Optimum design of pile cap considering minimization of environmental impacts

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Abstract

This article presents a formulation for the optimization problem that minimizes the CO_2 emission of pile caps with variations of geometry and pile position. The problem is defined by the design variables: concrete pile cap dimensions, rebar ratio, concrete compressive strength, the number of piles, the diameter, and length. The environmental impact was chosen as the objective function, taking CO_2 emission as the main parameter. The design procedure was based on the ABNT NBR 6118:2014 (2014), and by the formulation proposed by Blévot & Frémy (1967). Also, the soil structure interaction between the cap and the piles was considered in the optimization problem. The problem was implemented using MATLAB (2016) and solved via a Genetic Algorithm native to the program. Results obtained from numerical examples were compared with structural designs solutions located in the Grande Vitória metropolitan area, Espírito Santo, Brazil and validated with a commercial software. The analyses indicate that design optimizations of pile caps considering the compressive strength of concrete, the diameter and length of piles and the optimal geometry of the pile caps may lead to significant reductions of material consumption, and consequently, a reduction of environmental impacts.

Keywords: optimization, CO_2 emissions, Genetic Algorithm, soil structure interaction.

1. Introduction

The main objective of engineering is to design systems with satisfactory reliability, minimal cost and minimal environmental impact. The quest for excellence is a principle that is inseparable from structural engineering. However, the minimal cost usually rules the design, and the environmental impacts are not considered.

Moreover, the design of pile caps depends on the geotechnical profile of the surrounding strata, the loads applied on the element, the strength, diameter, type, and rebar of the piles, as well as the dimensions and geometry of pile caps. The design may vary depending on the skill of the structural engineer and the adopted parameters.

In this perspective, there is an ever-increasing demand for optimizing mathematical models that considers these aspects and obtain the optimum design reducing costs to predict the actual behavior of the structural element.

In this study, the strut and tie model proposed by Blévot & Frémy (1967) was used, which assumes a spatial truss inside the block composed of tensioned and compressed elements connected through nodes. Using an isostatic truss model, the forces of the struts and ties are calculated through the equilibrium between internal and external forces. The compression forces in the struts are resisted by the concrete, and the tension forces acting on the horizontal bars of the truss are resisted by the reinforcement. The method consists of calculating the tension force, which defines the necessary area of reinforcement, and verifying the compressive stresses in the struts, calculated in the sections located next to the column and the pile. The limit stresses were determined experimentally by Blévot & Frémy (1967) in tests having maximum allowable stresses on column nodes of 2.1 fcd for 4 or more piles and maximum allowable stresses on pile nodes of 0.85 fcd for 2 or more piles. Blévot & Frémy (1967) conducted 116 tests on blocks with two, three, and four piles subjected to the action of centered force and analyzed their behaviors. The researchers verified the relationship between the resistance capacity and cracking of the models with different distributions of reinforcement bars with equivalent areas.

The application of optimization techniques to the design of structural elements has steadily increased in recent decades as observed in the studies performed by Guerra & Panos (2006), Souza *et al.* (2007) , Senouci & Al-Ansari (2009), Erdal, Dogan and Saka (2011), Medeiros &

Kripka (2013), Hare *et al.* (2013), Kripka, Medeiros and Lemonge (2015) Alves & Tomaz (2018), Turini *et al.* (2019), Santoro & Kripka 2020, Tormen *et al.* (2020), and Breda, Pietralonga and Alves (2020).

However, as stated by Santoro & Kripka (2020), Tormen *et al.* (2020), Payá-Saforteza *et al.* (2009), Camp & Huq (2013), Park *et al.* (2014), Yepes, Martí and García-Segura (2015) and Yu *et al.* (2020), optimizations focused only on financial cost may not be enough to determine an optimal solution to the problem. Studies for the life-cycle of materials and their impact on the environment become an important factor that should also be considered.

Therefore, this article presents a formulation, considering the NBR 6118 (2014) standard, for the optimization of pile cap that minimizes carbon dioxide (CO_2) emissions, allowing the assessment of the influence of different geometries, number of piles, diameter, and length of piles for the final solution. The solution also evaluates the pile's ideal dimension (diameter and length) according to the geotechnical profile. The solution to the optimization problem was obtained via a Genetic Algorithm (GA) and the examples presented indicate the advantages and improvements achieved with this optimization technique.

2. Importance of CO_2 reduction in civil construction

The increase in the consumption of natural resources in recent decades became a worrisome statistic. The New Economics Foundation, World Wide Fund for Nature in association with the Global Footprint Network estimated these values with the earth overshot day, demonstrating the biocapacity of planet Earth correlated in terms of the carbon footprint. As presented by O'Neill *et al.* (2017), IPCC (2020) and the GFN (2020), the numbers are increasing every year, confirming a rise in carbon dioxide emissions.

The Global Cement and Concrete Association, included in the World Business Council for Sustainable Development, searching for the sustainable development of this industrial sector, presents data for the evolution of the industry via GNR (2016).

According to the GNR (2016), cement is the second most consumed material on the planet, which accounts for a significant portion of the environmental impact. According to Gan, Chen and Lo (2019) approximately one third of worldwide carbon dioxide emissions are generated by the construction sector. In order to quantify the environmental impact of cement, Silva, Gomes and Saade (2018) indicate the use of the life-cycle assessment (LCA) detailed in ISO 14040 (2006), a study that begins with the extraction of raw materials and potentially covers the entire lifespan of the material.

Therefore, it is essential to explore alternatives to optimize the consumption of raw materials used in civil construction in order to reduce environmental impacts and financial costs. Through numerous previous publications, Alves & Tomaz (2018), Santoro & Kripka (2020), Tormen *et al.* (2020), state that, if adequately implemented, optimization techniques are valid strategies for reducing the consumption of materials used for building structural elements.

3. The optimization problem formulation

The optimization problem for pile caps considering the minimization of carbon dioxide emissions can be formulated as presented in Eq. (1).

$$Min\ E\,(CO_2) = \left(V_b + N_e \cdot \pi \frac{d_{pile}^{\,2}}{4} \cdot L_{pile}\right) \cdot E_c + A_f \cdot E_f + A_s \cdot \gamma_a \cdot E_a \qquad (1)$$

Where, E_c: Emission of carbon dioxide per m³ of concrete as a function of f_{ck}; E_f: Emission of carbon dioxide per m² of formwork; E_a: Emission of carbon dioxide per kg of steel; V_b: Concrete volume of cap; N_e: number os piles; d_{pile}: pile diameter; L_{pile} pile lenthg; A_f: formwork area; A_s: Cap rebar ratio; $A_{s,pile}$: Pile rebar ratio, and γ_a: Specific weight of steel. Figure 1 presents the design variables.

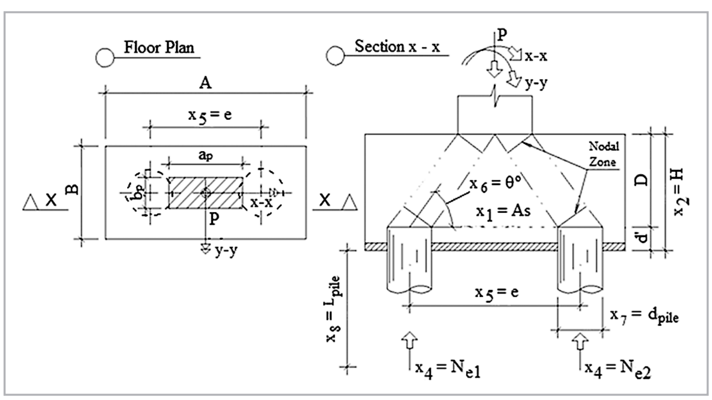

Figure 1 - Problem variables of the strut-and-tie method for a two-pile cap.

Where: $x_1 = A_s$ corresponds to the area of reinforcing steel (cm²), $x_2 = H$ is the effective height of the pile cap (cm), $x_3 = f_{ck}$ the concrete characteristic compressive strength (MPa), x_4 = Ne represents the number of piles, $x_5 = e$ the spacing between piles in (cm), x_6 = Slope of the strut (degrees); $x_7 = d_{pile}$ represents piles diameter; and $x_8 = L_{pile}$ the pile length.

3.1 Problem constraints

Problem constraints are summarized in Eqs (2)-(14), based on the NBR 6118 (2014) standard, as shown in topic 3.

$$h - \frac{A - a_p}{3} \leq 0 \quad (2)$$

$$h - \frac{B - b_p}{3} \leq 0 \quad (3)$$

$$R_{e,máx} / R_{e,lim} - 1 \leq 0 \quad (4)$$

$$45° \leq \theta \leq 55° \quad (5)$$

$$\sigma_{column} / \sigma_{column,lim} - 1 \leq 0 \quad (6)$$

$$\sigma_{pile} / \sigma_{pile,lim} - 1 \leq 0 \quad (7)$$

$$e_x / e_{x,min} - 1 \leq 0 \quad (8)$$

$$e_y / e_{y,min} - 1 \leq 0 \quad (9)$$

$$A_s - \frac{R_{sd}}{f_{yd}} = 0 \quad (10)$$

$$20 \leq f_{ck} \leq 50 \quad (11)$$

$$2 \leq Nº\ Piles \leq 6 \quad (12)$$

$$1 \leq L_{Piles} \leq L_{max} \quad (13)$$

$$d_{min} \leq d_{Piles} \leq d_{max} \quad (14)$$

Where $R_{e,máx}$ is the maximum load applied to the piles; $R_{e,lim}$: Compressive strength of the piles; σ_{column} is the stress acting on the compressed strut (column); $\sigma_{column,lim}$ the maximum allowable stress (column); σ_{pile} the stress acting on the compressed strut (pile); and $\sigma_{pile,lim}$ the maximum allowable stress (pile); e_x and e_y is the minimum spacing between piles in the x and y direction; A_s corresponds to the area of reinforcing steel, and R_{sd} the design tensile force acting on the strut.

The solution to the optimization problem was obtained with Genetic Algorithm available in a MATLAB (2016) toolbox via "*GA*" function. The parameters presented by Santoro & Kripka (2020) were used to measure CO_2 emissions. These values are presented in Table 1. For GA, used was the initial population contains 100 individuals. The rate of elite individuals and crossing of the intermediate type are 0.05 and 0.85, respectively, whereas the mutation rate is random. Figure 2 presents a flowchart of the optimization problem.

Table 1 - Emission values for each material.

Material	Emission of CO_2 ($KgCO_2/m^3$)	
Concrete	20MPa	140.05
Concrete	25Mpa	149.26
Concrete	30Mpa	157.5
Concrete	35Mpa	171.74
Concrete	40Mpa	182.14
Concrete	45MPa	194.70
Concrete	50MPa	225.78
Steel	CA-50	1.05
Steel	CA-60	1.05
Wood		1.78

Source: Santoro & Kripka (2020).

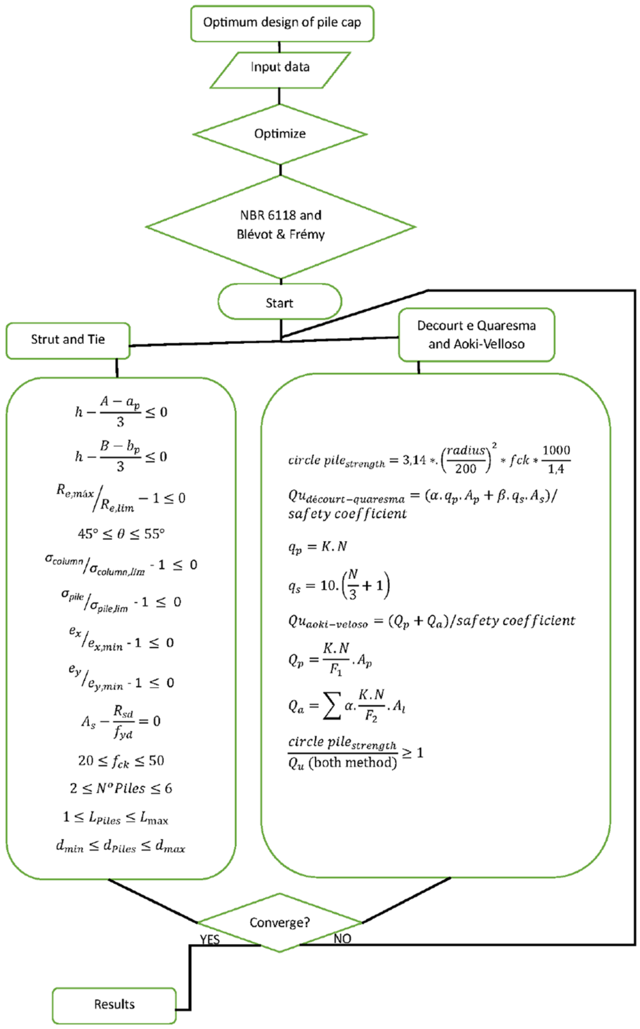

Figure 2 - Optimization Problem Flowchart.

4. Numerical applications

To show the impacts and the viability of the formulation proposed herein, three examples are presented. Results are analyzed in terms of CO_2 emission to verify the convergence between solutions. The examples are based on solutions located in the Grande Vitória metropolitan area, Espírito Santo (Brazil), and use the geotechnical profile presented in the Figure 3.

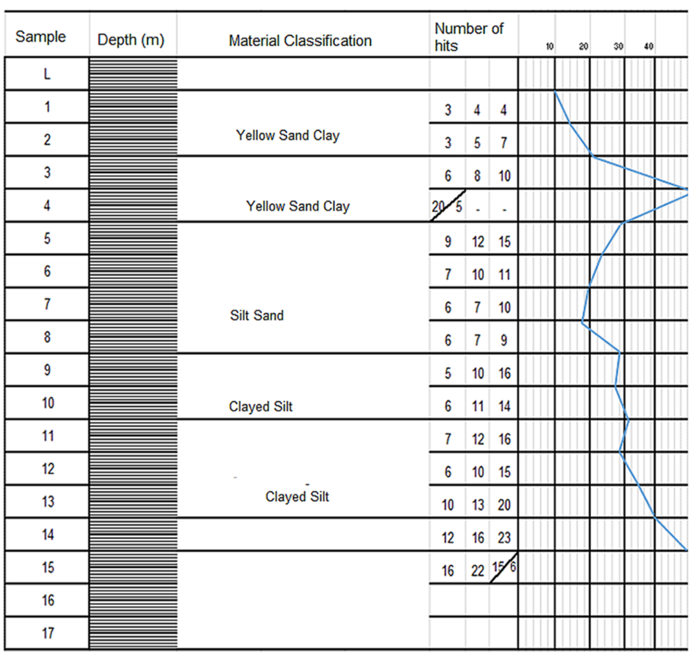

Figure 3 - Examples geotechnical profile.

The rebar area $A_{s1,2}$ includes only the principal reinforcement (bottom of the pile cap). Designs were elaborated with the commercial software CAD/TQS v.22 (2022) and considering reinforced concrete driven piles with a circular cross-section.

The methodology of analysis consisted of maintaining the number of piles of the original design and optimizing the concrete compressive strength (f_{ck}), the height of the pile cap (H) and the area of reinforcing steel (A_s). In a second analysis, the number of piles and pile cap geometry were also optimized. The analyzed examples considered the NBR 6118 (2014) standard and presents the characteristic loads. To analyze the final CO_2 emissions of the pile cap assembly, the CO_2 emission of the pile reinforcement was not analyzed, since this information was not available in the original design.

4.1 Example 1 – 4-pile cap

This example considers a concrete pile cap supported by 4 piles, as shown in Figure 4, with the following design parameters: diameter of the pile (d_e) = 70 cm, distance between piles (e) = 180 cm, height of the pile cap (H) = 130cm (approximately corresponds to the distance between the more distant pile to the center of pile cap), length of the pile cap along the x axis (A) = 290 cm, along the y axis (B) = 290 cm, width of the column in the x direction (a_p) = 30 cm, width of the column in the y direction (b_p) = 160 cm, vertical load (P) = 4650 kN, bending moment (x-x) = 750 kN.m, and bending moment (y-y) = 50 kN.m. For this example, in addition to the dimensions of the pile cap, the length and the number of piles, and the compressive strength of concrete are also considered as optimization parameters. Table 2 presents the quantitative of materials and Table 3 presents a comparison between optimal solutions for CO_2.

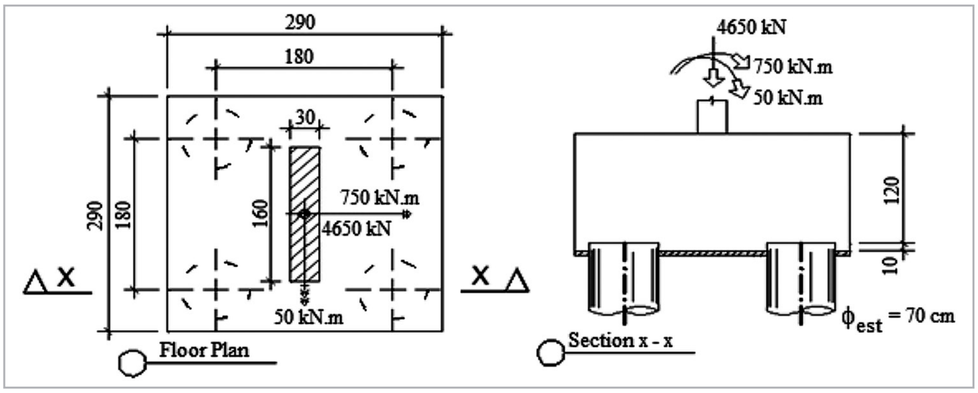

Figure 4 - Example 1 - Pile cap original design with loads values.

Table 2 - Example 1 - Numerical Results and quantitative of materials.

Solution	Cap										Pile			
	f_{ck} (MPa)	H (cm)	A (cm)	B (cm)	As_x (cm²)	As_y (cm²)	e (cm)	θ(°) (m³)	Vol Cap (m³)	steel mass (Kg)	N°. pile	L (cm)	ϕ (cm)	Vol Pile (m³)
Original Design	30	130	290	290	38.6	38.6	180		10.93	351.49	4	1300	70	20.01
Blévot & Frémy (1967) - (Best Design)	25	88	240	240	22.4	43.2	150	49	5.07	247.18	4	500	60	5.65
Blévot & Frémy (1967) - 3 piles	30	99	252	225	38.5	36.4	175	46	5.61	280.90	3	500	70	5.77

Table 3 - Example 1 - Numerical Results.

Solution		Original Design	Blévot & Frémy (1967) (Best Design)	Blévot & Frémy (1967) (3 piles)
Cap	CO_2 ($KgCO_2$)	2259.4	1062.0	1235.0
Pile	CO_2 ($KgCO_2$)	2823.7	797.9	814.52
Pile cap	CO_2 ($KgCO_2$)	5083.1	1859.9	2049.5
*P_{lim_pile}	kN	--	1531	2024
**R_{pile}	kN	--	1465	1842

*P_{lim_pile} – Pile resistent limit load;

**R_{pile} – Reaction load of cap in the pile.

As observed in Table 3, the reduction in CO_2 emission for the optimized solutions is clear. Notice that considering just the caps influence, the optimization provides a reduction of 52.9%, when considering 4 piles, and 45.3% for the cap with 3 piles. Also, a reduction in the dimensions is observed, and for the best solution, a smaller f_{ck} is necessary.

The optimized solution leads to a reduced length for the piles, and a smaller diameter, when considering the best solution with 4 piles. The reduction in CO_2 emission is around of 71.7% (4 piles) and 71.1% (3 piles). Therefore, the final pile cap CO_2 emission is then reduced in 63.4% (4 piles, best solution) and 59.7% (3 piles), with reduced dimensions for piles and caps, and a smaller fck, providing satisfactory results.

Figure 5 shows the composition of CO_2 emission in each element that composes the pile cap. It can be noticed that the concrete of the caps and piles is the principal element responsible for the CO_2 emission. However, for the 3 pile model, the piles represent 50.9% of the CO_2 emission, while for the 4 pile model, only 30.9%, where the concrete becomes more important in emission, with 63.9%. The steel represents 13.5% and 4.2% of the emission considering 3 and 4 piles, respectively. The formwork influence is less than 1% for both models. Another important point to observe is the pile length. In the original design, the geotechnical engineers considered the length of the pile practically in the impenetrable layer, leading to a conservative design from the point of view of the calculation. In the adopted methodology, the calculation is done iteratively as a function of the load that is transferred to the pile and as a function of its tip and friction load capacity, thus obtaining the ideal length of the pile.

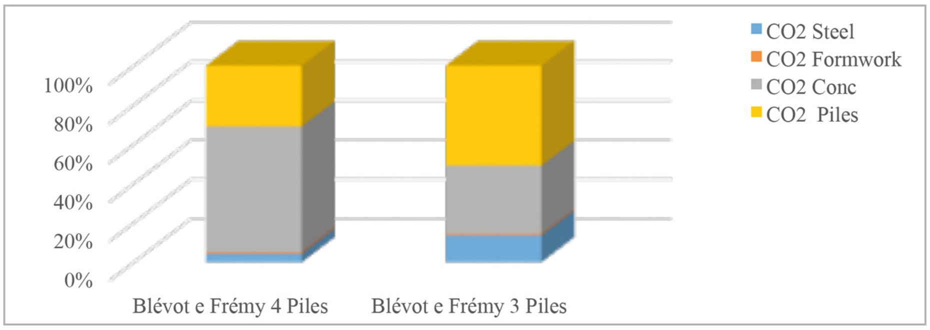

Figure 5 - Example 1 - Analysis of CO_2 composition for each solution.

Figure 6 presents the relation of CO_2 emission of the optimized solutions: Blévot & Frémy (1967) theory with 4 piles, and 3 piles, in relation to the original design. Results clearly show the relevant reduction in CO_2 emission for the optimized solutions, considering caps and piles independently, and for the complete pile cap.

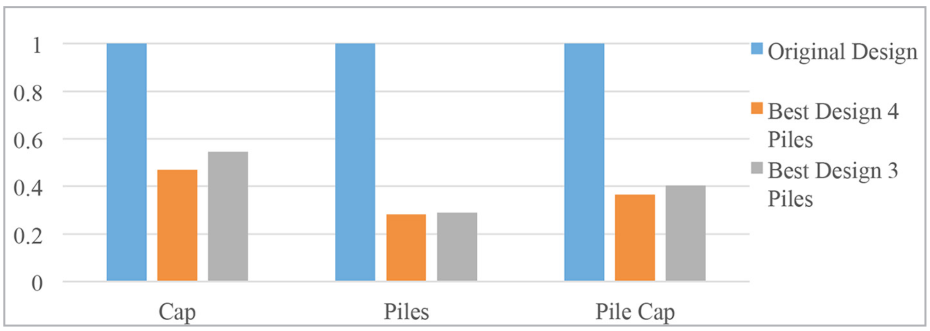

Figure 6 - Example 1 - CO_2 composition of optimized solutions x original design.

Figure 7 presents the optimized pile cap of the problem. To validate this result, the pile cap was calculated with the *TQS v.22* (2022), considering the Blévot & Frémy (1967) theory, and the design is shown in Figure 8. The validation shows that the proposed pile cap respects all resistance criteria and could be used with safety.

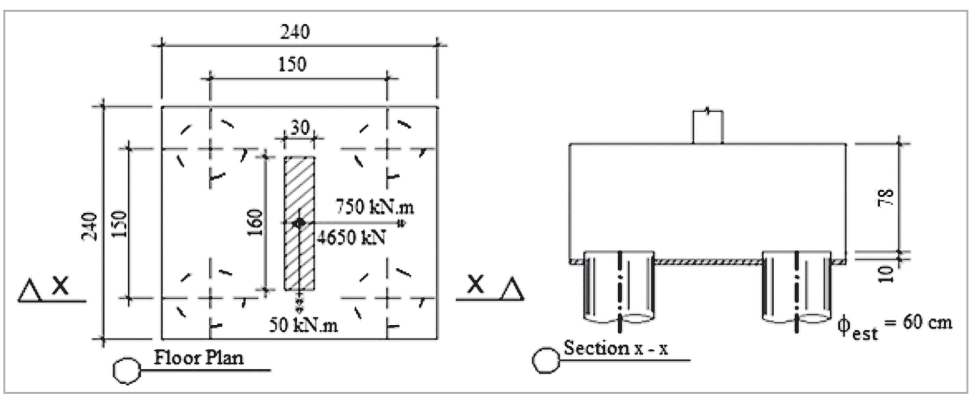

Figure 7 - Example 1 - Best design for CO_2 emission.

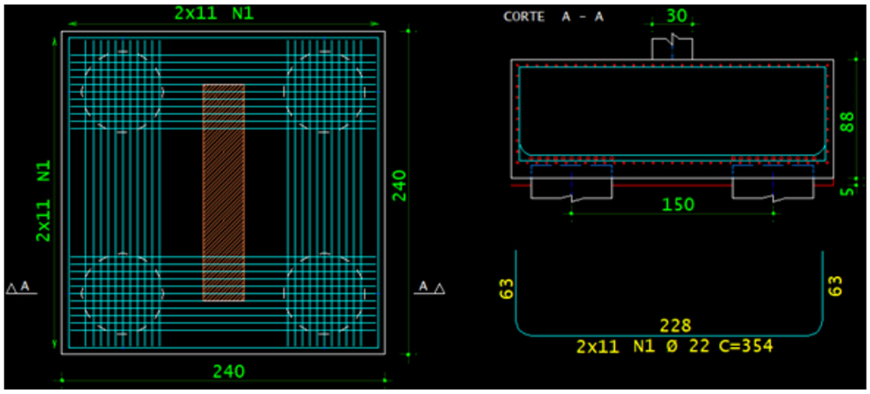

Figure 8 - Example 1 - Validation of the optimized pile cap design (adapted from TQS v.22 (2022)).

4.2 Example 2 – Rectangular 5-pile cap

The second example features a rectangular pile cap supported by 5 piles, as shown in Figure 9, with the following design parameters: diameter of the pile (d_e) = 70 cm, distance between piles (*e*) = 255 cm, height of the pile cap (*H*) = 170cm (approximately corresponds to the distance between the more distant pile to the center of pile cap), length of the pile cap along the x axis (*A*) = 365 cm, along the y axis (*B*) = 365 cm, width of the column in the x direction (a_p) = 40 cm, width of the column in the y direction (b_p) = 160 cm, vertical load (*P*)=5650kN, bending moment (*x-x*)=550kN.m, and bending moment (*y-y*) = 30 kN.m.

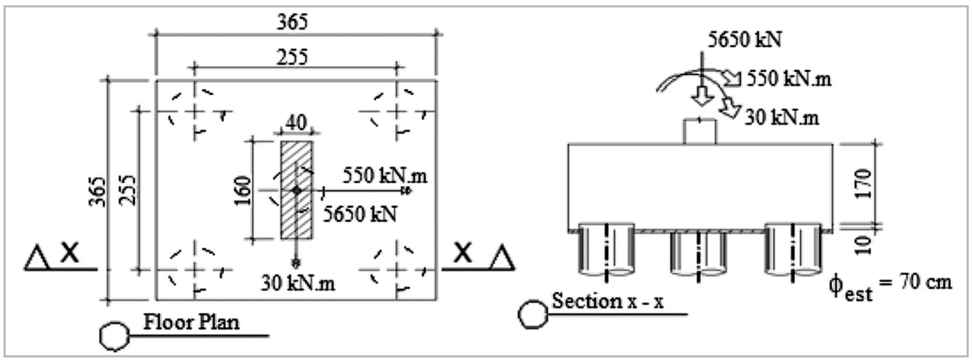

Figure 9 - Example 2 - Pile cap original design with loads values.

Table 4 presents the quantitative of materials and Table 5 presents a comparison between optimal solutions for CO_2 emission. The optimal solution is obtained using the method of Blévot & Fremy (1967), just as in previous examples, using 4 piles. The CO_2 emission is reduced in more than 65%, with a smaller fck, and reduced dimensions. The pile length is the minor necessary.

Table 4 - Example 2 - Numerical Results and quantitative of materials.

Solution	Cap											Pile			
	f_{ck} (MPa)	H (cm)	A (cm)	B (cm)	Asx (cm²)	Asy (cm²)	e_1 (cm)	e_2 (cm)	θ(°)	Vol Cap (m³)	Steel mass (Kg)	N° pile	L (cm)	ϕ (cm)	Vol Pile (m³)
Original Design	30	180	365	365	48.6	48.6	255	255		23.98	557.00	5	1300	70	25.01
NBR 6118	25	138	363	215	45.4	20.8	273	125	48	10.77	328.94	5	500	60	7.06
Blévot & Frémy (5 piles)	25	140	363	215	44.6	20.5	273	125	44	10.92	323.37	5	500	60	7.06
Blévot & Frémy (Best Design)	20	111	275	275	27.0	44.1	175	175	51	8.39	306.97	4	400	70	6.158
Blévot & Frémy (3 piles)	50	91	268	240	30.8	29.1	188	188	56	5.85	239.24	3	500	75	6.627

Table 5 - Example 2 - Numerical Results.

Solution		Original Design	NBR 6118	Blévot & Frémy (5 piles)	Blévot & Frémy (Best Design)	Blévot & Frémy (3 piles)
Cap	CO_2 ($KgCO_2$)	4380.9	3181.5	2152.2	1721.0	2009.0
Pile	CO_2 ($KgCO_2$)	3529.6	997.4	997.4	868.8	935.0
Pile cap	CO_2 ($KgCO_2$)	7910.5	4178.9	3149.6	2589.8	2944.1
*P_{lim_pile}	kN	--	1531	1531	1765	2296
**R_{pile}	kN	--	1413	1414	1636	2127

Considering the same number of piles of the original design (5 piles) and the NBR 6118 (2014) standard, a high compressive strength is necessary for concrete, even so, a reduction in CO_2 emission is obtained for caps, piles and for the pile cap. When the Blévot & Frémy (1967) theory is used for this reduction, it is even more effective, with a reduced fck, of just 25 MPa. Another proposal: a pile cap with 3 piles provides a reduction in emission too, around of 62.7% in the final pile cap. The pile length is reduced. However, a high value of fck is also needed, 50 MPa.

Figure 10 shows the composition of CO_2 emission in each element that composes the pile cap. Like previous examples, concrete provides the largest contribution to the final value of solutions, followed by the pile's contribution. An exception for the optimized solution using the Blévot & Frémy (1967) theory is the case with 3 piles, which in this case, the piles are the principal responsible for the CO_2 emission. The contribution of concrete is reduced in solutions featuring the optimization of the number of piles. The Formwork emission, related to the total emission of the pile cap is limited to a 1% or less, and the steel emission increases with the reduction in the number of piles.

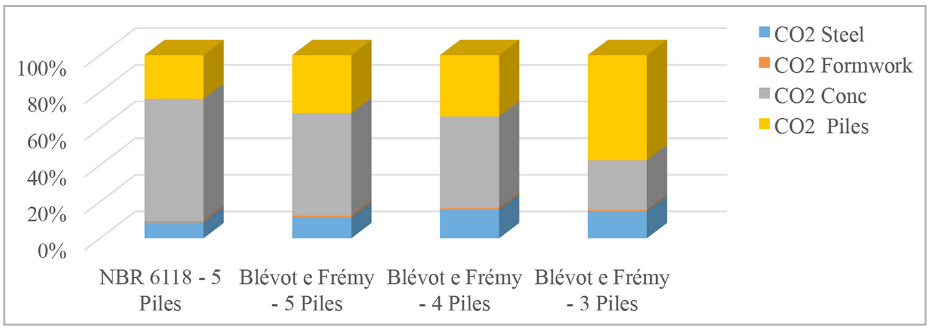

Figure 10 - Example 2 - Analysis of CO_2 composition for each solution.

Furthermore, Figure 11 presents the CO_2 emission of solutions in relation to the original design. For best design (Blévot & Frémy (1967) - 4 piles) the cap CO_2 emission represents just 40% of the original design, and the pile around 25%, resulting in a pile cap that corresponds a 33% of the original design CO_2 emission. The pile cap of the second-best design (Blévot & Frémy (1967) - 3 piles) represents 37% of the original design emission, followed by the other optimized solutions, Blévot & Frémy (1967) theory with 5 piles, and the NBR 6118 (2014) standard for 5 piles, that represents 39% and 53% of the original design CO_2 emission, respectively.

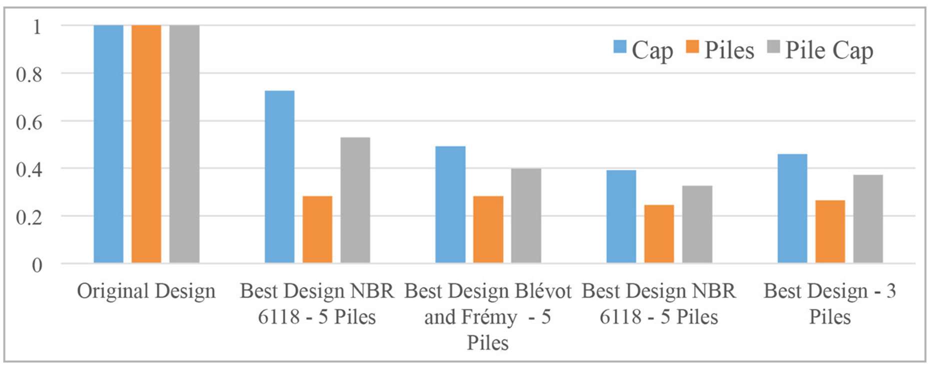

Figure 11 - Example 2 - CO_2 composition of optimized solutions x original design.

Figure 12 presents the optimized pile cap of the problem. To validate this result, the pile cap was calculated with the *TQS v.22* (2022) and the design is shown in Figure 13. For consistency, this design also considered the Blévot & Frémy (1967) theory. The validation shows that the proposed pile cap respects all resistance criteria, and reduces CO_2 emission. However, designed software is not prepared to optimize pile caps, even more, considering environment impacts.

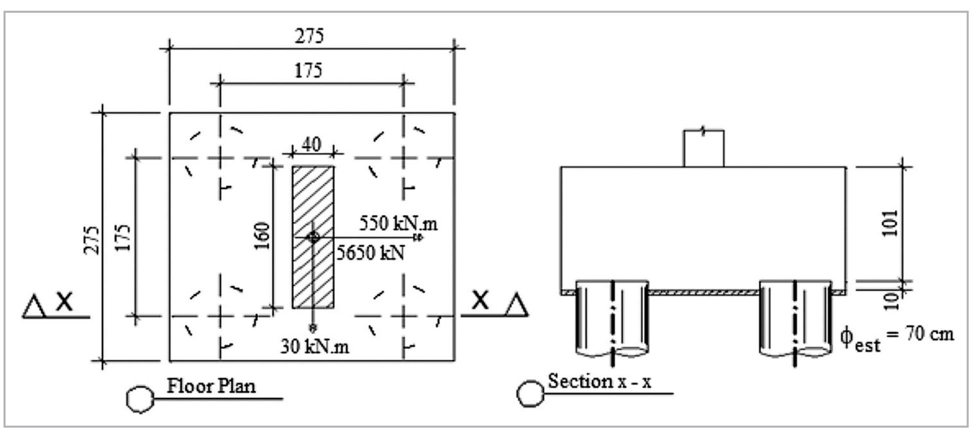

Figure 12 - Example 2 - Best design for CO_2 emission.

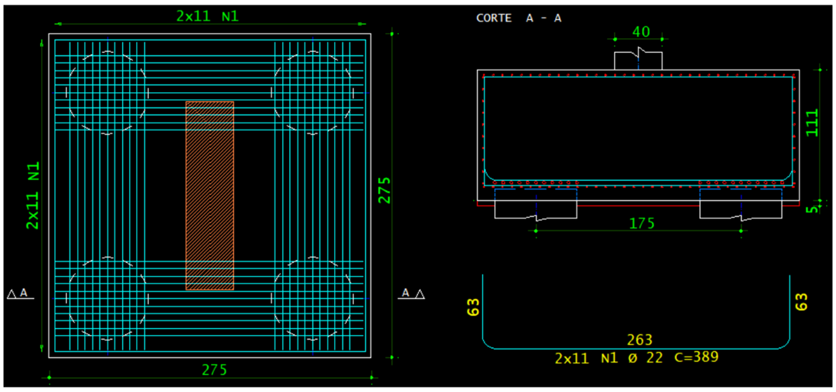

Figure 13 - Example 2 - Validation of the optimized pile cap design (adapted from TQS v.22 (2022)).

5. Conclusion

Conventional methods for designing pile caps are strongly influenced by the structural engineer's decisions. This methodology does not ensure that the design corresponds to the optimized solution, given the variables that must be considered for calculations and the choice of parameters.

The examples presented clearly show the advantages and the importance of using optimization techniques when designing structures, especially when considering the environmental impacts and soil structure interaction. Generally, reducing the number of piles of the final design leads to significant reduction of CO_2 emissions. The caps and piles are the principal elements responsible for the gas emissions, thus reducing the caps dimensions, the number, and the length of the piles provides important results.

The formulation proposed herein indicates that the NBR 6118 (2014) standard yields to conservative results of optimized designs. The most optimized solutions were obtained with the values proposed by Blevot & Frémy (1967). However, all examples provide optimized results, strongly improving the original design. This fact shows that considering optimization during the design, it is fundamental to reduce the quantity of materials, and consequently the reduce the environmental impacts.

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