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FOUNDATION OPTIMIZATION OF PREFABRICATED PILES

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Abstract. The prefabricated foundations of concrete are deep piles driven in situ with a high-quality concrete, due to its regularized and controlled production at factories. This concrete can be reinforced or prestressed so it can resist flexure, traction and shear force within the soil, and even during the transport and handling. The prefabricated pile to be treated in this current study is the centrifuged pile, which has a circular hollow section. This type of piles has a high-quality concrete, less self-weight, cheap cost of machinery (pile driver) and dispensable digging. Under the eyes of sustainability, nowadays people concern a lot about the reduction of construction supplies, avoiding the excessive waste of those. The objective of this research is to optimize the calculus of prefabricated concrete piles sizing with circular hollow section to minimize the involved components, consequently reducing the final cost of the item. In the optimization problem, the project variables are the diameter, the thickness and the length of the piles, the objection function is the volume, and the project constraints are defined by the ABNT norms. Therefore, in order to optimize, it's needed to evaluate the bearing loads, and the soil and pile structure resistance, searching for an optimal cost, ensuring the safety of the construction with less consumption of steel and concrete, attending to the project constraints. Thus, will be used the Excel's function SOLVER, allied with the semiempirical methods described by Aoki-Velloso (1975) and Décourt-Quaresma (1978) to obtain optimal project values.

Keywords: Optimization, prefabricated piles, geotechnics, centrifuged concrete, structural calculus

1 Introduction

Foundations arose with the need to stabilize and transmit building loads to stronger soil layers, ensuring safety and reliability to withstand the stresses of construction [1].

This article focuses on the prefabricated concrete piles with hollow circular section. This is a deep, indirect pile driven into the ground. Widely used in Brazil, despite the numerous other foundations available in the market, due to the good quality of the concrete, lower self-weight (hollow section), cheap machinery cost (pile divers) and no excavation required.

From the analysis of the soil, the dimensions of pile thickness and length and the requesting loads, respecting the technical standard NBR-6122 [2], aiming to reach the ideal of "Optimal Design" for the manufacture of these piles, where the goal is to make a structural optimization with the best performance of all possible parts to get the most cost effective product. Thus, the project aims to optimize the manufacturing of prefabricated piles.

The structural optimization of prefabricated piles will be solved by applying Numerical Methods to Structural Engineering, for this will have the Finite Element Method (FEM) and Mathematical Programming.

2 Bibliographic review

Prefabricated Concrete Piles are slender reinforced/prestressed structural elements that are driven into the ground by pile-driving equipment, which has an automatic or free-falling hammer that causes ground and surroundings vibrations. They are usually prefabricated in specialized firms, with their well-defined responsibilities, or on the building site, always in a process under strict control [3]. The length can vary from 6.0 to 12.0m because of transport restrictions, and at the ends there are metal welds for eventual amendments.

As already mentioned, the optimization process will only be done with hollow circular piles (Figure 1), produced through the centrifugation of the piece, a process also known as centrifugal thickening NBR 16258 [4]. The centrifugation ensures the removal of part of the water from the mixture, which decreases the water/cement factor and increases the mechanical strength of the piece and its impermeability. It also has a lower self-weight compared to the solid piles, which facilitates its transport and handling.

Figure 1. Centrifuged concrete piles (SCAC. Available at: < http://scac.com.br/> Access in May 17, 2017.)

However, according to NBR-6122 [2] the dimensioning of the pile should not only be done to support the acting efforts, but also those resulting from handling, transportation, lifting and pile driving.

To determine the geotechnical load capacity of the soil it is necessary to investigate its properties. In Brazil, the most popular method for this is the SPT test, "Standard Penetration Test", in which NBR-

6484 [5] describes the crimping of a standard sampler under the action of a standard 65 kg hammer, at a height of 75 cm. From the survey data a soil profile is built, revealing the stratigraphy with its classification, compactness and consistency.

There are numerous studies that statistically correlate SPT test data with soil mechanical properties. Alonso [6] uses the results obtained from percussion drilling to estimate the load-settlement curve of piles. Décourt [7] evaluates the energy of the SPT and normalizes the values of N_{SPT} with referential energies. Neves [8] presents a methodology for determining the efficiency of the SPT based on the Hamilton Principle and performing static load testing on the sampler. Ruver [9] presents a semi-empirical methodology for estimating the behavior of shoes resting on residual soils from the statistical correlation of results from simple recognition probes (N_{spt}) with the admissible stress and the settlements under work stress.

3 Problem description

3.1 Load bearing capacity of piles

Piles are structural foundation elements with the objective of carrying the load from the ground surface to deeper layers that have a good geotechnical bearing capacity. In order for these structural elements get to be considered as piles, they must have a minimum length [12] of

$$L_{min} = 4T \,, \tag{1}$$

where T eguals

$$T = \sqrt[5]{\frac{EI}{\eta_h}}. \tag{2}$$

where E is the modulus of elasticity of the concrete; I is the moment of inertia of the cross section of the pile and η_h is the constant coefficient of the horizontal reaction of the soil. A usual estimate for this last magnitude is the value of $50 \times N_{spt\ average}$ ($N_{spt\ average}$ is the average value of the SPT “Standard Penetration Test” along the side of the pile).

The load bearing capacity refers to the maximum load supported by the soil-foundation system before the soil or structural element (pile) ruptures. For the analysis of the load bearing capacity of piles, there are two main methods used in Brazil: load testing or the use of static formulas by semi-empirical methods [11]. In the present work, it was opted for the use of semi-empirical methods to determine the load bearing capacity of the pile during the optimization process.

The semi-empirical methods addressed in this research are obtained through soil properties in adapted theories of Terzaghi’s soil mechanics. The methods chosen for this work are Aoki-Velloso and Décourt-Quaresma [11], which were resubmitted in 1982 and 1987.

According to Alonso [11], two resistance parcels present in piles are considered: lateral friction (r_L), between the soil layers and the pile stem, Eq. (3), and the tip resistance (r_P), between the soil layer and the base of the pile, Eq. (4). The sum of these two parcels is equal to the rupture load (PR), Eq. (5). However, it should be taken into account a safety factor [2], thus obtaining an admissible load (C_{adm}), Eq. (6) that must be greater than or equal to the requesting load (C_k).

Thus for both methods, it is considered:

$$PL = U\Sigma(\Delta\ell \,.\, r_\ell) \tag{3}$$

$$PP = A \,.\, r_p \tag{4}$$

$$PR = PL + PP \tag{5}$$

$$C_{adm} = \frac{PR}{2} \tag{6}$$

Where U is the perimeter of the stem's cross section; A is the projection área of the pile's tip; $\Delta\ell$ is the section where r_ℓ is assumed as constant and PR is the rupture load.

The difference between the methods relies on the estimate between the values of de r_L and r_P [11].

The value "A" (area) of the hollow prefabricated piles it is considered as solid, due to its bushing in the driving [12].

3.2 Structural dimensioning of the pile

For a given pile geometry and a type of soil, the pile's bearing load capacity is obtained. The body of the pile, within the ground and during its drilling, must withstand the axial forces imposed on it. For this, NBR 6118 [13] and Alonso [11] describe the calculation of the Maximum Compression Normal through the following equation:

$$N_{rcd} = \frac{(0{,}85\ .f_{cd}\ .A_C) + (A_S\ .f_{\gamma d})}{\left(1 + \frac{6}{h}\right)} \tag{7}$$

where $f_{cd} = f_{ck}/\gamma c$ (concrete design strength); $f_{\gamma d} = f_{yk}/\gamma s$ (steel design strength); A_C is the área of concrete; A_S is the área of steel e h is the diameter of the piece.

As security, the value of N_{rcd} must be decreased by y_f.

$$N_{rck} = \frac{N_{rcd}}{y_f} \tag{8}$$

As for the steel area, two situations must be considered: the minimum area, defined by 0.5% of the concrete area, Eq (9), or the area of steel calculated according to the characteristics of the pile.

$$As_{min} = 0{,}5\%\ .\ A_c \tag{9}$$

When hoisted, a bending moment diagram appears in the piece. The most critical situation is the lifting by the GC or the extremities. The lifting process induces dynamic forces in the prefabricated elements, which are represented by the impact coefficient γ_d . Thus, the bending moment of calculus is given by:

$$M_d = \gamma_f\ .\ \gamma_d\ .\frac{q\ .\ l^2}{8} \tag{10}$$

Being γ_f in function of the variable loading – construction variable. In hoisting, the piece is considered to be horizontal and therefore the axial force is zero (N_d = 0). With the values of N_d e M_d, the dimensionless ν and μ, respectively, are calculated. For each value curve there is an reinforcement rate ω, forming an abacus in a rosette (figures 2 and 3), and depending on the ratio d´/h, there are two distinct interaction diagrams, according to d'/h = 0,05 ou d'/h = 0,1. Thus:

$$d' = c + \emptyset_t + \frac{\emptyset_l}{2} \tag{11}$$

where c is the covering of the reinforcement, Φ_l the diameter of the longitudinal reinforcement and Φ_t the diameter of the transverse reinforcement (coils).

Therefore, from the interaction diagrams (rosette abacuses), between the bending moment (μ) and the normal force (ν), for the relation d'/h, the possible reinforcement rates (ω) is defined, and then the area of steel needed to the piece as well.

$$A_S = \frac{\omega\ .\ A_C\ .\ f_{cd}}{f_{\gamma k}} \tag{12}$$

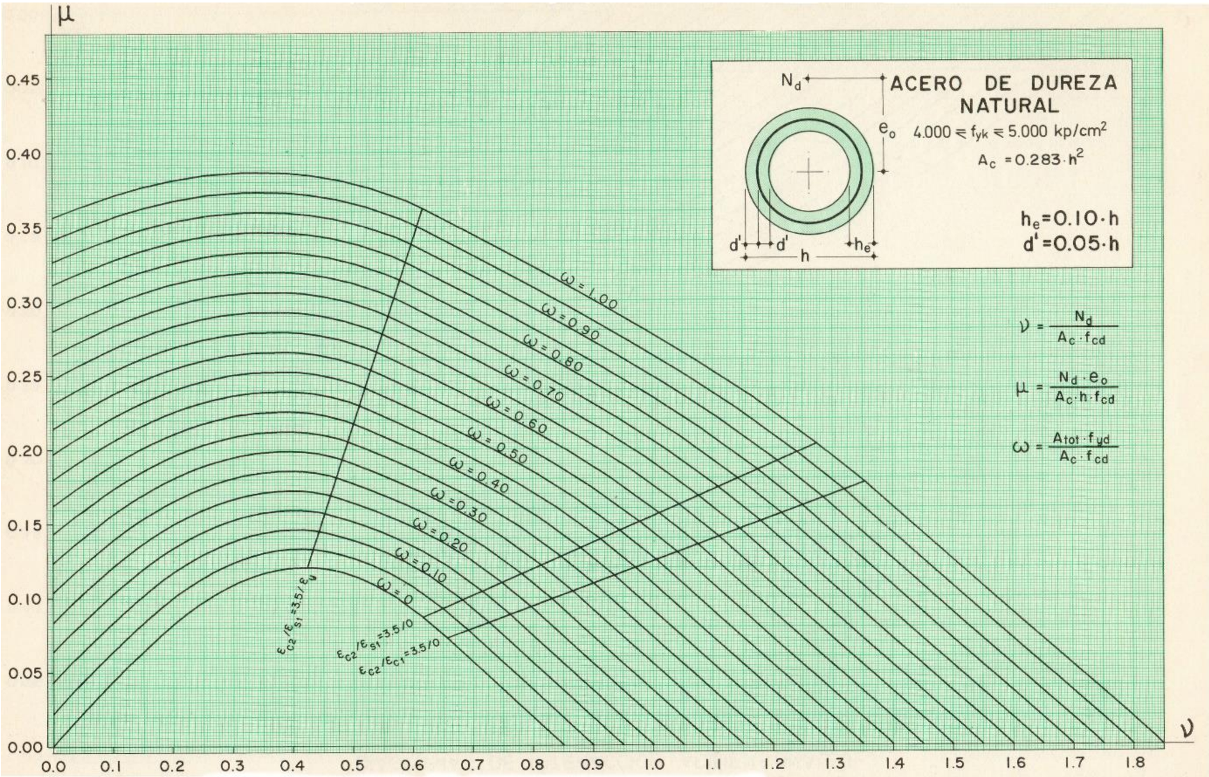

Figure 2. Interaction Diagram ν x μ, with $d'/h = 0.05$, to circular hollow section. [14]

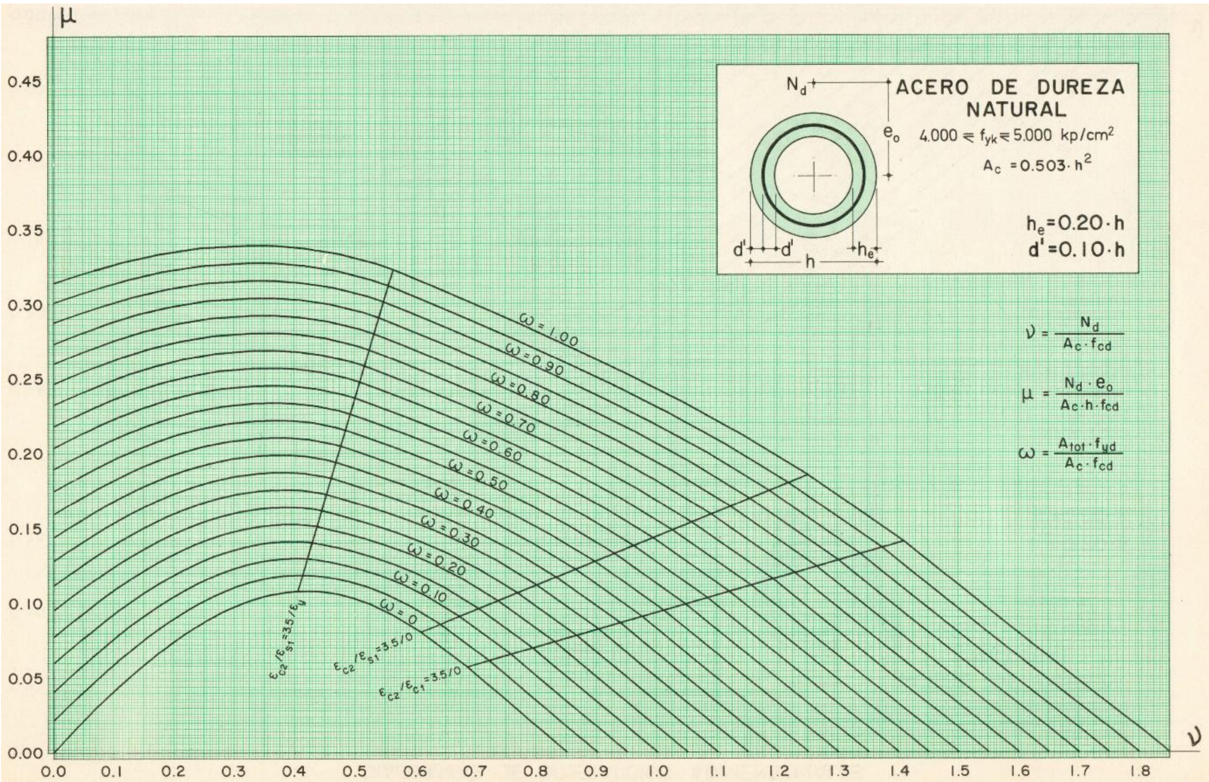

Figure 3. Interaction Diagram ν x μ, with $d'/h = 0.1$, for circular hollow section. [14]

For cracking, according to NBR-6118 [13], cracks occurring in reinforced concrete must not exceed 0.20 mm to 0.4 mm. Thus, two parameters of cracks characteristic opening on the concrete surface (w_k) are defined:

$$w_{k1} = \frac{h}{12{,}5\eta_1}\frac{\sigma_{si}}{E_{si}}\frac{3\sigma_{si}}{f_{ctm}} \tag{13}$$

and

$$w_{k2} = \frac{h}{12{,}5\eta_1}\frac{\sigma_{si}}{E_{si}}\left(\frac{4}{\rho_{ri}} + 45\right), \tag{14}$$

where h is the diameter of the piece; σ_{si} is the tensile stress at the center of gravity of the reinforcement considered; η_1 is the coefficient of surface conformation of the bars; E_{si} is the modulus of elasticity of the bar steel; f_{ctm} is the concrete strength at medium traction and ρ_{ri} is the armature rate. The value to be used in the design will be the lowest value between w_{k1} and w_{k2}.

4 Pile design optimization

4.1 The problem of optimization

The classical optimization process starts from an initial design, or from a group of initial designs, that is improved according to a certain optimization method.

A general optimization problem can be formulated in the standard form that follows. Being a problem defined by the values of a vector of *n* **design variables**

$$\boldsymbol{x} = [x_1 \quad x_2 \ \dots \ x_n]^T, \tag{15}$$

Minimize an **objective function** $f(\boldsymbol{x})$, subject to **equality constraints**

$$h_j(\boldsymbol{x}) = 0, \qquad j = 1, \dots, p, \tag{16}$$

And **equality constraints**

$$g_i(\boldsymbol{x}) \leq 0, \qquad i = 1, \dots, m, \tag{17}$$

The functions *f, g and h*, can be, in general, non-linear.

As mentioned, the main objective of this work is to develop an automatic spreadsheet for the optimization of prefabricated piles. The optimization in question aims to minimize the cost of the solution.

The initial element to be considered in the design is the soil, because due to the diversity of the soils in the planet, there is an infinite of combinations of components (water, air, mineral particles and organic matter), that results in different physical and mechanical characteristics. It is necessary, therefore, that the spreadsheet to be developed can consider this fact and receive this data (inputs) in a simple way, so that the user can easily insert and recalculate the optimal design.

Another important point to be made is the comparison between the optimal designs obtained for a given load and soil, with those presented in the catalogs of the manufacturers of precast piles. The current market offers standardized options for distinct workload values. These options often result in waste of materials and consequently of money, since the tables present discrete values of load. In the case of piles with circular hollow sections, the external diameters are also standardized, but wall thicknesses and special reinforcements can be modified for special designs, within certain predefined limits.

In order to optimize the design, it is necessary to evaluate the working loads, the structural strength, as well as the resistance of the soil (geotechnical resistance), seeking an optimum cost, guaranteeing the construction safety with a lower possible consumption, taking into account the design restrictions defined by ABNT standards. Thus, the Solver function of Excel will be used, coupled with the semi-empirical methods named Aoki-Velloso and Décourt-Quaresma [11] to obtain the optimal design.

4.2 Design variables

The design variables, individually, represent certain parameters of a certain design [15]. These values are independent of each other and constantly changed during the optimization process as requested by tool of the problem solver.

The choice of variables is a relevant step, because the more variables the design has, the more detailed it is.

In this work the variables will be represented by a vector $\boldsymbol{x}$.

$$\boldsymbol{x}^T = [x_1 \quad x_2 \quad x_3 \dots x_n], \tag{18}$$

being n the total number of design variables.

In this present study, were considered three design variables that consist of three geometric quantities that must be altered to obtain the optimal design. The design variables are given by the vector:

$$\boldsymbol{x}^T = [x_1 \;\; x_2 \;\; x_3] = [h \;\; e \;\; L], \tag{19}$$

where $x_1 = h$ is the outer diameter, $x_2 = e$ represents the thickness and $x_3 = L$ the length of the pile.

The diameter of the pile is a key feature of the design, since the lateral and tip resistances depend directly on this variable. In the market, the value of the pile is tabulated according to the diameters. The thickness variable design must contribute to the structural strength, in addition to serving as protection to the armor, saving it from attack by aggressive agents. The greater the armor cover, the greater the thickness. The diameters of the reinforcement bars also influence the thickness values. The length setting should take into account that the pile must reach depths that provide lateral and endurance resistance that fulfill the design requirements.

4.3 Constraints

Constraints are a set of limitations imposed on the system. They can be of inequality and equality, indicating, respectively, maximum or minimum values that must not be exceeded, or values that must be reached.

The standards NBR-16258 [4] and NBR-6118 [13] prescribe various limits, maximum or minimum, that must be obeyed in the design of a prefabricated pile. These limits have been translated here as design constraints, which are shown below:

- Workload:

$$C_{adm}(\, x \,) \geq C_k \quad : g_1 \tag{20}$$

- Minimum Thickness:

$$e \geq e_{min} \quad : g_2 \tag{21}$$

- Maximum Thickness:

$$e \leq e_{max} \quad : g_3 \tag{22}$$

- Minimum Diameter:

$$h \geq h_{min} \quad : g_4 \tag{23}$$

- Maximun Diameter:

$$h \leq h_{max} \quad : g_5 \tag{24}$$

- Minimum Lenght:

$$L \geq L_{min} \quad : g_6 \tag{25}$$

- Normal Maximum Compression:

$$N_{rck}(\, x \,) \geq C_k \quad : g_7 \tag{26}$$

- Maximun Cracking:

$$w_k(\, x\,) \leq w_{kmax} \quad : g_8 \tag{27}$$

Mathematically, in an optimization problem, the inequality constraints are written as $g_i \leq 0$, *i*=1,...,8. inequality constraints.

So, the constraint functions are rewritten as it follows:

$$g_1 = C_k - C_{adm}(\, x\,) \tag{28}$$

$$g_2 = e_{min} - x_2 \tag{29}$$

$$g_3 = x_2 - e_{max} \tag{30}$$

$$g_4 = h_{min} - x_1 \tag{31}$$

$$g_5 = x_1 - h_{max} \tag{32}$$

$$g_6 = L_{min} - x_3 \tag{33}$$

$$g_7 = C_k - N_{rck}(\, x\,) \tag{34}$$

$$g_8 = w_k(\, x\,) - w_{kmax} \tag{35}$$

4.4 Objective Function

The objective function corresponds to a unique value, connected with the whole design by agglutinating it. It must optimize the design in order to maximize it, minimize it or reach a desired value.

The volume of concrete is the most important data of the design, since from it is known the quantity of steel to be used, it is understood then that, optimizing the volume, it optimizes the whole design. Therefore the concrete volume will be the objective function.

The volume of a hollow cylinder is given by

$$V = \frac{\pi}{4} \,.\, L\, [h^2 - (h - 2e)^2] \tag{36}$$

The objective function is written as:

$$f(\boldsymbol{x}) = \frac{\pi}{4} \,.\, x_3 \;\; [\, {x_1}^2 - (\, x_1 - 2\, x_2)^2] \tag{37}$$

4.5 Numerical data

When subjected to stress, the materials exhibit mechanical properties that indicate their ability to deform and resist. The materials studied were soil, concrete and steel. The properties of the soil have already been discussed in item 3.1. The geotechnical profile considered in this work is represented in Figure 8. Refers to a soil in the city of Recife-PE.

The concrete applied in the design has a characteristic compressive strength (f_{ck}) of 40 MPa. The steel used in the design was ribbed surface rebar in CA-50 steel with flow resistance ($f_{\gamma k}$) of 500 MPa, modulus of elasticity (E_s) of 210 GPa and η_1 equals to 2.25.

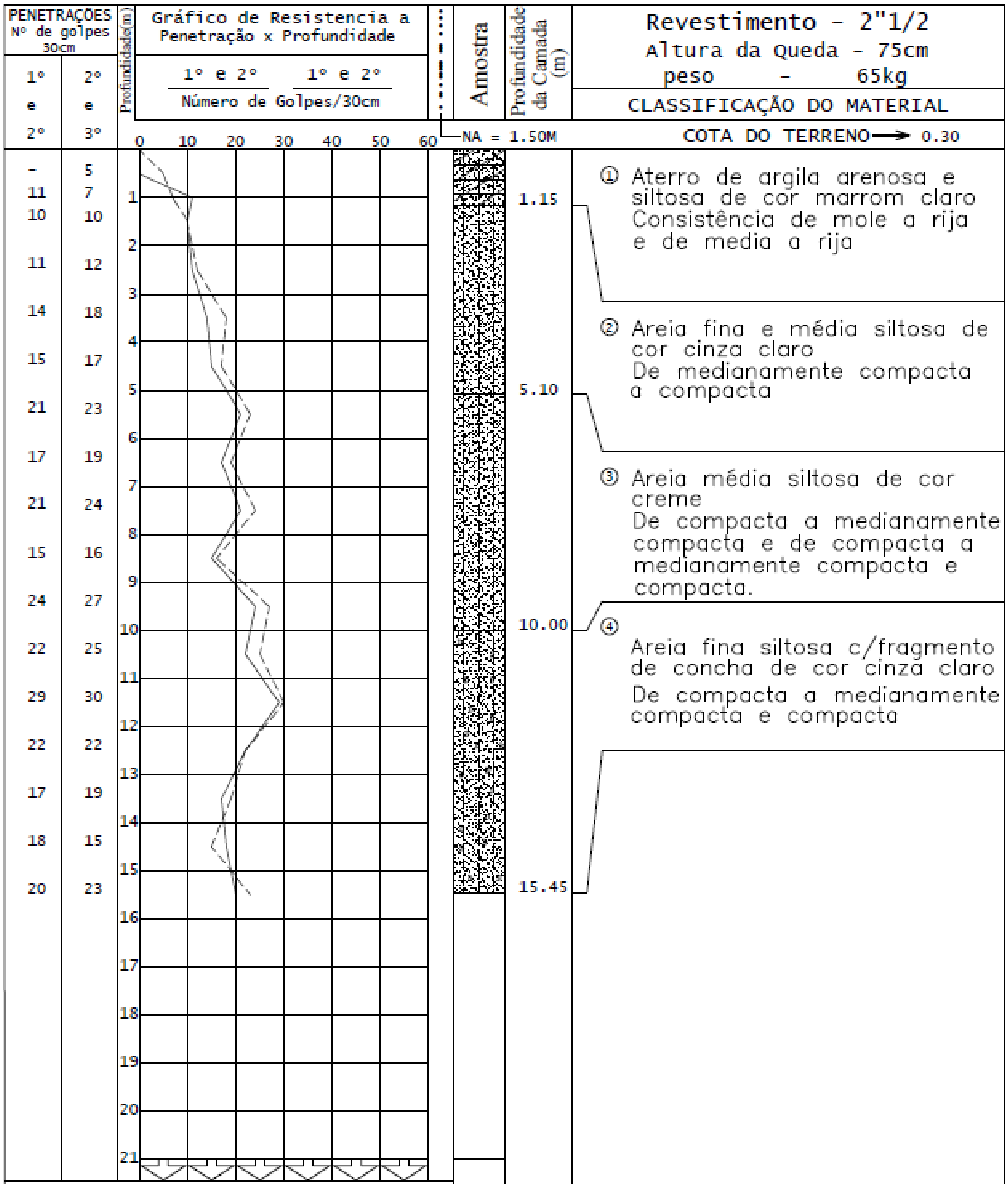

Figure 4. Profile of the soil adopted (Personal archive)

The standard length of the piles used in this work are shown in the table 1 below.

Table 1. Standard length based on diameter

h (cm)	*L* (m)
26	10.0
33	11.0
38 - 100	12.0

Source: Authors

For cracking, it was adopted a maximum value of 0.30 mm for the cracks opening, according to NBR-6118 [13] for environmental aggression class II and III. However, through the analysis of the optimal designs obtained, the cracks values varied between two numbers: 0.22 and 0.28 mm. Cracks of 0.22 mm were calculated on piles with *h* less than or equal to 33 cm, and piles with *h* greater than 33 cm, the crack was 0.28 mm. These cracks opening values were calculated for the bending stresses due to the lifting of the piece.

In order to make the design practical and applicable, minimum and maximum diameters were determined for the hollow piles, respectively equal to 26 cm and 100 cm. For thickness, minimum and maximum values were also adopted. The minimum thickness is defined based on the diameter (table 2) and for intermediate values described in the table, linear interpolation is performed based on the diameter. The maximum thickness must not exceed the cross-sectional radius. In relation to the longitudinal and transverse reinforcements, a relation between the diameters of the piles and the gauges of the reinforcements was defined (table 3).

Table 2 – Minimum thickness based on the pile's diameter.

h **(cm)**	e_{min} **(cm)**
26	6
33	7
38	7
42	8
50	9
60	10
70	11
80	12
100	15

Source: Authors

Table 3 – Reinforcement gauges based on the pile's diameter.

h (cm)	Φl (mm)	Φt (mm)
26 - 28	6.30	4.20
29 - 41	8.00	5.00
42 - 59	10.00	6.30
60 - 69	12.50	6.30
70 - 85	12.50	8.00
86 - 100	16.00	8.00

Source: Authors

The nominal covering value used in the designs was 2.5 cm, which complies with NBR-16258 [4]. A suitable covering guarantees protection against aggressive external agents.

The increase and reduction factors used, according to NBR-6118 [13] are:

-Increase Factor of the characteristic efforts – at work: $\gamma_f = 1{,}4$;

-Increase Factor of the characteristic efforts – handling: $\gamma_f = 1{,}2$;

-Increase Factor of impact at handling: $\gamma_d = 1{,}3$.

-Reduction Factor of the concrete strength: $\gamma_c = 1{,}3$;

-Reduction Factor of the steel strength: $\gamma_s = 1{,}1$;

As inicial design problem, it was assumed as:

$$\boldsymbol{x_0} = [30 \quad 7 \quad 15], \tag{42}$$

And from it, the Solver was executed to obtain an optimal design to a certain acting load.

4.6 Results obtained

From the analysis at the foundations market, pile's workloads (C_k) described in the catalogs of two relevant manufacturers were adopted. This methodology aims to generate parameters of comparison with the designs obtained in the present work.

Thus, 16 piles were designed for the soil profile chosen, using both the semi-empirical methods described in the research, Décourt-Quaresma and Aoki-Velloso. The data collected from the optimum design for each load are presented in table 4.

For a better comparative study between the market piles and those obtained in this work, it was designed piles where the variables h and e are fixed numbers, as established by the manufacturers, where L is the only design variable. In the tables 7, 8, 9 and 10, the reference manufacturers, 1 and 2, were individually separated for better analysis according to each semi-empirical method applied.

In tables 5 and 6 are the companies 1 and 2 respectively.

Table 4. Designs optimization based on the acting load

	Décourt-Quaresma Optimization				Aoki-Velloso Optimization			
C_k (tf)	h (cm)	e (cm)	L (m)	V (m³)	h (cm)	e (cm)	L (m)	V (m³)
50	26	6,00	9,62	0,36	26	6,00	9,18	0,35
80	28	6,60	15,49	0,69	28	6,72	14,03	0,62
90	30	6,63	15,53	0,77	30	6,63	15,17	0,75
100	32	6,87	15,66	0,85	32	6,87	15,34	0,84
125	36	7,43	17,17	1,15	36	7,48	17,25	1,15
140	39	7,35	15,84	1,17	39	7,35	15,62	1,16
170	43	8,12	16,27	1,45	42	8,37	16,94	1,51
185	45	8,39	16,24	1,57	45	8,39	16,01	1,55
190	46	8,44	16,31	1,6	47	8,60	15,91	1,64
235	53	9,26	16,44	2,07	53	9,26	16,03	2,02
255	55	9,50	16,54	2,25	55	9,50	16,05	2,18
260	56	9,57	16,56	2,3	56	9,57	16,05	2,23
315	62	10,22	16,78	2,80	62	10,22	16,09	2,68
335	64	10,42	16,87	2,97	64	10,42	16,11	2,83
400	71	11,09	17,08	3,56	71	11,09	16,13	3,36
500	80	12,07	17,34	4,50	80	12,07	16,16	4,19

Source: Author

Table 5. Standard Manufacturer 1 – Standard Characteristics of the Centrifuged Piles

Manufacturer 1			
Diameter h (cm)	Thickness e (cm)	Standart Length L (m)	Permissible Structural Load C_k (tf)
26	6,00	10,00	50
33	7,00	11,00	80
38	7,00	12,00	100
42	8,00	12,00	125
50	9,00	12,00	170
50	10,00	12,00	185
60	10,00	12,00	235
60	11,00	12,00	255
70	11,00	12,00	315
70	12,00	12,00	335
80	12,00	12,00	400
80	15,00	12,00	500

Table 6. Standard Manufacturer 2 – Standard Characteristics of the Centrifuged Piles

Manufacturer 2			
Diameter h (cm)	Thickness e (cm)	Standart Length L (m)	Permissible Structural Load C_k (tf)
33	7,00	5,4; 7,4; 9,4	90
42	8,00	5,4; 7,4; 9,4	140
50	9,00	5,4; 7,4; 9,4	190
60	10,00	5,4; 7,4; 9,4	260

Table 7. Comparative Data Aoki-Velloso 1: Optimal designs and Market Designs

	Optimization - Aoki-Velloso				Manufacturer 1 - Aoki-Velloso			
C_k (tf)	f (cm)	e (cm)	L (m)	V (m³)	f (cm)	e (cm)	L (m)	V (m³)
50	26	6,00	9,18	0,35	26	6,00	9,18	0,35
80	28	6,72	14,03	0,62	33	7,00	9,51	0,54
100	32	6,87	15,34	0,84	38	7,00	9,52	0,65
125	36	7,48	17,25	1,15	42	8,00	9,71	0,83
170	42	8,37	16,87	1,50	50	9,00	9,77	1,13
185	45	8,39	16,01	1,55	50	10,00	11,05	1,39
235	53	9,26	16,03	2,02	60	10,00	9,83	2,48
255	55	9,50	16,05	2,18	60	11,00	11,18	2,69
315	62	10,22	16,09	2,68	70	11,00	15,86	3,23
335	64	10,42	16,11	2,83	70	12,00	15,93	3,48
400	71	11,09	16,13	3,36	80	12,00	15,89	4,07
500	80	12,07	16,16	4,19	80	15,00	16,18	4,95

Table 8. Comparative Data Décourt-Quaresma 1: Optimal designs and Market Designs

	Optimization Décourt-Quaresma				Manufacturer 1-Décourt-Quaresma			
C_k (tf)	f (cm)	e (cm)	L (m)	V (m³)	f (cm)	e (cm)	L (m)	V (m³)
50	26	6,00	9,62	0,36	26	6,00	9,62	0,36
80	28	6,60	15,49	0,69	33	7,00	10,58	0,61
100	32	6,87	15,66	0,85	38	7,00	10,88	0,74
125	36	7,43	17,17	1,15	42	8,00	15,00	1,03
170	43	8,12	16,27	1,45	50	9,00	15,23	1,51
185	45	8,39	16,24	1,57	50	10,00	15,61	1,96
235	53	9,26	16,44	2,07	60	10,00	15,55	2,44
255	55	9,50	16,54	2,25	60	11,00	16,01	2,71
315	62	10,22	16,78	2,80	70	11,00	16,03	3,27
335	64	10,42	16,87	2,97	70	12,00	16,29	3,56
400	71	11,09	17,08	3,56	80	12,00	16,26	4,17
500	80	12,07	17,34	4,50	80	15,00	17,39	5,33

Table 9. Comparative Data Aoki-Velloso 2: Optimal designs and Market Designs

	Optimization - Aoki-Velloso				Manufacturer 2 - Aoki-Velloso			
C_k (tf)	f (cm)	e (cm)	L (m)	V (m³)	f (cm)	e (cm)	L (m)	V (m³)
90	30	6,63	15,17	0,75	33	7,00	9,86	0,89
140	39	7,35	15,62	1,16	42	8,00	11,04	1,35
190	47	8,60	15,91	1,64	50	9,00	11,20	1,84
260	56	9,57	16,05	2,23	60	10,00	11,29	2,50

Table 10. Comparative Data Décourt-Quaresma 2: Optimal designs and Market Designs

	Optimization Décourt-Quaresma				Manufacturer 2 - Décourt-Quaresma			
C_k (tf)	f (cm)	e (cm)	L (m)	V (m³)	f (cm)	e (cm)	L (m)	V (m³)
90	30	6,63	15,53	0,77	33	7,00	12,53	0,72
140	39	7,35	15,84	1,17	42	8,00	15,44	1,32
190	46	8,44	16,31	1,6	50	9,00	15,73	1,82
260	56	9,57	16,56	2,3	60	10,00	16,09	2,53

4.7 Results discussion

Based on the comparative data indicated in Tables 7, 8, 9 and 10 in most cases, the optimal designs obtained here reached their goal, since their volumes have lower values than those given by the market solutions.

It is interesting to note that the optimal design of the piles with C_k 80, 100 and 125 in Décourt-Quaresma, and C_k 80, 100, 125, 170 and 185 in Aoki-Velloso, presented larger volumes than the market, even if the values of diameter and thickness of the piles were the minimum possible, resulting in the increase of the length so that the desired capacity was reached in deeper layers.

For C_k 50 piles, the optimal and market dimensions converged in each case.

Table 12 shows that, for the same soil, the Aoki-Velloso method reached more excellent values than the Décourt-Quaresma, but the difference is minimal and can be neglected

5 Conclusions

Based on the semi-empirical methods for determining the bearing load capacity of deep foundations according to Décourt-Quaresma and Aoki-Velloso, an interactive data spreadsheet was created with the aid of the Excel Solver, in order to determine the best dimensions (design variables) of a prefabricated hollow pile, given a certain acting load, and respecting the ABNT norms, as well as the bibliographic references adopted (design restrictions), obtaining at the end the lowest volume (objective function) possible for the pile. Both semi-empirical methods adopted led to similar optimum designs.

According to the data obtained and analyzed, it is concluded that the prefabricated hollow piles of centrifuged concrete, now offered in the market, do not present optimal dimensions. So, the spreadsheet developed was able to define smaller values of diameter and thickness and to optimize for different loads the volume of the piles.

In addition to defining the dimensions of a prefabricated pile, the developed program is capable of optimizing the piece, in order to minimize its volume and reduce the consumption of raw materials. The authors are unaware of the existence in the Brazilian market of similar software capable of performing this task. Therefore the present article is relevant.

It is suggested to improve the present calculation process, considering as objective function the final cost of the piece, taking into account the costs of fabrication, transportation and driving of the piles. Another suggestion is the adoption of a maximum value for the N_{SPT} , for example equals to 33, where the pile can be driven, without any significant damage to its structural integrity, that means that the pile, in the calculation process, do not cross impenetrable layers of the soil. Also, one can analyze the layers below the base of the stake and alert the user of the program about the possibility of the occurrence of significant settlements.

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