

Optimization of CFA Pile Foundations: A Sustainable Approach Through Static Load Tests and Numerical Simulations

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ABSTRACT: Given the increasing importance of sustainability in geotechnical engineering, this study investigates how the optimization of foundation design using Continuous Flight Auger (CFA) piles can significantly reduce the carbon footprint and deliver meaningful environmental benefits. Conducted during the pre-construction phase of a project in Fortaleza, Brazil, the research integrates static load tests, numerical modeling via the Finite Element Method (FEM) using Plaxis 2D, and geotechnical model calibration based on in situ test data (SPT, DMT, and SDMT). The analysis focused on 600 mm diameter, 14-meter-long piles, evaluating the influence of the interface parameter (R-inter) in simulating load test behavior. The methodology also included comparisons with results obtained from widely used semi-empirical design methods. The optimized solution reduced the number of piles from 2,752 to 1,504, leading to a decrease in CO₂ emissions from 3.978 to 2.174 tons, an approximate 46% reduction, while maintaining structural safety and compliance with design standards. The findings highlight the effectiveness of numerical simulations in accurately predicting the load-bearing capacity of CFA piles, enabling more efficient foundation design, reducing concrete and steel consumption, lowering costs and construction time, and contributing to the achievement of the United Nations Sustainable Development Goals for 2030.

KEYWORDS: Sustainability, CFA piles, foundation optimization, numerical modeling, carbon footprint.

1 INTRODUCTION

In light of recent climate changes, sustainability in civil construction has become essential. This work highlights the importance of reducing material consumption and carbon footprint through the optimization of foundation designs. Civil construction industry accounts for up to 34% of total global carbon emissions (PROGRAMME; CONSTRUCTION, 2025), therefore it is urgent to adopt ways to reduce carbon footprint in structural projects.

According to sustainable design principles for foundation projects, this article proposes an assessment of foundation design optimization through a case study involving Continuous Flight Auger (CFA) foundations, as a means to reduce the number of CFA piles required and, consequently, lower the carbon footprint. The case study is located in the city of Fortaleza, the capital of the state of Ceará, in the Northeast region of Brazil. The optimization methodology followed established literature methods associating advanced geotechnical survey, and the estimation of carbon footprint regarded emission indexes related to the execution process of CFA piles.

2 STRUCTURAL AND SOIL CHARACTERIZATION

The construction project was composed by 03 main buildings: tower, museum and theater; and their structures were primarily composed of traditional reinforced concrete elements (floor, beams, columns, piles and pile caps). The tower's columns are subjected by permanent vertical loads ranging from 43 to 3,768 kN. The museum building has 7 floors with columns withstanding permanent loads varying from 49 to 2,183 kN. The theater building also has 7 floors, bearing permanent loads ranging from 25 to 1,477 kN. All three buildings have bottom floor based on elevation +15.50, resulting in 4m depth excavation as the topographic survey showed the surface of work site was around elevation +19.50.

The foundation soil initially consists of a 5-meter-thick layer of slightly compacted clayey sand. This is followed by a layer of slightly compacted silty sand extending to a depth of approximately 9 meters, and then by another layer of slightly compacted clayey sand reaching a depth of 11 meters. The fourth layer consists of medium to very stiff clayey silt, extending to a depth of approximately 17 meters.

Finally, a very dense sandstone layer was encountered down to a depth of 22 meters, representing the limit of the boreholes from SPT (Standard Penetration Test). The groundwater level was between elevations +8.60 and +14.30. The boreholes were carried out at the end of the rainy season and the expected subsurface flow conditions do not justify the 6-meter variation, so it is possible that the drilling fluids used on the boreholes influenced the accurate identification of the groundwater table position. Based on the initial SPT campaign, comprising approximately 50 boreholes, it was possible to develop the typical geotechnical profile described and presented in Figure 1.

Considering the constraints (noise and vibration limitations), schedule (productivity), costs and location of the worksite, the most suitable foundation solution was Continuous Flight Auger (CFA) piles.

The preliminary foundation design was performed using semi-empirical methods based on SPT tests. Later, the optimized foundation design considered more advanced geotechnical survey (prior static load test, plate load test, DMT and SDMT).

Due to the specific characteristics of the project as well as its scale and geotechnical constraints, it was necessary to conduct additional geotechnical investigations which were organized into investigation zones. Prior static load tests on test piles were also performed to optimize normative safety factors by increasing allowable loads on piles. Figure 2 presents the results obtained for each soil layer through Marchetti Dilatometer Tests (DMT), Seismic Dilatometer Tests (SDMT), and plate load tests.

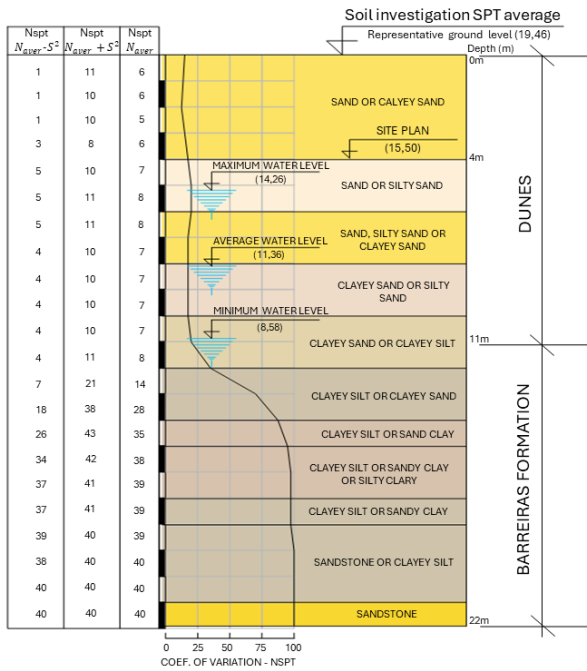


Figure 1. Simplified geotechnical profile used for ground modelling.

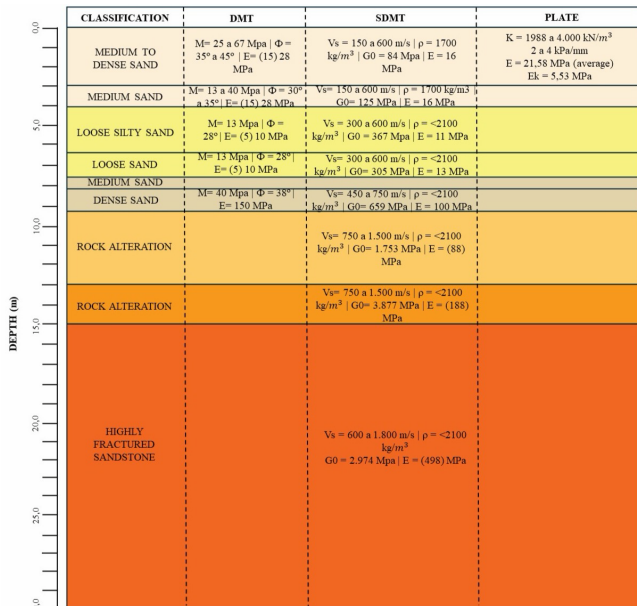


Figure 2. Results of the complementary tests.

The results of the supplementary geotechnical investigation campaign not only confirmed the previously identified stratigraphy but also provided valuable data for defining the soil strength and deformability parameters. Notably, the use of shear wave velocity (V_s) measurements enabled the identification of sections corresponding to the weathered rock zone and fractured sandstone. Based on these values, it was possible to estimate the small-strain shear modulus (G_0), which served as the basis for defining representative parameters to be used in numerical models.

3 LOAD-BEARING CAPACITY ANALYSIS

The load-bearing capacity of the Continuous Flight Auger (CFA) piles was evaluated using well-established semi-empirical methods which combine theoretical concepts with experimental data obtained from field tests and observations.

The methods applied were those proposed by Alonso-Urbano (1996), Antunes-Cabral (1996) and Décourt (1996). These methods correlate the shaft friction and end bearing resistance of piles with results from Standard Penetration Tests (SPT). Based on the load capacity analyses, the allowable loads and required pile length were determined for CFA piles with 600 mm of diameter and 14 m of length. The reinforcement used was 6 bars of 20 mm in diameter, with 6m in length, and transversal rings of 8 mm in diameter spaced 20 cm in pile length, weithing approximately 113 kg of steel per pile.

Figure 3 illustrates the distribution of the ultimate load for each applied method and references the range of ultimate loads obtained from the preliminary static load tests, considering an extrapolation of the results based on Van der Veen's (1953) method.

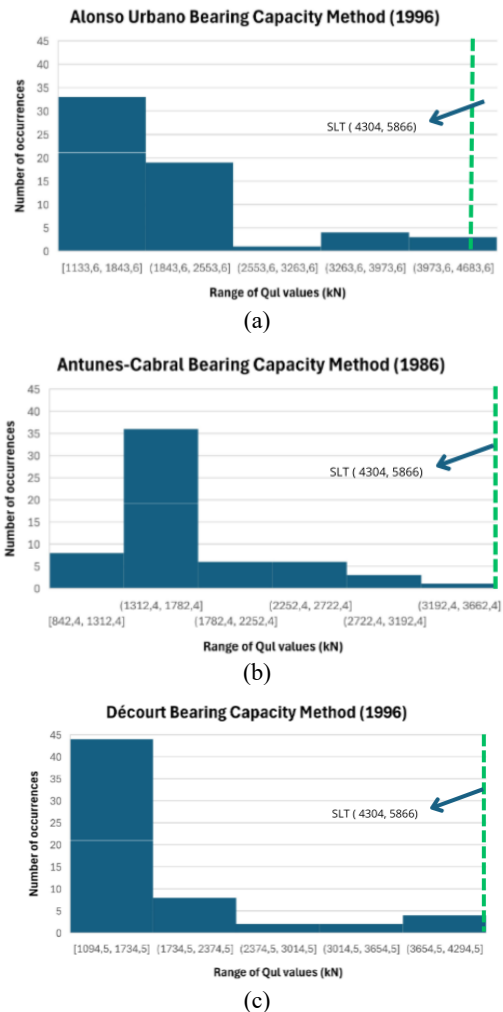


Figure 3. Bearing capacity estimation through methods considering static load test.

Based on the graphical analysis and the average distribution of values, the ultimate loads were determined as 2,051.7 kN, 1,707.8 kN, and 1,774.6 kN for the Alonso-Urbano, Antunes-Cabral, and Décourt methods, respectively. It is observed that, although the average aims to summarize how the dataset is represented, it does not fully describe the trend observed in the majority of the data for each method. Therefore, the ultimate load value adopted for the entire structure was obtained by averaging the most representative values from each method, resulting in a final value of 1,470 kN. Even though the value obtained from the semi-empirical methods is lower than the ultimate load estimated from the static load test results, it is observed that relying on such estimates would lead to an overly

conservative and costly design—not only in terms of planning, but especially from an environmental standpoint, as will be demonstrated later, given that the estimated ultimate load is less than half of the value measured in the static load tests.

Although a significant difference was observed between the estimated ultimate load and the values obtained from the previous load test, this result was expected due to the presence of lateritic soil in the Fortaleza region. This type of soil is common in the area, favored by the local climate and laterization processes that occurred in earlier periods, as identified through local mineralogical and geochemical analyses (Siqueira; Magini; Dantas; Fuck; Sasaki, 2014). It is characterized by a high content of iron and aluminum oxides, giving the soil a cemented structure (Santos, 2006). As a result, the soil presents greater hardness and stability, which contribute to its mechanical strength. Furthermore, according to Mascarenhas (2016), low activity of the clay fraction was identified in most of the lateritic soil samples analyzed, a characteristic that reduces plasticity and increases soil stiffness, thereby enhancing load-bearing capacity.

Preliminary foundation design based on SPT and semi-empirical methods resulted in 2,752 Continuous Flight Auger (CFA) piles with a diameter of 600 mm and 14m length. Later the total pile number was reduced to 1,504 with the results of advanced geotechnical survey based on DMT, SDMT, prior static load tests and numerical analysis.

4 STATIC LOAD TESTS

Figure 4 presents the summary graph of the static load test results for the analyzed piles, providing a clearer interpretation.

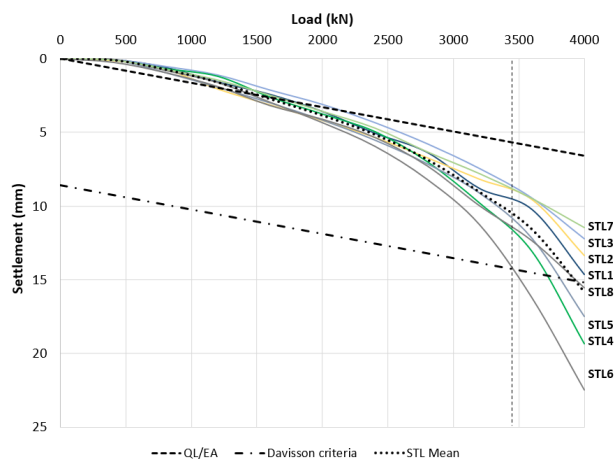


Figure 4. Static load test results.

Figure 4 presents the results of eight static load tests conducted on continuous flight auger (CFA) piles with a diameter of 600 mm and a length of 14 meters, showing an average concrete overconsumption of approximately 26%. Considering a maximum applied load of 4000 kN, the measured maximum settlements ranged from 11.45 mm to 22.48 mm. A convergence in the load-settlement response is observed up to approximately 3000 kN, beyond which increased dispersion among the curves becomes evident. This is particularly notable in the STL6 test, which exhibited the largest settlement during loading.

Nevertheless, a lower bound for the ultimate load capacity can be estimated using the Davisson criterion (Davisson, 1972), yielding a value close to 3500 kN when considering the STL6 result. This indicates that most of the tested piles had not yet fully mobilized their ultimate capacity within the applied load range. Given the consistency among the other test curves and

the typical reinforcement used for this pile type, an ultimate load capacity of 3600 kN was adopted for reference purposes.

Accordingly, for the case under analysis, the adoption of a working load of approximately 1800 kN per pile, corresponding to a minimum factor of safety of 2, is deemed appropriate. It is noted that the load capacity estimates obtained through semi-empirical methods were conservative, largely due to the influence of the lateritic soil, as previously discussed. To support numerical analyses concerning load transfer along the pile shaft, an average load-settlement curve was generated and is proposed for model calibration, in conjunction with field test data.

5 NUMERICAL ANALYSIS

Based on the results of the field tests, geotechnical parameters were obtained to support the development of a numerical model using PLAXIS 2D v21. The objective was to assess the stress distribution along the pile shaft, contributing to load capacity analyses and the definition of the required reinforcement.

An axisymmetric model was developed with dimensions of 35 × 35 meters, incorporating three refinement zones and a fine mesh consisting of approximately 6,995 elements, as illustrated in Figure 5. Displacements at the bottom boundary of the model were fully restrained in both horizontal and vertical directions, while the lateral boundaries were constrained horizontally. Vertical deformation was allowed at the top boundary. The pile was modeled as a cluster-type volume, considering the characteristic unit weight of reinforced concrete ($\gamma = 25 \text{ kN/m}^3$) and adopting linear elastic behavior with a modulus of elasticity $E = 30 \text{ GPa}$, estimated based on the guidelines provided by NBR 6118 (ABNT, 2024).

Due to the absence of laboratory tests, such as triaxial and oedometer consolidation tests, empirical correlations available in the literature were employed, particularly those proposed by Obrzud and Truty (2018), and Tazakka and Tirta (2024), to describe the stress-strain behavior of the soil using the Hardening Soil constitutive model.

Model validation was performed based on the results obtained from static load tests. Table 1 presents a summary of the parameters used in the model.

Table 1. Parameters used for the layers of the numerical model.

Layer	γ (kN/m ³)	ϕ' (°)	c' (kN/m ²)	E_{50}^{ref}	E_{oed}^{ref}	E_{ur}^{ref}
(MN/m ²)						
Medium-Dense sand (1)	19	40	15	50	50	150
Loose silty sand (2)	18	32	15	20	20	60
Dense sand (3)	20	40	15	120	120	360
Rock alteration (4)	22	45	6,000	215	172	1,550

To simulate the static load test in the numerical model, displacement increments were applied at the top of the pile, following the field test results, with the aim of verifying the maximum mobilized load. Considering the variability of the interface parameter (R_{inter}) in the concrete-soil interaction, three distinct models (MN1, MN2, and MN3) were developed, adopting R_{inter} values of 1.0, 0.9, and 0.8, respectively. This approach aimed not only to validate the model but also to perform a parametric analysis of representative interface values for CFA piles.

The model calibration was carried out based on the average load-settlement curve obtained from the static load tests

(SLTs), as well as the lower (STL7) and upper (STL6) boundary cases. The validation results are presented in Figure 6.

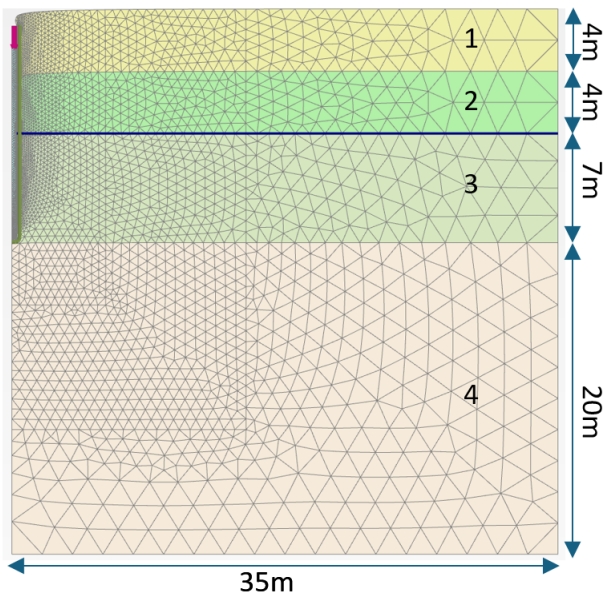


Figure 5. Numerical model developed.

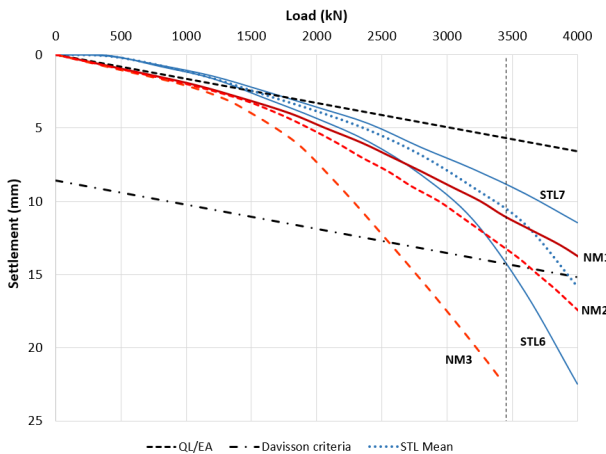


Figure 6. Numerical model validation.

It was observed that Model NM1, with an Rinter value of 1.0, showed the best agreement with the average results from the static load tests. Model NM2 exhibited a reasonable response, although closer to the lower bound observed. Model NM3, in contrast, proved to be conservative, falling outside the experimental range obtained from the SLTs. Therefore, it is verified that representative Rinter values for this type of pile, considering the stratigraphic profile in question, are on the order of 1.0. Accordingly, Model NM1 was adopted for the analysis of stress distribution along the pile and for reinforcement design, as illustrated in Figure 7.

Based on the numerical analysis, it is observed that the pile behaves predominantly through shaft friction. The load mobilized by shaft resistance was estimated at approximately 3,161 kN, accounting for about 79% of the pile's total load capacity. In contrast, the estimated end-bearing load was around 839 kN, representing approximately 21% of the total capacity.

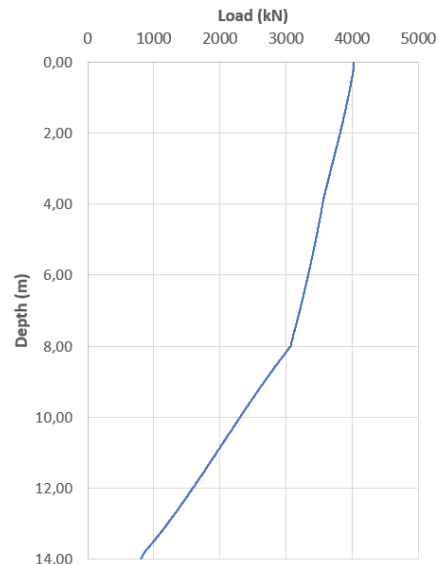


Figure 7. Bearing capacity estimation through methods considering static load test.

6 CARBON FOOTPRINT ESTIMATION

To estimate how much CO₂ was emitted by CFA Piles production some indexes were taken from both literature and interviewing foundation contractors. Basically, the carbon footprint was calculated by the sum of CO₂ emissions from concrete, steel and fuel for drilling machines. Table 2 summarizes the indexes used for CO₂ emissions.

Table 2. Parameters used for the layers of the numerical model.

Material	Index value	Unit
Concrete	0,35	Tons of CO ₂ per m ³ of concrete
Steel	1,85	Tons of CO ₂ per tons of crude steel
Diesel	2,69	Kg of CO ₂ per litre of diesel
Drilling rig	85	Liters of diesel per workday to drill 100m of pile length

According to a UK-based industry report, the production of concrete with 350 kg of cement per cubic meter generates 0,33 to 0,40 tons of CO₂ per cubic meter of concrete. Flower and Sanjayan (2007) estimated the emission of 0,29 to 0,41 tons of CO₂ per cubic meter of concrete with 300-400 kg of cement/m³. Therefore, it was assumed an index of 0,35 tons of CO₂/m³ of concrete.

The World Steel Association reported in 2023 that factories generate an average of 1,85 tons of CO₂ per ton of crude steel produced, thus the index used in this paper for steel production assumed the same average value of 1,85 tons of CO₂/tons of crude steel.

Local contractors reported an average of 88 liters of diesel per day for a standard Brazilian rig drilling 100 meters of soil. Corroborating with this information, Hosny *et al* (2016) estimated a consumption of diesel around 70-90 liters per workday for a standard rig to produce the same amount of pile length per day. The Environmental Protection Agency (EPA-US) shows a common conversion factor of 10,18 kg of CO₂ emissions per gallon of diesel, considering the Federal Register (2010) for gas emission standards. Thus, the index of CO₂ emissions assumed for diesel consumption is 2,69 kg of CO₂ per litre of diesel.

7 CARBON FOOTPRINT COMPARISON BETWEEN PRELIMINARY AND OPTIMIZED FOUNDATION DESIGN

The effectiveness of the optimized foundation design was evaluated by the difference in total material quantities related to CFA pile production, such as number of piles, total pile length, concrete volume, steel reinforcement weight and diesel fuel consumed by drilling rigs. The concrete volume calculation considered an average overconsumption of 30% which is a typical value for this type of soil profile.

Applying the indexes shown in Table 2, the carbon footprint of the preliminary foundation design was 5,620 tons of CO₂, although the optimized design indicated 3,071 tons of CO₂ emission. The reduction of 2,549 tons of CO₂ comparing the two different foundation designs illustrates how optimized foundations can have a huge environmental impact as well as economic benefits for the construction industry. Table 3 summarizes the results of the preliminary and optimized designs, as well as the associated CO₂ emissions.

Table 3. Quantitative resume of preliminary and optimized foundation designs of CFA piles.

Item	Optimized	Preliminary
Pile (unities)	1,504	2,752
Total pile length (m)	21,056	38,528
Concrete volume (m ³)	7,739	14,162
Steel reinforcement (kg)	169,952	310,976
Diesel (liters)	17,898	32,749
CO ₂ emission (tons)	3,071	5,650

8 CONCLUSIONS

An efficient optimization analysis of a Continuous Flight Auger (CFA) foundation design—based on numerical and statistical evaluation of load test results and aimed at ensuring structural safety—has yielded a marked reduction in carbon footprint. The numerical evaluation was conducted using PLAXIS 2D v21 and was informed by relevant literature.

The numerical modeling proved effective in reproducing the load–settlement behavior observed in the static load tests, highlighting the influence of the interface parameter on the pile–soil interaction. Among the evaluated configurations, an Rinter value of 1.0 showed the best agreement with the experimental results and was therefore adopted as representative for the analyzed CFA pile. The results also indicate that the pile behavior is predominantly governed by shaft resistance, accounting for 79% of the total load capacity, while end-bearing contributes about 21%. These findings support the reliability of the calibrated model for evaluating stress distribution along the pile and for use in design-related analyses.

This improvement was achieved through an assessment of concrete and steel consumption in the piles, and by employing established carbon footprint indicators reported in the literature. Compared with the preliminary design, a 45.6% reduction in carbon footprint was realized. Given the significant environmental impact of the construction industry, this reduction is particularly noteworthy. Moreover, as the resulting cost savings exceed those reported by the Programme and Construction study (2025), the considerable economic advantage of the optimized design is evident.

It is concluded that foundation design optimization, when executed with sound technical and managerial quality, can

significantly contribute to a project's environmental performance and positively influence its execution. It is recommended that such optimization be routinely pursued, supported by thorough analyses and validated through field testing.

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