French working group "geotechnics and climate change" - Carbon footprint of geotechnical structures: assessment and integration into design

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ABSTRACT: IPCC reports have demonstrated that greenhouse gas (GHG) emissions and climate change are strongly correlated. The infrastructure construction sector (public works activities only) accounts for about 3,5% of France's total carbon emissions. Considering that the total impact of this field is even greater when including the building sector and other related activities, geotechnics can and must play a significant role in reducing these emissions. Despite the multiple environmental impacts, the urgency of climate change necessitates a focus on GHG emissions, which can be identified and mitigated throughout project execution by prioritizing sustainable and durable technical choices. Ideally, carbon footprint and other environmental impact assessments should cover the entire lifecycle of structures, from site investigation to exploitation, including maintenance and end-of-life site restoration. Awareness of these issues and a thorough understanding of its consequences will enable the geotechnical domain to propose effective solutions. Within this framework, the French Committee of Soil Mechanics and Geotechnics (CFMS) and the French Committee of Engineering Geology (CFGI) are working on the establishment of recommendations to provide tools for evaluating, controlling, and reducing emissions related to geotechnical works considering the French context. This work seeks to provide geotechnical professionals with quantitative methods for assessing the carbon footprint of geotechnical structures, as well as essential tools and databases. It also provides best practices for reducing this footprint and qualitative assessments of other environmental impacts within a sustainable development framework. Therefore, it underscores the importance of incorporating environmental impact assessments in geotechnical engineering to mitigate climate change effects and promote sustainable development.

KEYWORDS: sustainable geotechnical engineering, carbon footprint, life cycle assessment, geotechnical structures.

1 INTRODUCTION, CHALLENGES AND OBJECTIVES OF THE WORKING GROUP

At a time when the world is facing the major challenge of climate change resulting in serious changes to our environment, France has adopted (in 2015 then revised in 2018-2019) a National Low Carbon Strategy which aims to achieve carbon neutrality by 2050 (MTES, 2020). In the efforts to reduce greenhouse gas (GHG) emissions required of all socioeconomic sectors, including construction, geotechnical engineering must play a significant role.

To this end, the French geotechnical community, through both societies CFMS (French Society of soil Mechanics and Geotechnics) and CFGI (French Society of Geological Engineering), launched a working group (WG) in 2022 to assess the carbon footprint of geotechnical structures. This working group brings together some twenty members representing geotechnical designers, contractors, public and research establishments.

The challenges and objectives of this working group are:

- Define and harmonize the method for calculating the carbon footprint of a "geotechnical structure", with the aim of identifying the most emissions-intensive work items.
- Identify ways of reducing these emissions and describe best practices for controlling emissions in geotechnical projects.

The term "geotechnical structures" includes a large list of structures in the scope of geotechnical engineering, as: earthworks, road and railways infrastructures, shallow and deep foundations, retaining walls, soil improvements, etc.

After three years' work, the WG has drawn up recommendations for assessing the carbon footprint of geotechnical structures, which will be published in 2026 (CFMS, 2026). It is important to note that this work was carried out in parallel with the working group on the adaptation of geotechnical structures to climate change.

This article summarizes the key points of this text: the general approach to carbon footprint assessment and the best practices to be implemented in design and works stages, to control and GHG emissions.

2 GENERAL METHOD FOR THE CARBON FOOTPRINT ASSESSMENT

2.1 *Life Cycle assessment*

Life Cycle Assessment (LCA) is a methodology developed to assess the environmental impacts of a system (which can be a product, a service, or a process) throughout its entire life cycle. It is a multi-stage approach that quantifies impacts across all stages of a product's life cycle, from cradle to grave, including production of raw materials and energy inputs, manufacturing and packaging, transportation and distribution, use or operation and end of life (waste treatment, recycling, reuse...). LCA is also a multi-criteria approach considering the different environmental impacts generated by the assessed system. These impacts are related to the use or depletion of primary resources (metals, fossils, water...), the adverse effects caused by emissions to air, soil and water, or the production of solid waste. Damages to human health, ecosystem quality and resources are then considered. The LCA methodology is described in the International Organization for Standardization (ISO, 2006) 14040 and standards and follows four phases: definition of the objectives and scope of the study, calculation of the life cycle inventory, assessment of environmental impacts, and interpretation.

For the carbon footprint assessment, the working group recommends applying the LCA approach by conducting a single-criterion analysis using exclusively the "carbon footprint" indicator.

It is, of course, possible to extend the approach to other environmental indicators if the aim is to assess the environmental footprint (in the broad sense) of a structure. However, the working group decided to focus on the "carbon footprint" indicator for the purposes of the current study.

2.2 *Carbon footprint assessment*

GHG emissions related to an activity are calculated by multiplying operational data (such as mass or area) by the relevant emission factor, which represents the quantity of greenhouse gases emitted by an activity or material, usually expressed in carbon dioxide equivalent, CO_2eq. Introduced by the IPCC, this unit simplifies the comparison of different GHG by consolidating their impacts into a single index, representing CO_2 emissions that result in the same radiative forcing.

The carbon footprint is defined by the sum of all emissions associated with each activity related. Therefore, it is crucial to clearly define the scope of the studies and identify the sources of emissions.

In conventional geotechnical projects, the main sources of emissions generally remain the same, although their relative importance may vary depending on the techniques used. These sources are as follows:

- Emissions linked to the manufacture of materials.
- Transport of materials from the manufacturing plant to the construction site (truck, train, ship, etc.).
- Energy consumed at the construction site (fuel, grid electricity, etc.).
- Transportation of people to the construction site.
- Transportation of equipment (delivery/removal).
- Equipment manufacturing.
- Transportation of waste from the construction site to the treatment site.
- Waste treatment.
- Land use change, etc.

It is important to note that the carbon footprint is subject to uncertainties stemming from the assumptions made. Consequently, the aim of this assessment is not to deliver a precise value but to offer a useful order of magnitude for evaluating current challenges and identifying potential avenues for reduction.

Several frameworks are available for conducting a GHG emissions inventory, providing principles and methodological foundations for a successful analysis: relevant standards include ISO 14040, ISO 14044, NF EN 17472, and EN 15084+A2 (along with its French national annex).

2.3 *Key parameters*

In the construction sector, a few key materials are responsible for the majority of carbon emissions. These emissions come primarily from the energy-intensive processes involved in producing these materials, particularly during extraction, processing, and manufacturing. Here's a closer look at some of the most impactful materials:

- Cement/grout/concrete.
- Steel used in the form of tubes, sheets or reinforcement for concrete.
- Lime and hydraulic binders used in soil treatments.

Cement production accounts on its own for about 2% of anthropogenic GHG emissions in France (Guiraud, AFGC, 2022), and this is linked to the cement production process. Cement production requires high temperatures and burns fossil fuels (coal, heavy oil), and the decarbonization of limestone is a chemical reaction, which emits CO2. Since cement is the main component of concrete and grout, its carbon impact extends to all these commonly used materials. A mean value for the carbon content of Portland cement is between 900 and 1000 kg CO_2eq. per ton, whereas for the other components of concrete the emission factors are below 100 kg CO_2eq per ton. The cement type must always be known for any deep foundation and ground improvement technique carbon footprint calculation.

Steel is a vital structural material in construction—used in formwork, piles, reinforcements, and sheet piles. Its environmental impact varies greatly depending on how it's produced. Steel made in traditional blast furnaces (from iron ore and coal) is highly carbon-intensive. However, there's a major advantage: steel is 100% recyclable, and recycled steel produced via Electric Arc Furnaces (EAF) has a much lower carbon footprint—especially if the electricity used is from renewable sources. In many regions, reinforcing bars and structural profiles already contain a high proportion of recycled content, making them a more sustainable option compared to virgin steel.

Lime, often used for soil stabilization, has a production process similar to that of cement: the calcination of limestone. This results in significant CO_2 emissions, although slightly lower than Portland cement on a per-ton basis. Hydraulic binders, which are often blends of lime and other reactive materials, also carry a high embodied carbon. Their impact depends on the specific formulation, but they remain carbon-intensive due to their energy-demanding production and chemical decomposition processes.

One of the objectives of the recommendations guide is to provide orders of magnitude for carbon emissions for the main products available on the market, with a focus on upcoming standards developments.

2.4 *Databases of emission factors and carbon calculators*

When conducting a life cycle assessment, it is important to have a single reference system and to ensure that the impact factors used cover all the impacts being studied and the entire life cycle (unless you choose to explicitly limit yourself to certain stages).

One of the key points is the certification of emission factor data according to the relevant standards.

A set of indicative emission factor values and their associated references are provided in the recommendations for:

- Construction materials (metals, cements, hydraulic binders, and other materials).
- The main earthworks operations, based on average data on machine consumption and performance or specific site monitoring.

An inventory of commercially available and open-source carbon calculators was also compiled. The following table lists the free tools available to the public for the main types of geotechnical structures.

Table 1. Recommended free and open-source carbon calculators

Geotechnical field or structure	Carbon calculator	Reference Organization
Earthworks, roads and linear infrastructures	SEVE TP	FNTP, 2025
Foundations, retaining structures, soil improvement	EFFC/DFI CIOGEN SEVE TP	EFFC, 2023 AFGC, 2024 FNTP, 2025
Bridges, including foundations	CIOGEN SEVE TP	AFGC, 2023 FNTP, 2025

3 GENERAL RECOMMANDATIONS FOR THE CARBON FOOTPRINT MITIGATION

3.1 *Integration of carbon footprint assessment in the standard geotechnical missions*

It is crucial to provide the project leader with information tailored to the level of detail required and the decision-making challenges. The geotechnical engineer is suited to perform this task within the scope of their expertise due to their understanding of technical solutions and execution methods.

To optimize the strategy for reducing GHG emissions, it is essential to act at every stage. In the French context, it is advisable to implement actions that align with the sequence of standard missions outlined in the French Standard of Geotechnical Engineering NF P 94-500 (AFNOR, 2013). The earlier the carbon issue is addressed in the project's initial phases, the greater the potential for GHG reduction.

The Table 2 presents several proposals related to the carbon subject (geotechnical studies scope), highlighting the minimum recommendations (underlined) as well as additional recommendations that must be adjusted to the specific context and requirements.

Table 2. Some recommendations to be implemented at various phases of a geotechnical project to manage and reduce its carbon footprint.

Feasibility studies (G1)	**Design studies (G2)**	**Execution stage (G3/G4)**	**Diagnosis studies (G5)**
Identify the primary sources of GHG emissions and explore strategies for their reduction	Assess the carbon footprint of the solution examined	Actualize the carbon footprint incorporating the supplies and works methods	Integrate the carbon footprint into the technical diagnostic solution
Provide an estimate of the footprint of the proposed structures	Identify possible pathways to reduce emissions	Manage the carbon footprint of structures and ensure compliance with specifications	
Suggest possible changes (placement, functionality, etc.) based on the expected impact	Include the carbon footprint in multi-criteria analyses to support the decisions	Monitor GHG emissions and propose alternatives to reduce	

3.2 *Quality of the geotechnical investigations*

Quality and reliability of geotechnical investigations are essential for obtaining detailed knowledge of soil characteristics and their variability across the site. They enable engineers to accurately design structures according to specific ground constraints, reduce uncertainties and risks, thus optimizing resources and costs, ultimately minimizing the carbon footprint of structures.

The benefits include:

- Fine-tuning to specific site conditions.
- Fewer uncertainties on geotechnical parameters.
- Better anticipation of environmental and technical risks (pollution, groundwater, cavities, etc.).
- Greater precision in foundation design and therefore lower costs.

On the other hand, an inadequate reconnaissance campaign leads to extra costs due to oversizing, hazards during the construction phase, delays, and emergency modifications to construction methods that are not always appropriate. These situations can have a major impact on design, safety, costs and GHG emissions.

To improve the quality of geotechnical studies, several recommendations are made:

- Refer to the appropriate guidelines as for example (USG, 2016) concerning the consistency of geotechnical investigations (nature, quantity, depth...).
- Enhance the skills of survey teams, by requiring the "geotechnical surveyor" qualification, which has been registered in the directory of French professional certifications since 2018.
- Implement independent monitoring of investigations (e.g. geotechnical project management assistance), focusing on

compliance with the planned program, traceability, adaptation to the site, and compliance with standards.

- Comply with Eurocode 7 requirements, by systematically providing raw data and test reports.
- Report bad practices to national organizations and unions to reinforce the culture of integrity and prevent damaging deviations.

High-quality geotechnical testing is a major leverage for making projects more reliable, controlling costs, and reducing environmental impact.

3.3 *Other actions*

Reducing the carbon footprint of geotechnical projects also requires broad engagement from all stakeholders. This can be achieved through a structured program of training and awareness-raising actions throughout the sector.

1. Identifying the key stakeholders involved across the geotechnical project lifecycle to tailor training to their specific roles and responsibilities. These groups include project owners and decision-makers, who should integrate environmental goals into strategic and financial planning; design offices and geotechnical engineers, responsible for creating low-carbon solutions; construction firms and subcontractors, who must adopt sustainable methods on site; and infrastructure operators, who play a role in ensuring long-term sustainable performance during operation and maintenance.
2. Raising awareness of environmental challenges. All stakeholders must understand the environmental issues that affect their work, particularly those related to climate change and ecological transition. Awareness programs should explain the implications of extreme weather events on geotechnical structures, identify the major sources of greenhouse gas emissions—such as material production, transport, and energy use on site—and highlight the national and international legislative context, including France's National Low Carbon Strategy and its carbon neutrality objective for 2050.
3. Providing technical training in eco-design practices. To ensure the practical application of sustainable approaches, technical training is required. This includes instruction in life cycle assessment (LCA) methods to evaluate environmental impacts over the full lifespan of a structure, criteria for selecting low-carbon materials and environmentally responsible construction techniques, integration of carbon footprint evaluation into early design stages, and best practices to minimize emissions during the execution phase—through optimized transport, efficient equipment, and waste reduction.
4. Thinking about multifunctional structures as soon as the first preliminary design stage, for example by planning for geothermal foundations.
5. Disseminating tools and practical resources. The success of low-carbon practices depends on access to operational tools and up-to-date information. This includes providing technical guidelines specific to geotechnical eco-design, carbon footprint calculation tools linked to current emission factor databases, and case studies or experience feedback sheets that document successful low-carbon projects and lessons learned.
6. Ensuring continuous learning and knowledge sharing. Training must be maintained over time to reflect the ongoing evolution of technologies, materials, and regulations. This requires the implementation of continuous professional development programs and the creation of knowledge-sharing platforms where practitioners can exchange experiences, innovations, and emerging best practices.
7. Encouraging innovation and stakeholder commitment. Lastly, fostering innovation and engaging stakeholders in low-carbon initiatives can be supported through incentive mechanisms. Competitions, awards, and voluntary certifications may be introduced to recognize and reward outstanding environmental performance in geotechnical engineering, thereby promoting a broader cultural shift across the sector.

4 BEST PRACTICES ALONG THE PROJECT STAGES

It is worth recalling that best practices are intended to promote the development of sustainable, low-carbon geotechnical structures with minimal environmental impact.

4.1 *During preliminary stages*

The approach is part of a broader context that goes beyond geotechnical site investigation alone. However, the contribution of geotechnics can influence the selection of sustainable solutions for the construction of structures. The approach may also be initiated by the geotechnical engineering consultancy, even in the absence of a specific program addressing carbon footprint considerations.

The objective is to carry out a comprehensive geotechnical study to identify soil characteristics and site-specific constraints, to avoid overdesign of the structures.

4.2 *During design stage*

The integration of carbon footprint considerations into design contracts—particularly project management contracts—represents a crucial step toward achieving the sustainability objectives of geotechnical structures.

Contractual documents must clearly state the priority given to reducing GHG emissions throughout the entire life cycle of the structure. By engaging stakeholders from the outset to consider lower-emission alternatives, design-phase project management contracts can significantly influence the selection of technical solutions.

One of the key aspects during the design stage is the comparison of the carbon footprint of the various possible technical solutions, with a particular focus on identifying low-carbon alternatives. Reducing the project's carbon footprint also involves optimizing material quantities and implementing the use of low-carbon materials.

The design phase is a key stage in evaluating the project's impact, as it is when a reliable estimate GHG emissions can be produced to guide decision-making by the project owner.

4.3 *During tender and contract stages*

The tender and contract stages play a key role in controlling the carbon footprint of geotechnical works. This is the phase where decisions regarding materials, techniques, and responsibilities are formalized. By specifying low-carbon objectives early, project owners can create the conditions for real emission reductions during the construction phase.

The table below summarizes recommended actions to include in tender and contract documents, along with their purpose and expected benefits.

Table 3. Recommended actions during tender and contract stages

Actions	Explanation	Expected Benefit
Set clear carbon footprint objectives	Explicitly state that reducing GHG emissions is a project priority.	Ensures that all bidders are aware of and aligned with climate goals.
Require a carbon footprint estimate	Ask bidders to submit a GHG emissions estimate based on standard methods and databases.	Allows comparison of proposed solutions not just by cost, but also environmental impact.
Promote low-carbon technical variants	Encourage contractors to propose alternative solutions (materials, methods) with lower emissions, and explain their benefits.	Stimulates innovation and opens the door to eco-efficient methods.
Define emission tracking requirements	Specify how the contractor will monitor GHG emissions during construction (frequency, format, items to track).	Enables follow-up and continuous improvement during the project.
Include carbon in bid evaluation criteria	Assign a weighting (e.g., 10–20%) to the carbon footprint in the offer scoring system.	Reinforces carbon as a decisive factor, alongside cost and quality.
Specify emission factors and tools to use	Indicate the accepted databases and calculation tools to ensure consistency.	Ensures comparability and reliability of emissions data between bidders.

This structured approach ensures that geotechnical contractors are not only evaluated on price and technique, but also on their ability to contribute to carbon reduction goals.

4.4 *During construction stage*

The carbon footprint of a project can still be optimized during the construction stage. But to be relevant, a carbon footprint follow-up must be implemented as soon as possible, ideally based on specifications given by the contract. To find the right balance between accuracy and effectiveness of the follow-up, it can focus on the most impactful items. Then, the impact of any adaptation, change, optimization, alternative should be evaluated in comparison with the base project regarding also the carbon footprint. For example, on the choice of material, which is a major lever at this stage, to promote low-carbon alternatives, the carbon footprint, including transport, should be highlighted in the approval process.

Another possible action is to implement the “observational method”. Among geotechnical design methods, the observational method (or interactive design) represents an original approach to adapting and optimizing structures based on observations of their behavior during construction. This method, which has been developed mainly for projects in delicate contexts where conventional methods may prove inadequate, results in structures that are not unnecessarily oversized and costly. This optimization, without compromising safety and behavior objectives, can significantly reduce a project's carbon footprint.

4.5 *In service stage*

The service phase corresponds to the expected duration of use specified in the design. This can be 25, 30, 70, 100 years or even more. During this period, the performance of the structure is theoretically guaranteed for the intended use. At the end of this period, the structure reaches the end of its service life and should be rebuilt, reinforced or upgraded. A new service life is defined. Extending the service life is also a very interesting leverage to reduce the carbon footprint of a geotechnical structure over its life cycle. This can be done by tailored monitoring and maintenance.

During the service phase of the structure, the carbon impacts are reduced to three main items:

- Monitoring or inspection phase.
- Maintenance work.
- “Little” works.

Each part of the structure, with its specific features, will have its own monitoring and maintenance schedule. For example, an embankment has requirements that are different from a retaining wall or a rock slope.

Inspections are used to assess health check of the structure. Some are mandatory, for example inspection of retaining structures or culverts. Some are not, for example for embankments. The health check allows the little work to be planned and helps to prioritise it. The carbon impact of this activity is limited to travel to the site and is therefore very low, even negligible over the lifetime of the structure.

Maintenance is generally specified in the structure's documentation and is scheduled with the teams responsible for managing the infrastructure. Its scope depends on the type of structure. The various activities included in routine maintenance can be for a linear infrastructure:

- Cleaning ditches, clearing drains, cleaning grates.
- Brush clearing, mowing, removing woody vegetation.
- Clearing blocks from protective structures or stone traps
- etc.

The carbon impact is difficult to anticipate but can be quantified after a few years of practice. It will include the travel of teams to the site, the energy consumption of the various machines, the purchase of small equipment, the removal of waste, etc.

“Little works” have a slightly higher impact as they require more raw materials. The carbon impact is also difficult to assess in advance, but a normal forecast of small works can be used as a basis for calculation, including subcontracting, purchases of materials such as cement, aggregates and sand, geotextiles, riprap, cold mix, etc.

Somehow, over the entire lifetime of the structure, the impact of these operations during service stage, is negligible compared to the impact of construction work and infrastructure use.

5 CONCLUSIONS

The geotechnical sector has a unique opportunity to actively contribute to climate change mitigation by integrating carbon footprint assessments into routine design practices.

For three years, between 2022 and 2025, French geotechnical engineers working in the Geotechnics and Climate Change Working Group have pooled their knowledge and experience to unify and structure the approach to assessing the carbon footprint of geotechnical structures, and to identify levers for reducing it. The result will be a set of recommendations to be published in 2026 (CFMS, 2026). They include:

- The Life Cycle Analysis approach using the “carbon footprint” indicator for all sources of emissions.
- A list of the appropriate databases of emission factors for the geotechnical structures.
- Good practices during design stages: carbon footprint assessments in the geotechnical engineering missions, quality and supervision of geotechnical investigations, training in eco-design practices for the geotechnical engineers, thinking about multifunctional structures for example by planning for geothermal foundations.
- Good practices during tender and work stage: specifying low-carbon objectives in Tenders and contracts, promoting innovative low-carbon variants and materials, implementing carbon footprint follow-up during works stage.

- Good practices during service: extending the service life by tailored monitoring and maintenance.

By adopting the methodologies, tools, and best practices outlined in this work, engineers can reduce GHG emissions at every project stage. Ongoing collaboration between stakeholders—designers, contractors, and project owners—will be essential to scale up these efforts and drive the transition to low-carbon infrastructure.

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