{R_{sk}}{(1-\alpha)}\right] \frac{L}{A_p E_p} \tag{6}$$

Where: $S_{máx}$: Maximum Pile Settlement.

$R_{bk}$: Peak load capacity.

$R_{sk}$ : Lateral load capacity.

$E_s$ : Average soil modulus of elasticity.

$d$ : Pile diameter.

$\alpha$: Proportion of applied load transferred by the base.

$A_p$ : Cross sectional area.

$E_p$ : Modulus of elasticity of the pile.

For group of piles, the study is an extension of the application for a single pile, with the total value multiplied by the group settlement factor. This factor depends on the distance between the elements of the group. The greater the distance, the lower the reduction factor, the inverse occurs for very close piles. The factor ranges from 1 (isolated piles) to values higher than 10 (piles working as a single block). Its use is presented by the equation below.

$$s_g = g_f \cdot s_0 \tag{7}$$

Where: $S_g$: Total settlement of the pile group.

$g_f$: Pile Group Settlement Factor.

$s_0$ : Laying of an isolated pile.

$\beta$ : Ground scattering angle.

## 3 WORK PROGRAM

This paper analyzes a group of three axially and horizontally loaded piles using the geotechnical analysis software GEO5 version 2020. The foundation is inserted in a non-cohesive soil (medium and dense sand). It was verified the behavior of bearing capacity, settlement, and efficiency of the pile group with the variation of geometric parameters of the piles and soil parameters. The diameter, length and distance of the piles, and the internal friction angle of the medium sand were varied. The Spring (Winkler) method was used for determining the displacements. For the load capacity study, the NAVFAC DM 7.2 method was used. Finally, for the settlement analysis was used the FEM and the method of Poulos & Davis (1980).

The following image represents the three-dimensional model, the stratification and the axes considered in the simulations.

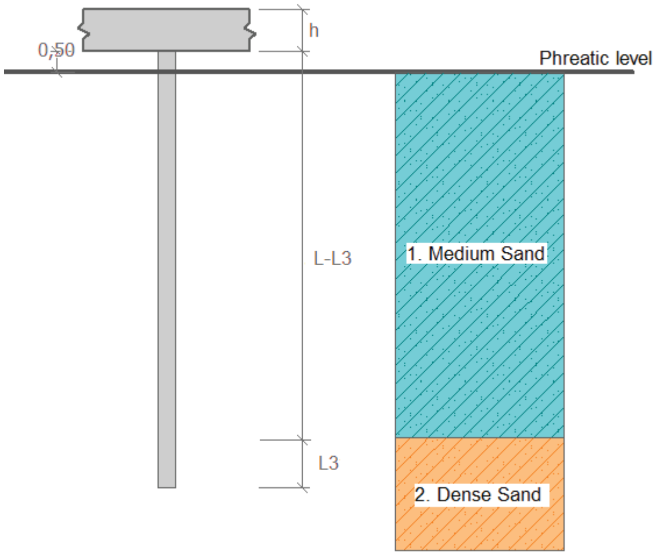



Figure 2: Representation of soil stratification [First author].

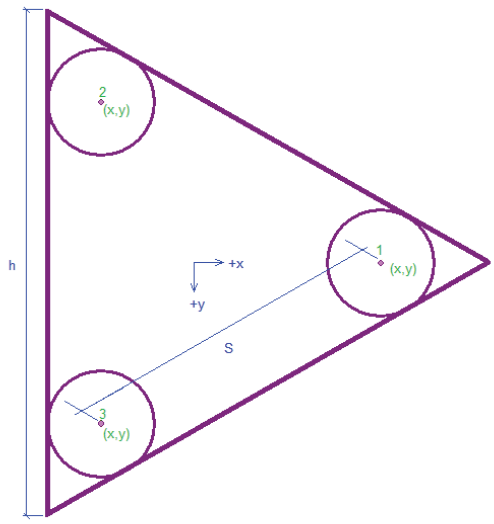



Figure 3: Top view of the pile group and representation of the axes used [first author].

The following tables show the variables and properties of the pile materials and the two soil types.

| Piles | |
|---|---|
| Number of piles | 3 |
| Length (L) | 10, 15 e 20 m |
| Diameter (D) | 0.4, 0.6 e 0.8 m |
| Ratio s/d (ratio between the distance and the diameter) | 2, 3 e 4 |
| Group efficiency $\eta_g$ (LáBarré) | 0.66, 0.76 e 0.82 |
| Axial loads | 1980, 2280 e 2460 kN |
| Horizontal loads | 396, 456 e 492 kN |
| Deformability modulus of concrete | $E_{def}$ = 29 GPa |
| Poisson coefficient of concrete | ϴ = 0.2 |
| Characteristic Strengths of concrete | $f_{ck}$ = 20 MPa (compression)<br>$f_{ct}$ = 2.2 MPa (traction) |
| Concrete elasticity modulus | $E_{cm}$ = 29 GPa |
| Tensile strength of steel | $f_{yk}$ = 500 GPa |
| Modulus of elasticity of steel | E = 200 GPa |

Table 2: Variables and properties of the pile materials [first author].

| Soil | | |
|---|---|---|
| Characteristic | Medium Sand | Dense sand |
| Soil Stratification (m) | L-L3 | L3=3xD |
| Poisson coefficient | ϴ = 0.35 | |
| Dry specific weight (kN/m3) | 19 | 21 |
| Saturated specific weight (kN/m3) | 21 | 23 |
| Soil modulus of deformability (MPa) | 50 | 150 |
| Unit reaction coefficient k (MN/m3) | 113, 128 e 143 | 240 |
| Internal friction angle Φ (º) | 26, 28 e 30 | 40 |
| Soil Cohesion (kPa) | 0 | |
| Critical depth | $k_{dc}$ = 12.5 | |

Table 3: Variables and properties of the soils [first author].

## 4 RESULTS AND DISCUSSIONS

To generate the results, the load capacity coefficient Nq was considered equal to 72, because it corresponds to the value for the 40º internal friction angle of dense sand.

In total 81 simulations were carried out, and problems were observed in some of them. The models with pile lengths of 15 and 20 meters, diameter of 0.4 meters and s/d ratio of 2 and 3, presented excess reinforcement (ratio) with the necessary sizing. However, they will be considered to recognize the sensitivity of the factors.

### 4.1 Load capacity

The analysis is separated in three parameters: the normal end strength ($q_b$), the shear strength ($q_s$) and the pile efficiency η. In the examples of each parameter the intermediate case was sought, which represents the simulations in its great majority.

#### 4.1.1. Normal tip resistance ($q_b$)

The tip strength indicates the stress that is transferred to the soil through the cross-sectional area of the pile. It was observed that by increasing the length of the piles, there was an increase in resistance. As for example in the 0.6 meters diameter model with the values are 5,974.43 kPa, 8,710.44 kPa (+45.8%) and 11,446.42 kPa (+91.6%) respectively at 10, 15 and 20 m.

With increasing diameter, the resistance hardly changes. As for example in the model with length 15 m, ratio s/d=3 and friction angle equal to 28º with strength of 8,650.72 kPa, 8,710.44 kPa (+0.7%) and 8,770.12 kPa (+1.4%) respectively at diameters of 0.4, 0.6 and 0.8 m.

As the distance between the piles increases, there is a considerable increase in resistance. This is what is seen in the example of length 15 m, diameter 0.6 m and internal friction angle 28º, with strength of 7,564.33 kPa, 8,710.44 kPa (+15.2%) and 9,398.10 kPa (+24.2%) respectively at s/d values of 2, 3 and 4.

With increasing the internal friction angle of the medium sand, no change in resistance occurs. As an example, the simulation of 15 m length, 0.6 m diameter and s/d=3 ratio, the resistance value of 8,710.44 kPa is the same for the 26°, 28° and 30° angles.

It was observed that what generates change in the ultimate strength is the variation in pile properties. The change in the soil friction angle does not affect the results.

#### 4.1.2. Shear or lateral resistance ($q_s$)

The lateral resistance indicates the dissipation of loads into the soil through the lateral area along the pile shaft. For the increase of the length of the pile, the lateral resistance hardly changes. As for example in the 0.6 meters diameter pile, s/d=3 ratio and 28º internal friction angle, with values of 22.69 kPa, 22.35 kPa (-1.5%) and 22.18 kPa (-2.3%) respectively for lengths of 10, 15 and 20 m.

For the increase in diameter, there is also an increase in resistance values. This is visible with the model with a length of 15 m, ratio s/d=3 and $\Phi$ =28º, and the values 15.17 kPa, 22.35 kPa (+47.3%) and 29.27 kPa (+92.9%) respectively for diameters of 0.4, 0.6 and 0.8 m.

When increasing the distance between the piles, an increase in resistance occurs. For example, the simulation of L=15 m, 0.6 m diameter and 28º friction angle, with lateral strength of 19.41 kPa, 22.35 kPa (+15.2%) and 24.12 kPa (+24.2%) corresponding to s/d ratios of 2, 3 and 4 in order.

Finally, for the increase of the internal friction angle of the medium sand, the resistance also increases a little. This can be verified in the example of length 15 m, diameter 0.6 m and ratio s/d=3, being the strength 21.80 kPa, 22.35 kPa (+2.5%) and 22.99 kPa (+5.5%) respective to angles 26º, 28º and 30º.

The following table summarizes the variations generally observed in the analyses and the sensitivity for each parameterization.

| Parameter | $Q_b$ | % medium | $Q_s$ | % medium |
|---|---|---|---|---|
| increase of L | increases | 50% | decreases and increases | 2% |
| increase of D | increases | 2% | increases | 50% |
| increase of s/d | increases | 15% | increases | 15% |
| Increase of $\Phi$ | equal | - | increases | 2,5% |

Table 4: Abstract of sensitivity of the strengths to the increase in the variables studied [first author].

#### 4.1.3. Pile efficiency (η)

The pile efficiency is given by the ratio between the total capacity and the theoretical excavated volume (Rc/V). As for increasing the length, diameter, and internal friction angle of the medium sand, one can notice derisory changes in efficiency (very low percentages).

The only parameter that generated significant changes in the load transmission efficiency was the increase in the distance between the piles. To exemplify, the simulation with 0.6 m diameter, 10 m length and internal friction angle of 28º, with efficiency of 650.23 kPa, 748.74 kPa (+15.2%) and 807.86 kPa (+24.2%) for s/d ratio of 2, 3 and 4 in order.

The most important thing to analyze in this topic are the values of the most and least efficient piles, which are represented by A and B in the following table.

| L | D | s/d | Φ medium sand | $R_s$ | $Q_s$ | $R_b$ | $Q_b$ | $R_c$ | $R_c/V$ | $R_s/R_c$ | $R_b/R_c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (m) | (m) | - | (º) | (kN) | (kN/m²) | (kN) | (kN/m²) | (kN) | kPa | (%) | (%) |
| 10 | 0.6 | 4 | 30 | 470.77 | 24.98 | 1822.59 | 6446.09 | 2293.36 | **811.11** | 20.5 | 79.5 |
| 20 | 0.4 | 2 | 26 | 316.73 | 12.60 | 1242.62 | 9888.47 | 1559.36 | **620.45** | 20.3 | 79.7 |

Table 5: Abstract of sensitivity of the strengths to the increase in the variables studied [first author].

With the previous table it is observed that the least efficient pile was characterized with the largest length, the smallest diameter, the smallest s/d ratio, and the smallest angle of internal friction of the medium sand. The best performing pile, on the other hand, was characterized by the shortest length, largest diameter, largest s/d ratio and largest angle of internal friction. In addition, it is observed that the percentage of load mobilization by lateral friction and by tip resistance in both cases are practically equal.

Finally, one should always remember that each project requires a thorough study of its needs, considering all available resources, material and financial.

### 4.2 Settlement

In this topic some simulations will be discarded. In the models with excess steel, the settlement by the Poulos & Davis method is not generated by the software. These are the simulations characterized by L=15 m, d=0.4 m and s/d=3 and 4, and L=20 m, d=0.4 m and s/d=3 and 4. Another group of simulations will not be used since, for no apparent reason, GEO5 also did not generate results, these are those for L=10 m, d=0.4 m and s/d=3 and 4.

#### 4.2.1. FEM

In this method all piles were considered as floating, with the value of the tip resistance equal to zero and the loads distributed only along the shaft.

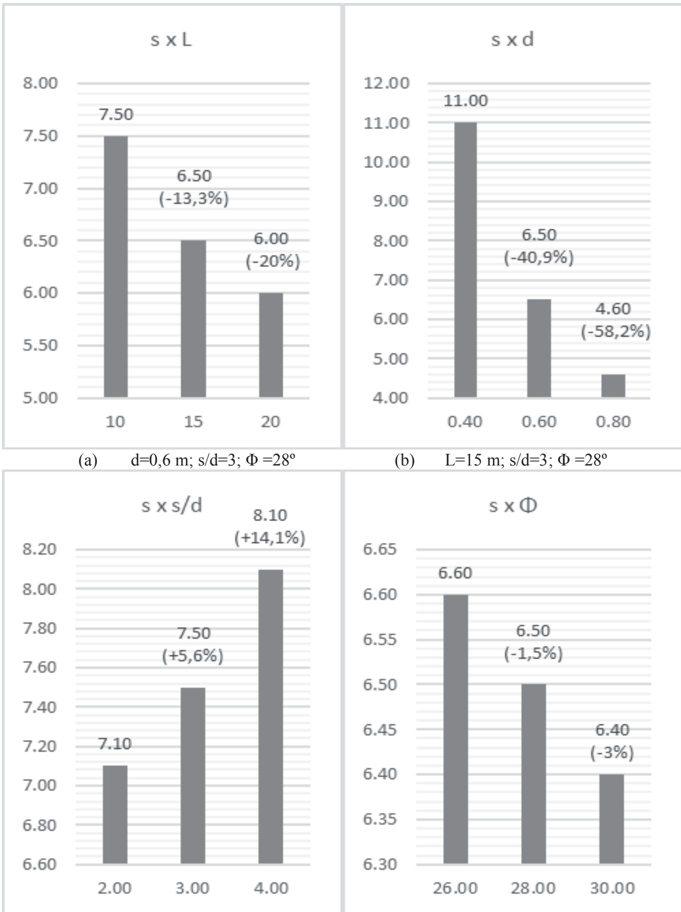
For the increase in length, a decrease in settlement was observed. As for example the model with 0.6 m diameter, internal friction angle 28º and s/d ratio equal to 3, and maximum settlement values of 7.50 mm, 6.50 mm (-13.3%) and 6.00 mm (-20%) for the lengths 10, 15 and 20 m.

With the increase of the diameter, there was a reduction of the maximum settlement. This is exemplified by the model with length equal to 15 m, angle Φ=28º and distance ratio between piles equal to 3, with values of 11.00 mm, 6.50 mm (-40.9%) and 4.60 mm (-58.2%) of settlement, respective to diameters of 0.40 m, 0.60 m and 0.80 m.

The increase of the distance between the piles generated an increase in the final maximum settlement. As for example the model L=10 m, diameter of 0.60 m and Φ=28º with values of 7.10 mm, 7.50 mm (+5.6%) and 8.10 mm (+14.1%) of maximum settlement for s/d ratios of 2, 3 and 4.

Finally, for the increase of the angle of internal friction, a decrease in the maximum settlement value is observed. Which can be verified with the example of L=15 m, s/d= 3 and diameter d=0.6 m, with values of 6.60 mm, 6.50 mm (-1.5%) and 6.40 mm (-3%), for Φ of 26º, 28º and 30º in order.

The above data is shown in the graphs below.




(a) d=0,6 m; s/d=3; Φ =28º (b) L=15 m; s/d=3; Φ =28º

(c) L=10 m; d=0,6 m; Φ =28º (d) L=15 m; d=0,6 m; s/d=3

Figure 4: Finite element method settlement plotted A through D [first author].

### 4.2.2. Poulos & Davis (1980)

In this method a limit settlement of 25 mm was pre-established if the value did not reach the critical settlement of the structure (foundation rupture).

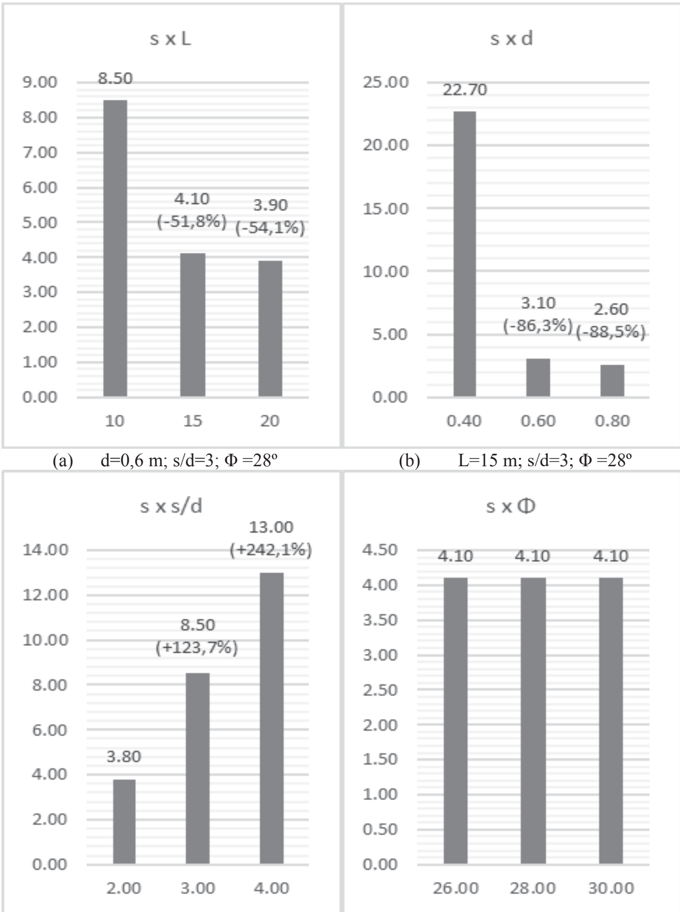
As the length of the piles increased, a reduction in settlement was observed. As for example in the model with diameter 0.6 m, internal friction angle equal to 28º and s/d ratio equal to 3, the verified values are 8.50 mm, 4.10 mm (-51.8%) and 3.9 mm (-54.1%) for the lengths 10, 15 and 20 m.

For the increase in diameter, the settlement showed a reduction. This is observed with the example L= 15 m, angle Φ=28º and ratio s/d= 3, the settlements are 22.70 mm, 3.10 mm (-86.3%) and 2.60 mm (-88.5%), respective to diameters of 0.40 m, 0.60 m and 0.80 m.

With the increase of the distance between the piles, the settlement values increased by approximately 35% in most cases. However, the most unfavorable case will be used as an example. In the model with d=0.60 m, Φ=28º and L=10 m, the values are 3.80 mm, 8.50 mm (+123.7%) and 13.00 mm (+242.1%) for s/d equal to 2, 3 and 4, in order.

Finally, for increasing the internal friction angle of the soil, no change was observed in the settlement values.

The above data is shown in the graphs below.




(a) d=0,6 m; s/d=3; Φ =28º (b) L=15 m; s/d=3; Φ =28º

(c) L=10 m; d=0,6 m; Φ =28º (d) L=15 m; d=0,6 m; s/d=3

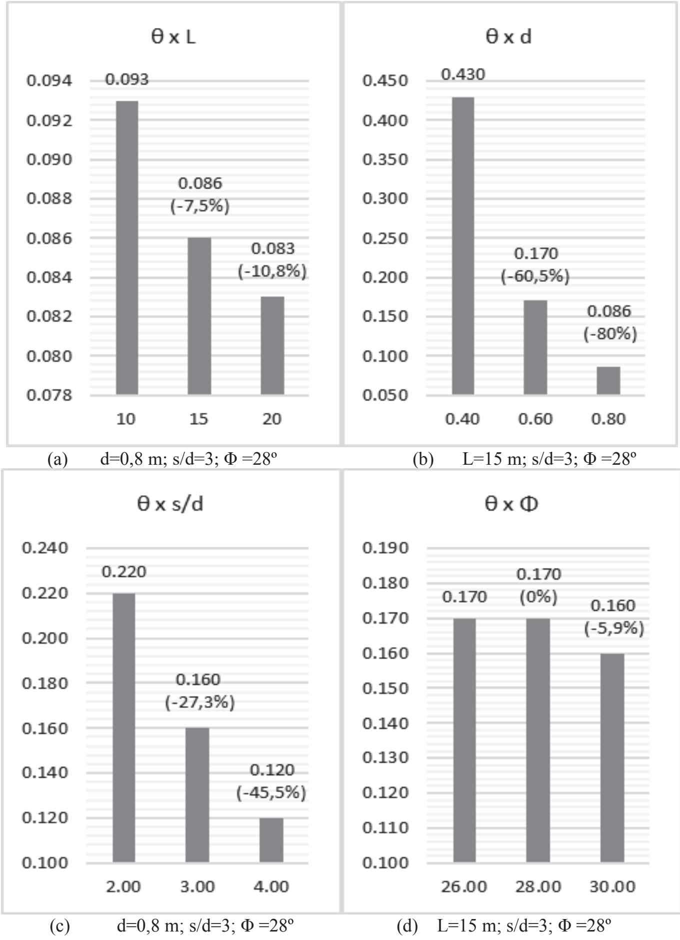
Figure 5: Poulos & Davis (1980) method settlement plotted A through D [first author].

### 4.3 Maximum rotation and displacement of the piles

In this topic it was observed that both increasing the geometric parameters (length, diameter, and distance between the piles) and increasing the angle of internal friction causes the rotation to decrease.

The following graphs show the variation of rotation at the pile head in degrees (y-axis) as a function of the change of parameters cited (x-axis).

The parameter that caused less change in the rotation of the piles was the increase of the internal friction angle of the medium sand, as shown in the images below.



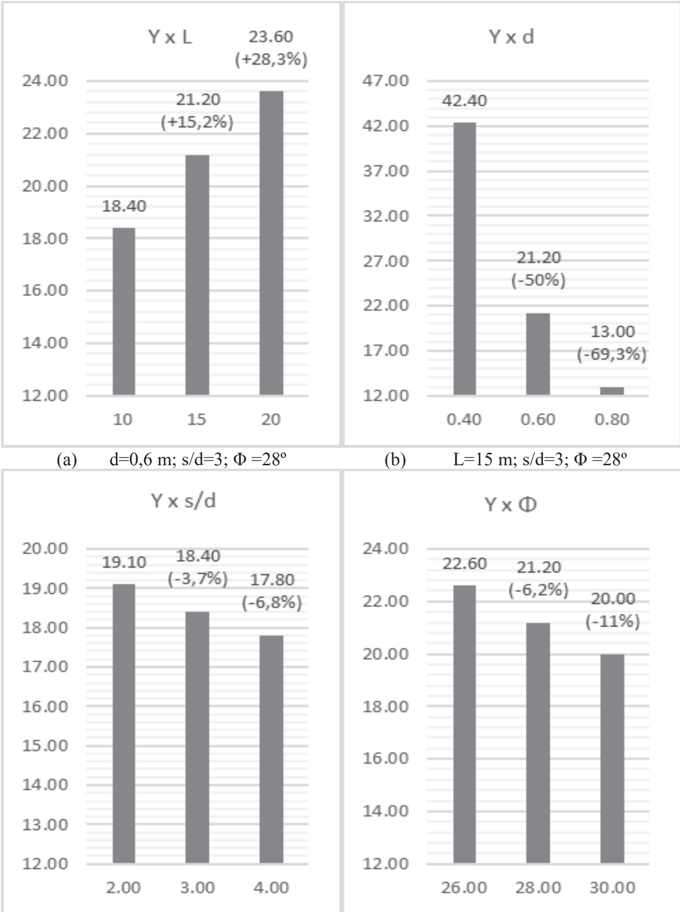
(a) d=0,8 m; s/d=3; Φ =28º
(b) L=15 m; s/d=3; Φ =28º
(c) d=0,8 m; s/d=3; Φ =28º
(d) L=15 m; s/d=3; Φ =28º

Figure 6: Maximum rotation at the pile head plotted A through D [first author].

For the maximum displacement, an increase only occurs when the length of the pile is changed. For the other parameters there is a decrease in the final values. The following graphs illustrate the percentage of variation of the displacements.

It can be observed that the change that generated the greatest reduction in displacement was the increase in pile diameter.

Finally, it is important to say that all the values presented are negative due to the direction of the axis where the horizontal loads were applied. To facilitate the visualization of the variations, the values are presented as positive, being the y axis the displacement in millimeters and the x axis the variation of the parameters.




(a) d=0,6 m; s/d=3; Φ =28º (b) L=15 m; s/d=3; Φ =28º

(c) L=10 m; d=0,6 m; Φ =28º (d) L=15 m; d=0,6 m; Φ =28º

Figure 7: Maximum displacement at the pile head plotted A through D [first author].

## 5 CONCLUSIONS

From the 81 analytical models studied, it can be concluded that the ultimate strength of the piles increases according to the increase of the length and the distance between the group elements. As for increasing the diameter and the angle of internal friction of the medium sand, the change is insignificant. The shear strength shows increase when the values of distance between piles and diameter are increased. With the increase of pile length and angle of internal friction, the change is insignificant.

One of the most important parameters of this study is the efficiency of the cuttings. For this topic, it was observed that the only change that causes efficiency reduction is the increase in length. For alterations in the other parameters there is always an increase, with the distance between the piles being the variable that generates the highest percentage of increase. Furthermore, it can be observed that the most efficient pile has 31% higher results than the least efficient, shown in the item 4.1.3.

In the settlement through the method of Poulos & Davis (1980), the values increased only with the increase of the distance between piles. For the other variables, a decrease in the total values was observed. On the other hand, in the FEM analysis, the increase of all variables studied caused the decrease of the maximum settlement value.

The comparison of the settlement methods allows us to conclude that, in approximately 81% of the cases, the settlement results presented by FEM are higher than those presented by Poulos & Davis (1980) methods. This result was already expected, since the FEM considers analysis points at the soil-pile interfaces and express more faithfully the actual changes that occurred. Moreover, the values obtained by the Poulos & Davis method presented a high percentage of variation between them, making it difficult to recognize a pattern of variation.

In the strain analysis, both the maximum rotation and the maximum displacement were identified in the pile head. In the rotation, there is a decrease in the results with the increase of all changed parameters. The increase in diameter was the one that generated the highest average percentage influence.

For the $Y_x$ displacement, the only factor that increased the results was the increase of the length of the piles. Increasing the other variables generated decreases in considerably high percentages.

Finally, if the objective of the structural project is the reduction of the maximum rotation in case of higher horizontal loads, the increase of the pile's diameter would be the main factor for this correction. It is important to remember that any project alteration can imply in problems in the execution of the foundation or in the economics of the enterprise. It is indispensable that a thorough study be carried out, since it may require a larger excavation area or major changes in the reinforcement sizing. Besides, when resuming the previous conclusions, the increase of the pile diameter has almost no influence in the improvement of the pile efficiency.

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