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Review on carbon footprint in deep foundations: Case study for helical piles in Brasília, DF

Revisão da pegada de carbono em fundações profundas: Estudo de Caso para estacas hélice em Brasilia-DF)

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ABSTRACT: The construction industry is one of the main sources of carbon emissions. This article aims to evaluate the carbon footprint of helical piles using data from a construction project in Brasília, DF. The chosen methodology is Life Cycle Assessment (LCA), utilizing the Building Life Cycle Database (ICE) and national emission factors related to the fuel consumption of equipment. In addition to data analysis, the research will include a literature review of existing studies on civil construction, foundations, and carbon footprints. The objective is to identify the environmental impact of helical piles and contribute to more sustainable practices in the construction industry in Brasília. It is expected that the results will help in choosing more sustainable solutions and reducing carbon emissions associated with deep foundations, as well as raising awareness about the importance of considering the carbon footprint in construction projects in the city.

KEYWORDS: LCA methodology; Helix piles; Deep Foundations; Carbon footprint, construction sustainability.

1 INTRODUCTION

Climate change is having a significant impact on our environment, making it essential to adopt concrete measures to mitigate its effects. It is well known that energy consumption is the main source of greenhouse gas emissions, encompassing sectors such as transportation, electricity generation, heat generation, buildings, manufacturing, construction, fugitive emissions, and other forms of fuel combustion. For instance, in 2016, heat and electricity generation accounted for 30% of emissions, while transportation contributed 15%, and manufacturing and construction contributed 12% (WRI Brazil, 2020).

In a more specific context, greenhouse gas emissions in Brazil increased by 8.9% in 2016, reaching a total volume of 2.28 billion metric tons of carbon dioxide equivalent (CO_2e), compared to 2.09 billion recorded in 2015 (World Resources Institute Brazil, 2017). These figures position Brazil as the seventh-largest emitter of greenhouse gases globally. To meet the commitments of the Paris Agreement, the country has established ambitious climate targets, incentivizing the implementation of long-term measures to reduce emissions.

In this context, research on carbon footprint plays a crucial role. The carbon footprint, defined in 1990 (Gao et al., 2014), represents the cumulative amount of greenhouse gas emissions (GHG) generated by individuals, companies, or entities, measured in tons of carbon dioxide equivalent (CO_2e) emitted annually. GHG encompasses a range of gaseous compounds, such as perfluorocarbons, methane, carbon dioxide, nitrous oxide, hexafluoride, sulfur, and hydrofluorocarbons. Effective measures to reduce these carbon emissions include promoting sustainable buildings, the use of renewable energies, sustainable water consumption (Okeke et al., 2018), as well as the conservation of green spaces and the development of emissions measurement tools in construction (Cheng et al., 2011).

In the field of civil construction, deep foundations, such as helical piles, play a fundamental role in environmental sustainability. They are often employed in engineering projects that require structural support in challenging soils. However, the construction of these foundations involves significant consumption of resources, energy, and materials, substantially contributing to the carbon footprint of a project.

To evaluate the carbon footprint, various notations and symbols are used. In this article, the carbon emissions factor is denoted by "FE." The term "FETC" refers specifically to the emissions factor related to total fuel consumption, while "CE" denotes the carbon footprint in general. Additionally, "EC" is used to represent carbon emissions, while "EC-GHG" specifies greenhouse gas emissions. It is crucial that these definitions are clearly understood to ensure accurate analysis.

Recognizing the importance of adapting deep foundations to make them more sustainable is imperative, as this can contribute to the reduction of greenhouse gas emissions. Strategies include the use of materials with lower carbon intensity, minimizing resource and waste consumption, employing energy-efficient equipment and technologies during the construction of these foundations, and effective management of construction and demolition waste, emphasizing recycling.

Therefore, when considering the construction of deep foundations, especially in challenging soils, it is crucial to adopt a sustainable approach that takes into account the environmental impact. Such an approach not only helps meet carbon emission reduction goals but also results in more resilient and durable structures, providing long-term benefits to the environment and society.

Most studies emphasize the importance of assessing emissions during the construction phase of buildings (Keoleian et al., 2001; Junnila and Horvath, 2003; Junnila et al., 2006). However, few studies focus on the construction phase of foundations, which involves the use of large volumes of steel, concrete, and heavy machinery, resulting in significant CO_2 emissions. According to the Paris Agreement, signed on December 12, 2015, and ratified on November 4, 2016, it became necessary for countries responsible for about 55% of global emissions to commit globally. In this context, each country set specific targets, and the European Union, along with 193 other countries, including Brazil, which together account for more than 90% of greenhouse gas emissions, adhered to the treaty. The goal of this agreement is to achieve decarbonization targets by 2050 (IPCC, 2018).

Several countries have implemented emission control policies, but in Brazil, the inclusion of a carbon tax in tax reform has not yet been defined. According to a report by WRI Brazil in 2020, this document offers valuable insights into possible paths toward a transition to a low-carbon economy. The report indicates that the country is ready to adopt new economic approaches aligned with the low-carbon economy and highlights the benefits of adopting these policies (WRI Brazil and The New Climate Economy, 2020).

Based on the justifications presented above, the proposed research finds solid grounds for its realization. The gap in studies specifically addressing the construction phase of foundations, along with the need for emission control policies aligned with international commitments, such as the Paris Agreement, and the potential for a low-carbon economy, highlight the relevance of this study. Additionally, the WRI Brazil 2020 report corroborates the country's readiness to adopt sustainable economic approaches, emphasizing the importance of investigating the carbon footprint in helical piles in the region. Therefore, the proposed research is justified as a significant step toward understanding and mitigating CO_2 emissions associated with this phase of construction in Brasília-DF.

2 CARBON FOOTPRINT IN DEEP FOUNDATIONS

The carbon footprint of deep foundations can be significant due to the intensive use of construction materials, transportation of heavy materials and equipment, and the use of large machinery for drilling and excavation. The carbon footprint of these foundations can be reduced by adopting more sustainable construction techniques, such as using low-carbon construction materials and implementing more efficient transportation models. Additionally, the use of renewable energy-powered equipment and the adoption of construction techniques that reduce waste and pollution can also decrease the carbon footprint of deep foundations.

Life Cycle Assessment (LCA) is a methodology used to assess the environmental impacts of processes or products. In the case of deep foundations, LCA considers the environmental impacts of all phases of the foundation construction process, including material extraction, manufacturing, transportation, installation, and disposal. This includes an analysis of the types of materials used in the foundation, the amount of energy and water used during construction, and the emissions of greenhouse gases and other pollutants.

The Life Cycle Assessment (LCA) Matrix for Continuous Flight Auger (CFA) Pile is a tool that allows the assessment of the environmental impacts of this foundation technique. It is divided into life cycle stages of the structure, from raw material extraction to the end of the foundation's service life.

2.1 *Definition of the limit for calculating the carbon footprint in continuous flight auger piles in this study*

For the calculation of the carbon footprint during the installation phase of continuous flight auger piles, a case study of a residential building located at Brasília-DF, was used. The building comprises five floors, a penthouse, common areas, and two basements. The foundation uses continuous flight auger piles and sheet piles for containment. Six SPT tests revealed varied soil, ranging from soft to stiff sandy-silty clay to hard clayey silt, with the water table at 21 meters. The soil resistance varied from Nspt 8 (soft) to 50 (very compact). The piles have an average depth of 20.6 meters, a diameter of 60 centimetres, and support loads of 30 to 600 tons per pile. Thus, the limit of the carbon footprint during the installation phase of continuous flight auger piles is established in Figures 1 and 2.

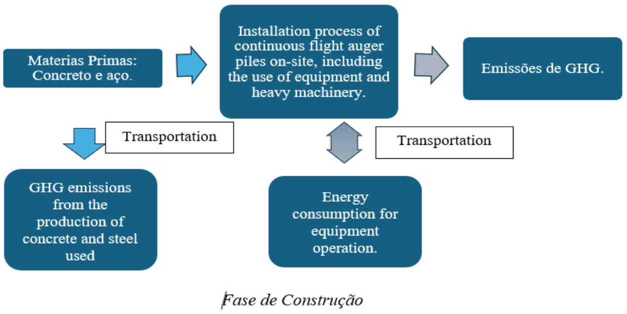

Figure 1. Limit of the carbon footprint in the construction phase of continuous flight auger piles. According with Bilec (2007)

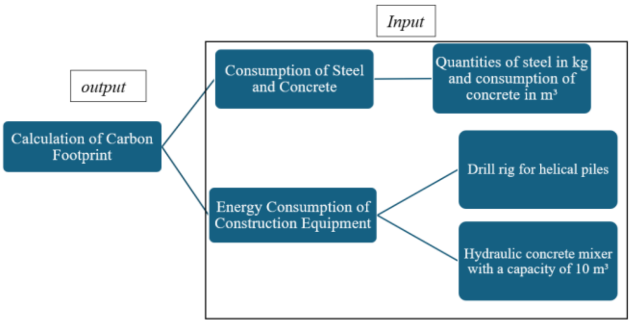

Figure 2. Helical pile limits for settlement calculation, including transport and installation phase. According with Li, et al (2019).

2.2 *Calculation of emissions.*

In this section, we outline the methodology for calculating emissions. Our approach closely mirrors that employed by Zhang and Wang (2016). We will evaluate the carbon emissions associated with the construction of continuous flight auger piles in the collapsible soil of the Federal District. This assessment adopts methodological principles similar to those detailed by Zhang and Wang. The analysis encompasses various aspects, including quantifying carbon emissions linked to concrete transportation necessary for pile foundations, as well as emissions stemming from the production and utilization of critical materials like steel and concrete. Furthermore, we will consider specific carbon emissions generated during the construction phase of the continuous flight auger piles.

By applying this approach, in alignment with Zhang and Wang's work, we aim to ensure a consistent evaluation of the carbon emissions inherent in the implementation of these piles, thereby contributing to a comprehensive analysis of the environmental impact of this construction practice. We will utilize the following equations, reflecting the methodology proposed by Zhang and Wang:

Manufacturing Emissions of Materials:

$$Cmat = \sum Ai \times FEiCmat = \sum Ai \times FEi \qquad (1)$$

Emissions from On-Site Construction Activities:

$$Cact = \sum Aj \times FEjCact = \sum Aj \times FEj \qquad (2)$$

Emissions from Concrete Transportation:

$$ETC = QCT \times FETC \qquad (3)$$

Total Carbon Footprint:

$$RCTotal = (Cmat + Cact + ETC) \qquad (4)$$

The amount of carbon emissions related to materials ($Cmat$) is determined by the quantity of material or activity of each type, represented by Ai, multiplied by the specific carbon emission factor for that material or activity, represented by FEi. Similarly, carbon emissions associated with activities performed at the construction site ($Cact$) are calculated by multiplying the quantity of each type of activity, represented by Aj, by the specific carbon emission factor for that activity, represented by FEj.

Additionally, emissions from concrete transportation (ETC) refer to emissions generated during the transportation of concrete from the production site to the construction site of the helical piles. These emissions are determined by multiplying the quantity of transported concrete (QCT) by the specific carbon emission factor for concrete transportation ($FETC$). For a more comprehensive and accurate assessment of environmental impact, concrete transportation emissions are integrated into the calculation of the total carbon footprint ($RCTotal$), allowing for consideration of all emissions stemming from material manufacturing, on-site activities, and transportation required for helical pile foundations.

2.3 Determination of the Carbon Emission Factor

To calculate the carbon emission factors (CE) for various construction materials in civil engineering projects, we use the recognized and comprehensive "Carbon and Energy Inventory" (ICE) database, as referenced by Hammond and Jones (2011). The research approach is aligned with Hammond and Jones (2011) and the ICE methodology, focusing on the calculation of specific CO_2 emissions for reference units, allowing for the precise determination of carbon emission factors. This method provides a detailed analysis of CO_2 emissions throughout the life cycles of materials and processes, from extraction to application.

The carbon emission factor, representing CO_2 emissions per unit of activity or product, is determined as follows (Equation 5): Emission Factor = Specific Emissions / Reference Unit. This approach emphasizes the importance of using reliable and up-to-date data from recognized sources, such as national emission inventories or scientific databases. In the absence of Brazilian data, we use the ICE database, as done by Hendler K. J. (2020). ICE provides comprehensive information on carbon emissions related to construction materials and processes, enabling accurate data on the emissions of various construction components and facilitating a detailed analysis of the carbon footprint of deep foundation structures. In compliance with the ICE database's terms of use, we provide proper attribution to the authors and ensure access to the most recent version.

Furthermore, when considering the environmental impact of concrete transportation, the carbon emission factor is crucial. This factor reflects greenhouse gas emissions from concrete transport vehicles, influenced by factors such as distance, vehicle type, fuel, and traffic conditions. Sustainable transport practices are essential to reduce this environmental impact. Emission factor data will be obtained from Costa (2012) and the greenhouse gas emission inventory guidelines developed by SindusCon (2022). This data will be presented in tabular format to enhance understanding and support sustainable decision-making.

Table 1. Portland Cement, Steel and Concrete Emission Factor. Hammond and Jones (2011).

Material	EC ($KgCO_2/Kg$)	EC-GHG ($KgCO_2e/Kg$)
CEMI Portland Cement	0,93	0,95
Virgin bar or rod	2.58	2.74
25/30 MPa	0.106	0.113

Table 2. Emission Factors for Mixer Truck and Drill. Source: Costa (2012) and SindusCon (2022).

Equipment	EC (tCO_2/L)	EC-GHG (tCO_2e/L)
Concrete Mixer Truck e CFA Drill	0,0032(Costa)	3,140 (SindusCon)

3 DATA COLLECTION

In this section, the main sources of emissions associated with concrete transportation and continuous flight auger pile installation will be presented. Aspects such as the manufacturing of materials, specifically concrete and steel used in the structure, and the energy consumption involved in the concrete transportation processes will be discussed.

3.1 Drill and Mixer Usage and Fuel Consumption in Construction

Using the values related to these 79 piles, a statistical analysis was conducted, which resulted in the measures of central tendency presented in Table 3. This analysis was based on data provided by Sonda Engenharia and Concrecon, which included operational records and monitoring data for the equipment used in the construction of the continuous flight auger (CFA) piles. The data were obtained from the Perfuratriz Hidráulica EM 800S – CZM and the HTM 1004 hydraulic mixers. The reliability of the data was ensured through meticulous data collection and analysis of the drilling and concreting times.

Table 3. Statistical Measures for Drilling and Concreting Time at a Construction Site in Brasília, DF

Statistical measures calculated for drilling and concreting of continuous flight auger piles calculated in minutes			
AM of concreting time	12,9	AM of drilling time	29,3
SD of concreting time	6,4	SD of drilling time	8.9
CV for concreting time	49,6	CV for drilling time	30,2

Measures of central tendency, including arithmetic mean (AM), standard deviation (SD), and coefficient of variation (CV), were calculated to evaluate the efficiency and variability of the operations. The data were carefully processed and organized to facilitate accurate statistical analysis, providing a clear view of the operational performance and variability of the pile installation processes.

3.2 Helical Pile Material Quantity

The data related to the materials used in the construction of helical piles, which have depths ranging from 15 to 23 meters and a diameter of 60 centimeters, were utilized. These details were kindly provided by SCCAP, the company responsible for the foundation project, and were directly extracted from the project's foundation plan, and can be found in Table 4.

Table 4. Average Steel and Concrete Consumption per Pile.

Data Type	Average per Pile
Steel Consumption	86,54 kg
Concrete Consumption	6,65 m³

3.3 Data on Concrete Transportation to the Construction Site

The transportation of concrete to the construction site located in the city of Brasília, approximately 7.6 miles away from the production point. A total of 525.1 cubic meters of concrete were used in the concreting of the 79 piles. This is equivalent to 53 truck trips, each with a concrete-carrying capacity of 10 cubic meters. The distance covered on each trip was approximately 7.6 miles, resulting in a total of 53 trips to complete the concreting process for the 79 piles. The transportation calculation for hydraulic concrete mixer trucks involves 56 trips, each covering approximately 7.6 miles, to transport 79 piles. This results in an average mileage of 5.39 miles per pile.

3.4 Labor data during the construction of helical piles

According to the information provided by the construction company, there were 3 people in the field at the time of pile construction, along with 1 supervising engineer. With this data, is it possible to estimate the carbon footprint related to the labor force.

4 RESULTS

As detailed in the previous sections, this study involved an assessment of construction methods, material consumption, transportation, and equipment use. All this information was carefully collected and analysed to calculate the carbon emissions associated with this construction process.

4.1 Calculation of the carbon footprint from equipment usage

According to the emission factor of the machines, as detailed in Table 2, and the time data collected in Section 3, we will perform the calculation in Table 5 to estimate the carbon emissions associated with this equipment during the project execution according to Equation 2 for calculating emissions per activity on the construction site.

Before proceeding with the calculations, it is important to convert the volume of concrete used in each pile from cubic meters to metric tons. To convert 6.65 m^3 to metric tons, I should multiply it by 2.4 t/m^3, which would result in a value of 15.96 t.

Table 5. Calculation of emissions produced by the equipment.

Equip-ment	Usage Time (hours)	Fuel Consump-tion per Hour (L/h)	Carbon Emissions per Pile (tCO_2e)
Hydraulic Con-crete Mixer	1/6	59,85	31,3215
Drilling Ma-chine	13/30	6,4	8,7083
Total ($KgCO_2e$)			40.029,8

4.2 Carbon Footprint Calculation for Materials Used in the Installation of Helical

The results of carbon emissions related to these materials will be presented in Table 6, using the emission factors of the materials found in Table 1.

Table 6. Calculation of emissions produced by the steel-reinforced concrete.

Material	Quantity of Material /Pile (kg)	Emission Factor ($KgCO_2e/Kg$)	Carbon Emis-sions Calcu-lation per Pile $KgCO_2e$
30 MPa Concrete	15960	0.113	1803,48
Civil Steel	86,54	2.74	237,12
Total			2040,6

4.3 Carbon footprint calculation for transportation

To cover 5.39 miles (approximately 8.67 kilometers) with a total weight of about 21.06 metric tons and a fuel consumption rate of 0.0196 L/t.km, you would consume approximately 4.117 liters of fuel. The machine fuel consumption, as reported by SindusCon, is

4,117 liters, with an emission factor of 3.140 tCO$_2$e per liter. This calculation results in carbon emissions of approximately 12.927 tCO$_2$e per pile.

4.4 *Calculation of the carbon footprint produced by the workforce.*

According to Li's 2019 study, during a work shift with 30 people at the construction site, a significant amount of carbon dioxide consumption was estimated. As indicated in Table 8, it was estimated that 460 kgCO2 were produced per shift for 30 people. However, it's important to recognize that conditions and activities may vary between the two contexts. Therefore, the numbers presented here are used as an approximate estimate of carbon emissions related to the workforce in this study.

Table 8. Calculation of emissions produced by the personnel on the construction site.

Source of Consumption	Specification	Carbon Footprint per Shift (kgCO$_2$)
Office	4 people	61,33

4.5 Summary of Results

Table 9 shows two key results obtained regarding the carbon footprint of continuous flight auger pile construction.

The total carbon footprint per continuous flight auger pile is calculated by summing the emissions of each component, resulting in 55.058,73 kgCO$_2$e per continuous flight auger pile.

Table 9. Summary of Carbon Footprint Results.

Aspect Analysed	Emissões de Carbono (kgCO$_2$e/estaca)
Equipment Usage	40.029,00 (73 %)
Materials - Concrete and Civil Steel	2.040,6 (4%)
Concrete Transportation	12.927,00 (23%)
Labor (Li, 2019)	61,33 (0,1 %)
Total Carbon Footprint /pile	55.058,73

5 CONCLUSIONS

Table 9 provides a summary of the results from the analysis of the carbon footprint associated with the construction of continuous flight auger piles in a specific project in Brasília, DF. This study is crucial for assessing the environmental impact of this construction process and offers valuable insights for adopting more sustainable practices in the construction industry.

Key Findings: The results highlight that carbon emissions are significantly influenced by the use of equipment, particularly hydraulic concrete mixers and continuous flight auger rigs. This finding underscores the need to consider more efficient and lower carbon footprint alternatives in the selection and use of equipment during construction. Additionally, concrete transportation also represents a significant portion of emissions, emphasizing the importance of optimizing transportation logistics, exploring on-site concrete pouring options, and reducing the distance between the concrete plant and the construction site.

Limitations and Necessary Improvements: The study had some limitations, including the fact that the LCA matrix developed for piles is based on existing literature.

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