

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

Revue de l'empreinte carbone dans les fondations profondes: Étude de cas pour les pieux hélicoïdaux à Brasília, DF

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ABSTRACT: It is essential to highlight that the civil construction industry is a significant contributor to carbon emissions. The aim of this article is to develop a flowchart using the Life Cycle Assessment (LCA) methodology, which has already been employed to calculate the carbon footprint of deep foundations. This flowchart will be specifically tailored to assess the carbon footprint of helix piles used in a building project located in Brasilia, DF. Alongside this, the article will include a literature review of previous research within the foundation sector concerning carbon footprint analysis.

RÉSUMÉ: Il est essentiel de souligner que l'industrie de la construction civile est un contributeur significatif aux émissions de carbone. L'objectif de cet article est de développer un organigramme en utilisant la méthodologie d'Analyse de Cycle de Vie (ACV), qui a déjà été employée pour calculer l'empreinte carbone des fondations profondes. Cet organigramme sera spécifiquement adapté pour évaluer l'empreinte carbone des pieux hélicoïdaux utilisés dans un projet de construction situé à Brasilia, DF. En parallèle, l'article comprendra une revue de la littérature des recherches précédentes dans le secteur des fondations concernant l'analyse de l'empreinte carbone.

Keywords: LCA methodology; helix piles; deep foundations; carbon footprint.

1 INTRODUCTION

Climate change is exerting 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 (CO₂e), 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. 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 (CO₂eq) 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, which contribute to a healthy environment in the long term, 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 and drilled piles, play a fundamental role in environmental sustainability. They are often employed in engineering projects that require structural support in challenging soils, such as collapsible soils. However, the construction of these foundations entails significant consumption of resources, energy,

and materials, substantially contributing to the carbon footprint of a project.

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, waste and resource consumption minimization, the use of 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 such as collapsible soils, it is crucial to adopt a sustainable approach that takes into account the environmental impact. Such an approach not only contributes to meeting 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, G et al, 2001; Junnila and Horvath, 2003; Junila et al, 2006). However, it is notable that few of these studies emphasize the construction phase of foundations, which involves the use of large volumes of steel, concrete, and heavy machinery, resulting in significant CO₂ emissions to the environment. 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 worldwide. In this context, each country established specific targets, and the European Union, along with 193 other countries, including Brazil, account for more than 90% of greenhouse gas emissions and have 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 towards 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 towards understanding and mitigating CO₂ 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

The calculation of the carbon footprint during the Installation phase of continuous flight auger piles will be carried out. In this way, the limit of the carbon footprint in the installation phase of continuous flight auger piles is established in Figures 1 and 2.

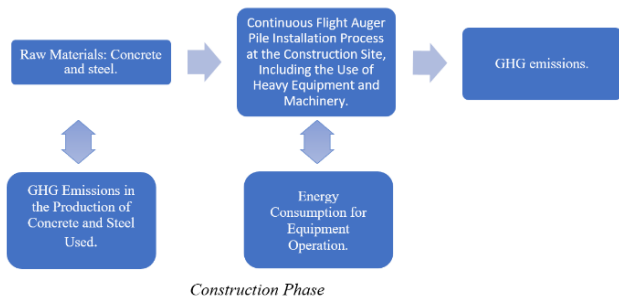


Figure 1. Limit of the carbon footprint in the construction phase of continuous flight auger piles. According with Bilec (2007).

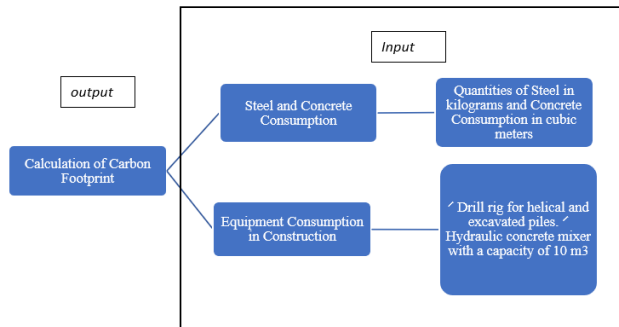


Figure 2. Helical pile limits for settlement calculation, including transport and installation phase. According with Li, et al (2019).

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 foundation, 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. As per the preceding paragraph, we will utilize Equations 1, 2, 3, 4, and 5, which reflect the methodology proposed by Zhang and Wang.

Manufacturing Emissions of Materials:

$$C_{mat} = \sum A_i \times FE_i, \quad (1)$$

Emissions from On-Site Construction Activities:

$$C_{act} = \sum A_j \times FE_j, \quad (2)$$

Total Carbon Footprint:

$$C_{Total} = (C_{mat} + C_{act}), \quad (3)$$

Emissions from Concrete Transportation:

$$ETC = QCT \times FETC, \quad (4)$$

Total Carbon Footprint R:

$$RC_{Total} = (C_{mat} + C_{act} + ETC), \quad (5)$$

The amount of carbon emissions related to materials (C_{mat}) is determined by the quantity of material or activity of each type, represented by A_i , multiplied by the specific carbon emission factor for that material or activity, represented by FE_i . Similarly, carbon emissions associated with activities performed at the construction site (C_{act}) are calculated by multiplying the quantity of each type of activity, represented by A_j , by the specific carbon emission factor for that activity, represented by FE_j . Therefore, the total carbon footprint (C_{Total}) is obtained by adding the emissions from material manufacturing (C_{mat}) to the emissions associated with on-site activities (C_{act}). Additionally, concrete transportation emissions (ETC) refer to emissions generated during the transportation of concrete from the production site to the construction site of 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 (RC_{Total}), allowing for consideration of all emissions stemming from material manufacturing, on-site activities, and transportation required for helical pile foundation.

2.3 Determination of the carbon emission factor

To calculate carbon emission factors (CE) for various construction materials in civil engineering projects, we use the widely recognized and comprehensive "Carbon and Energy Inventory" (ICE) database, as referenced in Hammond and Jones (2011).

Research approach aligns with Hammond and Jones (2011) and the ICE methodology. We focus on

calculating specific CO₂ emissions for particular reference units, enabling us to determine carbon emission factors. This method offers a detailed analysis of CO₂ emissions throughout material and process life cycles, from extraction to application.

The carbon emission factor, representing CO₂ emissions per unit of activity or product, is determined as follows (Equation 6): Emission Factor = Specific Emissions / Reference Unit.

Emphasizing 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, reliance will be placed on the ICE database, as also done by Hendler K. J. (2020). ICE provides comprehensive information on carbon emissions related to construction materials and processes. By using ICE, the aim is to obtain accurate data on the carbon emissions of various construction components, facilitating a detailed analysis of deep foundation structures' carbon footprint. Respecting the terms of use of the ICE database, proper attribution to the authors will be provided, and access to the most recent version ensured. Regarding the environmental impact of concrete transportation, the carbon emission factor is crucial. This factor reflects greenhouse gas emissions from concrete transport vehicles. Elements like distance, vehicle type, fuel, and traffic conditions influence these emissions. Sustainable transportation practices are essential to reduce this environmental impact. Data on emission factors will be sourced from Costa (2012) and the greenhouse gas emission inventory guidelines developed by SindusCon (2022). This data will be presented in a table 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)
CEM I 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. To enable this analysis, the data was properly processed and organized.

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

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 m ³

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 a comprehensive assessment of construction methods, soil analysis, 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 m³ to metric tons, I should multiply it by 2.4 t/m³, which would result in a value of 15.96 t.

Table 5. Calculation of emissions produced by the equipment.

Equipment	Usage Time (hours)	Fuel Consumption per Hour (L/h)	Carbon Emissions per Pile (tCO _{2e})
Hydraulic Concrete Mixer	1/6	59,85	31,3215
Drilling Machine	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 Emissions Calculation 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_{2e} per liter. This calculation results in carbon emissions of approximately 12.927 tCO_{2e} 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 carbon dioxide consumption was estimated, as indicated in Table 7, where 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 7. 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 8 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_{2e} per continuous flight auger pile.

Table 8. Summary of Carbon Footprint Results.

Aspect Analysed	Carbon Emissions (kgCO _{2e} /pile)
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 8 presents a synthesis of the results obtained from the analysis of the carbon footprint associated with the construction of continuous flight auger piles in a specific project in Brasília, DF. This analysis is crucial for assessing the environmental impact of this construction process and, at the same time, provides valuable insights for the adoption of more sustainable practices in the construction industry. A notable point is the considerable impact of carbon emissions resulting from the use of equipment, especially hydraulic concrete mixers and continuous flight auger rigs, as well as bored piles in the drilling and concreting process. This finding underscores the need to consider more efficient and lower carbon footprint alternatives in the selection and use of equipment during the construction process. Additionally, concrete transportation also represents a significant portion of emissions in pile construction, 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 as strategies to minimize transportation-related emissions. It is important to note that most emission factors were derived from the literature and attempt to replicate the reality of the Brazilian industry, although this approach may not be entirely accurate.

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