Strategies for geotechnical engineers to minimise environmental footprints of projects: from decision-support tools to innovative approaches

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ABSTRACT: Geotechnical engineers have a responsibility to minimise the environmental footprint of construction by making informed decisions. While optimising material use can contribute to more sustainable designs, the selection of a technical solution often has an even greater impact. To make informed decisions, engineers must be able to assess and compare the environmental impacts of various design alternatives, including greenhouse gas emissions. This requires effective and user-friendly decision-support tools to integrate environmental considerations into the early stages of design. This article examines the scientific challenges involved in developing effective environmental assessment tools for geotechnical engineering and presents *Ecow* as a comprehensive solution developed to address these challenges. Three case studies are presented. The first examines a real-life project where on-site emissions were measured. The second explores the use of *Ecow* for a culvert project comparing soil replacement, foundation piles and stone columns. The third focuses on vertically loaded micropiles, illustrating how adapting the regulatory framework can enable more sustainable design approaches.

KEYWORDS: Environmental footprint, environmental indicators, multi-criteria analysis, sustainable designs, safety factors, Ecow.

1 INTRODUCTION

Climate change, largely driven by human activity, is causing rising global temperatures, more frequent extreme weather events and widespread environmental disruption. A major contributor is the accumulation of greenhouse gases (GHG) that trap heat in the atmosphere.

In response, international strategies aim to significantly limit carbon emissions and reduce their impact. Geotechnical engineers have a role to play in this effort. They must adapt their practices to support lower-carbon solutions and help develop more sustainable infrastructure and buildings.

To this day, multi-criteria analysis in most geotechnical engineering projects remains primarily focused on cost, schedule and technical complexity. However, the sustainability of geotechnical solutions should be given equal consideration, and it does not have to conflict with traditional performance criteria. Incorporating environmental impact into decision-making requires engineers to be capable of quantifying footprints and understanding the magnitude of the metrics involved.

2 SUSTAINABLE ENGINEERING DESIGN DECISIONS

2.1 *General framework*

Life Cycle Assessment (LCA) is a standardised method for evaluating the environmental impacts of a product across its entire life cycle. When applied to construction, it accounts for all material and energy flows. The EN 15804 standard highlights the need for a comprehensive life cycle assessment across various environmental indicators, including resource depletion, water pollution and eutrophication.

The key indicator, global warming potential, is emphasised due to its relevance and strong scientific documentation. It is expressed in CO_2 equivalent (tonnes of CO_2e), a standardised unit that includes all greenhouse gases (GHG) based on their warming potential. While this article primarily focuses on this indicator, it will also briefly address other environmental indicators.

2.2 *Challenges*

Calculating the environmental footprint of a geotechnical project proves to be complex due to the numerous parameters and limited reliable data. This is further complicated by an evolving regulatory framework, calculation methods and key indicators likely to change in the coming years.

Emission factors (EFs), sourced from public and private databases, are used to estimate emissions but vary in methodology and carry uncertainty. Comparing them requires caution, including consideration of uncertainty ranges.

EFs are context-specific, so data must align with the project's scope for instance geographic location. While international databases such as Ecoinvent exist, most tools rely on national data. Selecting appropriate emission factors depends on their relevance and availability.

Lastly, environmental impact assessments for geotechnical projects require many input parameters such as material types, suppliers, drilling equipment, fuel consumption and more. Yet these assessments are most influential during early project stages when key design decisions are made. Paradoxically, accurate data is often lacking at this time. Thus, engineers must balance input data availability with result precision to make informed choices.

2.3 *Decision-support tool Ecow*

Various tools exist to calculate greenhouse gas (GHG) emissions for geotechnical engineering projects. Most have significant limitations, especially regarding input requirements, making them primarily suitable only during the execution phase. To address this, Terrasol developed *Ecow*, a decision-support tool on the web platform *Orbow*.

Ecow enables comprehensive assessment and comparison of the environmental footprint across all geotechnical project types such as earthworks, foundations, retaining walls, soil reinforcements and more. By synthesising existing databases, it streamlines input parameters to suit the knowledge level of design engineers, while offering advanced options for construction engineers with detailed site data. The tool also facilitates scenario-based comparisons.

Ecow incorporates a carefully curated set of EFs relevant to geotechnical applications and adopts ten environmental indicators of the EN 15804 standard to support multi-criteria life cycle assessment.

Calculations focus on key emission sources including material manufacturing, transportation to site and on-site energy consumption such as fuel and electricity.

Material production and transportation emissions are calculated from quantities, while energy emissions use data from the European Federation of Foundation Contractors

(EFFC) and Deep Foundation Institute (DFI), based on carbon measurements from several geotechnical projects.

By integrating environmental impact into early design decisions, *Ecow* helps geotechnical engineers identify more sustainable solutions and answer questions such as whether it is better to use more short piles or fewer long ones, whether soil substitution or rigid inclusion is more eco-friendly, and whether stone columns or soil mixing is preferable - all while ensuring that comparisons are made for the same performance criteria.

2.4 *From estimated to verified emissions: setting up a validation method*

An important advantage of the methodological approach proposed by EFFC and DFI is that it provides energy-use ratios for a wide range of techniques. This greatly simplifies the estimation of construction-stage emissions: instead of defining specific equipment types, production rates, or operational parameters - information that is often unknown during early design stages and highly dependent on the contractor's methods and equipment fleet - the engineer can rely on robust, technique-based energy ratios. As a result, the approach offers a practical and streamlined way to estimate implementation-related emissions while maintaining consistency with industry practice.

However, this simplified approach must be used with caution, as it naturally carries significant uncertainties. It is therefore more appropriate to reason in terms of ranges rather than absolute values. Moreover, although the ratios originate from real construction sites, the precise methodology used on these reference projects to quantify energy-related emissions is not always explicitly documented. To reduce these uncertainties, it is essential to verify that the computed values remain consistent with actual emissions. In this respect, validation checks on real projects are required both to ensure scientific credibility of the calculation tools and to enrich the underlying project database.

2.5 *Lessons learned from on-site monitoring*

To strengthen the reliability of *Ecow*, a key objective was to compare the tool's estimated emissions with the measured emissions on construction sites.

One of the first projects on which this validation exercise was conducted is the M-Lyon Building in Lyon, France, a mixed-use development (offices, retail/services, and housing) with a total surface area of about 31,000 m². The building will consist of a ground-floor base and office levels up to the 8th floor.

On this project, the objective was to monitor the diaphragm wall works carried out at the start of construction and verify carbon emissions (climate change indicator) related to:

- construction materials (steel, concrete, bentonite),
- transportation of these materials to the site,
- energy consumption during execution (diaphragm wall rigs, cranes for cage handling, earthmoving equipment, bentonite slurry plant).

The diaphragm wall layout consists of a 76 m × 53 m rectangle (Figure 1), with a wall thickness of 800 mm and an approximate depth of 20 m. The construction works took place in 2023.

This monitoring exercise highlighted that obtaining a complete and accurate carbon footprint requires the contractor to provide a large number of documents, which can sometimes be difficult to obtain. Site managers are not yet accustomed to delivering such information, and some environmental data is simply not known.

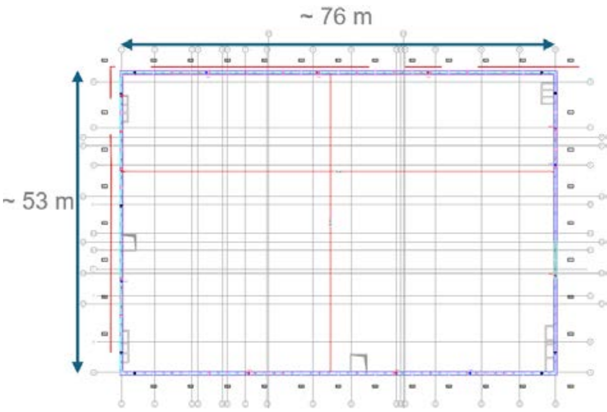

Figure 1. Plan view of the M-Lyon Building diaphragm wall

Another major issue concerns the difficulty of distinguishing fuel consumption per operation. For instance, a single fuel-powered compressor was used to supply all equipment. This allowed measuring total emissions associated with fuel or diesel consumption, but not separating them by unit operations, such as diaphragm wall excavation, reinforcement cage installation, or concrete placement. As a result, it was necessary to rely on total energy-related emissions, even though this phase of work was relatively simple, with few on-site equipment and no other tasks being carried out simultaneously. One can imagine that during more advanced construction stages, involving multiple tasks and works, it would be unrealistic - or at least very difficult - to obtain emissions data specific to each individual task.

Table 1 summarises the main categories of information (i.e., documents requested from site managers) needed to assess on-site emissions.

Table 1. Data required for a reliable emissions assessment

Work package	Required data (simplified)
Equipment delivery/removal	• Number and type of trucks • Transported volumes • Origin/distance travelled
Guide walls	• Steel and concrete deliveries (trucks, types, volumes, origins) • Steel emission factors (origin, recycling rate) • Concrete emission factor • Excavation volumes and removal logistics • Diesel consumption for handling, formwork, installation
Diaphragm walls	• Deliveries of steel, concrete and CWS joints (trucks, types, volumes, origins) • Steel and concrete emission factors • Diesel consumption of trench cutters/grab rigs • Diesel for cage handling, excavation, spoil management • Spoil transport after decantation (number/type of trucks, destination)
Bentonite slurry plant	• Delivery/removal of plant and silos • Bentonite deliveries • Diesel consumption of the plant and desanders

It is worth noting that, despite only covering a very small fraction (diaphragm wall) of the overall building works, the list of required documents is extensive and proved laborious to obtain.

Nevertheless, collecting delivery notes for all materials, together with monitoring the compressor's actual fuel consumption, made it possible to assess the site's emissions with a satisfactory level of accuracy.

Furthermore, tracking the actual volumes of concrete placed revealed losses in granular materials of around 10%, which aligned well with the initial estimates. The availability of construction site data made it possible to assess actual greenhouse gas emissions for the three main emission categories presented above. Table 2 shows the results obtained after analysing and post-processing the on-site data provided by the contractor.

Table 2. GHG emissions based on data collected on site

	Construction materials	Transportation	Energy consumption
Emissions ($t\ CO_2e$)	1407.0	76.1	189.3

The total emissions based on data collected on site amounts to approximately 1672 $t\ CO_2e$, which is close to the average estimate obtained with *Ecow* (see Figure 2: 1516 $t\ CO_2e$).

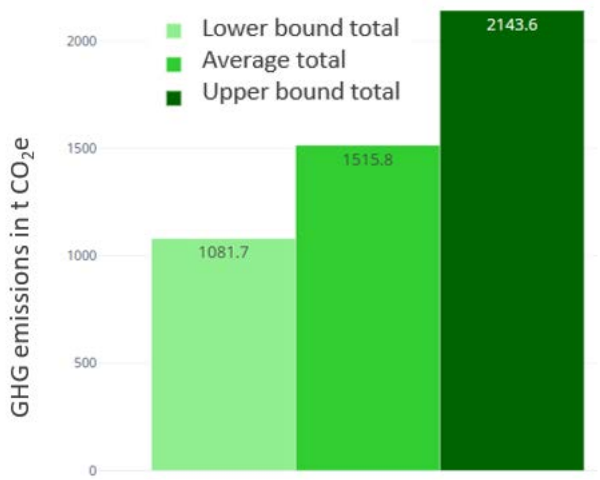

Figure 2. GHG emissions estimate computed with *Ecow*

In this case study, on the diaphragm wall works of the M-Lyon Building project in France, after analysing and post-processing, *Ecow*'s estimated emissions differed by only around 10% from the total emissions derived from site data. This result is very satisfactory, as it demonstrates that the tool captures the correct order of magnitude for emissions. While this observation is based on this particular project, it is clear that such a comparison should ideally be carried out on a larger number of projects to further validate the approach.

Although validating results against real projects is essential, monitoring emissions directly on construction sites is not yet a widespread practice, and its implementation remains challenging. In fact, assessing emissions requires collecting a large amount of detailed information, including equipment operating times, fuel consumption, site logistics, and variations in construction methods. Such data is often difficult to gather, which makes rigorous on-site monitoring complex and resource-intensive.

3 CASE STUDY

3.1 *Introduction*

As part of this article, a design project for a 45-meter-long culvert constructed on compressible ground prone to settlement is discussed. This case study is inspired by a real bridge structure studied in 2024 as part of the A69 motorway project between Toulouse and Castres in southwestern France. Three different design solutions are compared (cf. Figure 3):

- Solution 1: Soil replacement
- Solution 2: Foundation piles
- Solution 3: Vibro-replacement stone columns

For this case study, most EFs used are extracted from EcoInvent 3.8 (2021).

To enable a meaningful comparison, geotechnical design calculations were performed to size each solution to achieve similar technical performance. While each alternative has distinct advantages and limitations, all meet the required performance criteria for the culvert. However, they differ significantly in complexity, cost and planning requirements. This article focuses solely on their environmental impact to highlight key differences.

3.2 *Solution 1: soil replacement*

The soil replacement solution involves excavating the compressible soil layer and replacing it with material that is not prone to consolidation.

The environmental footprint of this solution depends heavily on the location of the construction site and the source of the replacement material. Emissions estimates are based on the guidebook developed by CEREMA and the findings of the French TERCO2 project, a collaborative research initiative involving several construction companies.

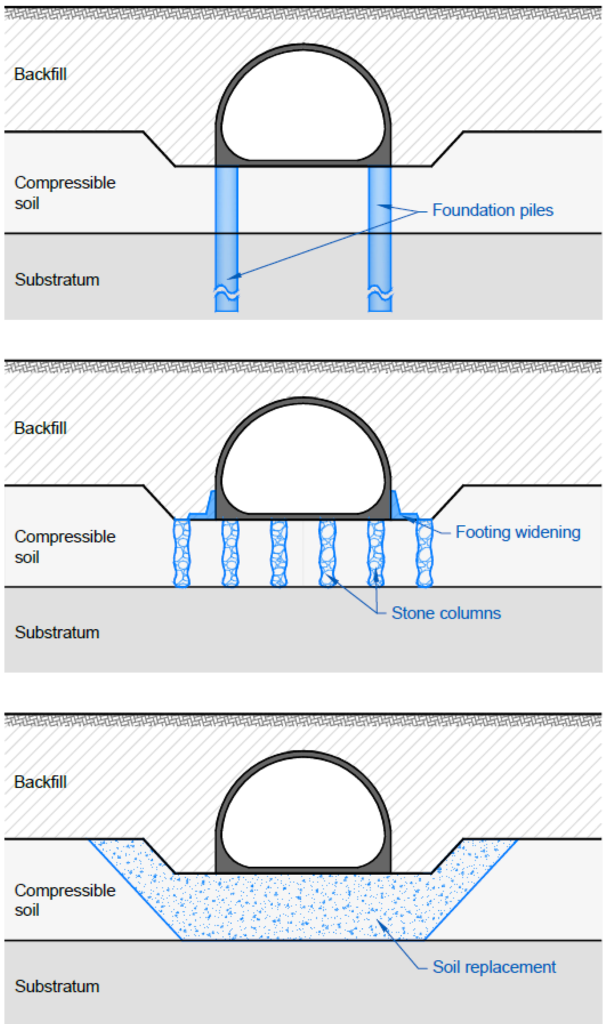

Figure 3. Schematic of the three design alternatives analysed.

The scenario assumes that a total of 7,500 m^3 of soft soil material is excavated and transported by road to a disposal site. It is further assumed that the construction site is located at an average distance of 10km from the quarry and 3km from the disposal site, as defined in the CEREMA guidelines for typical conditions in France.

The assessment does not account for any potential lime treatment, which would significantly increase the environmental impact of the soil replacement method.

As part of this article, the environmental impacts related to any pumping activity are not considered.

Table 3 presents the GHG emissions for the soil replacement alternative. For earthworks, no data was available to assess environmental impacts beyond the carbon footprint.

Table 3. GHG emissions for the soil replacement solution.

	Lower bound	Average	Upper bound
Emissions ($t CO_2e$)	17.7	29.6	41.4

3.3 *Solution 2: foundation piles*

The foundation pile solution consists of a line of piles installed beneath each culvert wall. This scenario considers bored piles with recovered casing. Each pile has a diameter of 1 meter, a length of 11 meters and is spaced at 3-meter intervals along the length of the culvert, resulting in a total of 15 piles per line.

Table 4 presents the GHG emissions for the foundation pile alternative. Results for other environmental indicators are provided in Figure 5 (see Section §3.5).

Table 4. GHG emissions for the foundation pile solution.

	Lower bound	Average	Upper bound
Emissions ($t CO_2e$)	177.1	234.4	333.0

3.4 *Solution 3: stone columns*

The vibro-replacement stone columns solution involves installing stone columns beneath the culvert. To improve load distribution and reduce differential settlement, the base of the culvert walls is widened.

The stone columns are 0.8 meters in diameter and arranged in a regular grid pattern with 1.3-meter spacing in both directions. Each column extends to a depth of 7.5 meters beneath the culvert, with additional columns extending 5 meters laterally on each side. In total, 533 stone columns are installed, corresponding to an estimated stone volume of approximately 2,000 cubic meters.

The footing widening corresponds to 72 cubic meters of concrete and 11 tonnes of steel.

Table 5 presents the GHG emissions for the vibro-replacement stone column alternative. Results for other environmental indicators are provided in Figure 5 (see Section §3.5).

Table 5. GHG emissions for the stone column solution with uncertainty intervals.

	Lower bound	Average	Upper bound
Emissions ($t CO_2e$)	62.0	92.5	126

3.5 *Comparison*

Figure 4 and Figure 5 compare the environmental footprint of the three design alternatives for the culvert foundation. Figure 4 focuses solely on GHG emissions, while Figure 5 presents a comparison across ten environmental indicators.

The soil replacement solution produces the lowest GHG emissions, while the foundation pile solution shows the highest emissions due to the use of cement and steel, both linked to high emissions. Notably, if the footing widenings in the stone column solution were excluded, its emissions would be similar to those of soil replacement and statistically indistinguishable because of overlapping uncertainty ranges.

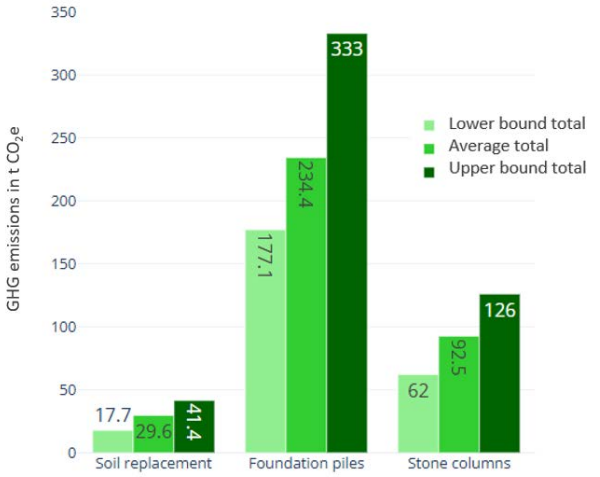

Figure 4. Comparison of GHG emissions for the three design alternatives.

Due to limited data availability, the comparison across all environmental indicators is limited to the stone column and foundation pile alternatives. For most indicators, the stone column solution is slightly less environmentally harmful. However, the foundation pile performs better for three indicators, reversing this trend.

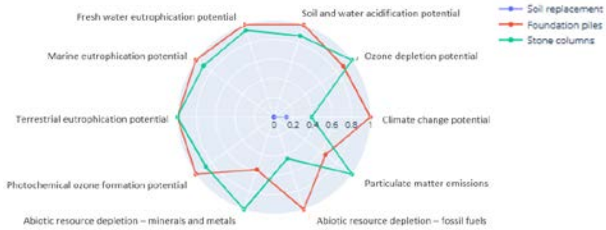

Figure 5. Comparison of 10 environmental indicators for the three design alternatives.

It is essential that this environmental impact assessment be integrated with planning and cost evaluations. Additionally, the feasibility of the soil replacement and stone column design alternatives depends on the availability of suitable materials from nearby quarries, which in turn is highly dependent on the project's geographical location.

4 ADAPTING THE REGULATORY FRAMEWORK FOR MORE SUSTAINABLE DESIGNS

4.1 *Discussion on safety levels*

Beyond the comparative analysis of design alternatives, it is valuable to adopt a broader approach by examining the impact of safety factors on environmental footprint. Within the Eurocode framework, and more generally in design codes based on the limit state principle, safety factors are applied to material resistances. This implicitly limits displacements, although displacement assessments are not always explicitly conducted.

For some structures, settlements or horizontal displacements do not compromise performance, which opens the possibility for further optimisation by allowing higher working stress ratios. However, this must be balanced against the risk that reducing the safety factors may, in some cases, trigger second-order failure mechanisms. The objective is not to eliminate the safety margins entirely but to rationalise them on a case-by-case basis to optimise design where appropriate.

Maintaining an adequate level of safety remains essential. Beyond the associated risks, implementing repair solutions often results in a higher environmental footprint.

4.2 *Case study*

4.2.1 *Introduction*

In this section, the case study focuses on fourteen micropiles under axial loading in a homogeneous soil layer. The analysis investigates the impact of varying the overall safety factor. The characteristic serviceability limit state case is considered, with a load of 500 kN per micropile. Three aspects are studied in parallel:

- Bearing capacity, calculated using the *Fondprof* module (*Foxta*)
- Settlement, calculated using the *Taspie+* module (*Foxta*)
- Greenhouse gas emissions, calculated using *Ecow* (*Orbow*)

Only the friction component is considered in the analysis as the focus is on micropiles. The overall safety factor on the friction resistance (Q_s) according to the French national application standard for the implementation of Eurocode 7 for deep foundations (NF P 94-262/A1) for the characteristic SLS is 1.98 ($\frac{\gamma_R}{\beta_s} \cdot \gamma_{R,d1} \cdot \gamma_{R,d2}$).

As per French practice, the transfer laws used to characterise friction are based on the two-stage semi-empirical formulation proposed by Frank and Zhao. Although this method is theoretically valid only below the creep load, it is applied here in all cases purely for reference purposes.

Although the design approach discussed here follows the French national application standard, a similar methodology could have been carried out using other reference frameworks, such as the BS or DIN standards). In practice, the global factors used for SLS combinations are broadly comparable across these standards, so the resulting conclusions would remain valid.

4.2.2 *Comparison*

Figures 6 to 9 show the effects of reducing the safety factor from 2 to 1.5, which corresponds to the creep load. This reduction increases settlement by 40%, from 5 mm to 7 mm, a value that remains acceptable. At the same time, it significantly reduces GHG emissions. For a safety factor lower than this, the creep load is exceeded, and settlements logically diverge. Figure 8 shows that the trend observed for GHG emissions is consistent across all ten environmental indicators.

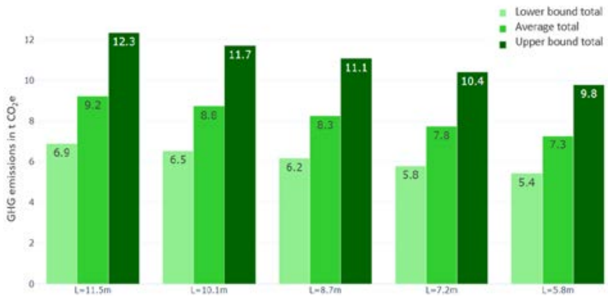

Figure 6. Comparison of GHG emissions of the micropiles.

The results appear consistent and can be explained by the fact that, in a single-layer system, micropile length increases with the safety factor. However, the use of casing over the first 3 meters means material quantities are not fully proportional to length. As a result, the relationship between material quantities (grout, steel, and bentonite) and the safety factor is not strictly proportional but closely aligned.

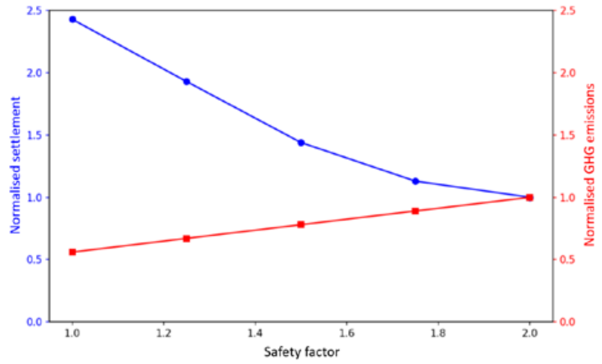

Figure 7. Normalised settlement and normalised GHG emissions as a function of the safety factor on bearing capacity.

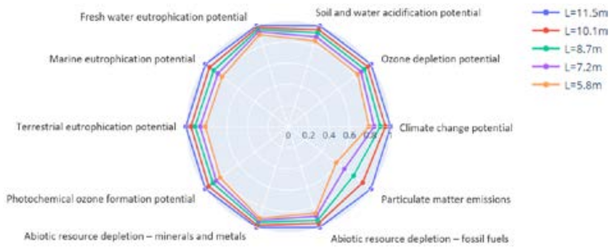

Figure 8. Comparison of environmental indicators of the 14 micropiles according to their length.

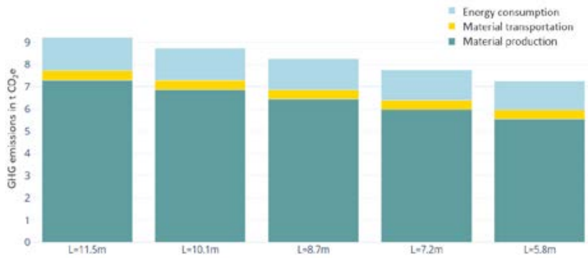

Figure 9. Breakdown of GHG emissions by category of the micropiles, considering average uncertainty.

Figure 9 shows that emissions from material production, material transportation and energy consumption are roughly proportional to micropile length and therefore to settlement and the safety factor. Relaxing the settlement criterion thus leads to a significant reduction in emissions.

This proportionality would differ even more if reinforcement was not installed along the entire length or if micropile length did not vary with the safety factor, for example if the friction of a soil layer is neglected.

Eliminating safety factors in design is clearly unacceptable, but this case study demonstrates the benefits of optimising safety margins by reassessing acceptable deformation levels. Reducing the safety factor by up to 25% can lower GHG emissions by approximately 20 to 25%, with only a minimal increase in settlement. Current regulatory safety factors are calibrated to keep structures within the elastic domain, leaving a margin before reaching the plastic domain.

This finding underscores the value of developing unconventional computational approaches by revisiting safety factors in specific combinations and improving displacement estimates over time under varying loads. The exercise presented, while simplistic, encourages reflection on the potential value of adjusting safety factors based on load cases and load duration, as the blanket application of safety factors does not always allow for optimisation. Such approaches could enhance utilisation rates in both new and rehabilitation projects, promoting sustainability. Reducing safety factors requires thorough knowledge of soil properties, necessitating comprehensive site investigations.

By adopting displacement-based design methods and refining understanding of time-dependent behaviour, engineers can improve material efficiency while maintaining safety and performance, ultimately supporting more sustainable geotechnical solutions.

5 CONCLUSION

This article discusses the challenges facing geotechnical engineers in assessing the environmental footprint of their projects. It introduces *Ecow*, a comprehensive decision-support tool that can be used for all types of geotechnical projects and throughout every project phase, from early design with limited data to the execution stage.

The article also emphasises the importance of collecting on-site emission data to validate and calibrate the assessments generated by such tools. The M-Lyon Building project, used here as an illustrative example, shows how valuable such measurements can be for comparing modelled emissions with those actually observed on-site. Establishing reliable monitoring procedures during construction is essential to ensure that environmental assessments truly reflect field practices. Ultimately, confronting calculated results with real data is a prerequisite for giving scientific credibility to the tools used and for strengthening confidence in their ability to support informed and responsible design choices.

The second case study compares three distinct geotechnical design alternatives for the same project, highlighting that rethinking design approaches rather than just optimising structures can yield significant benefits.

The third case study examines the influence of safety factors on bearing capacity verification by analysing their impact on vertical settlement and the environmental footprint. It demonstrates that reducing safety factors increases settlement but can also lower emissions. While eliminating safety factors is clearly unacceptable, this case study shows the benefits of optimising safety margins by reassessing acceptable deformation levels.

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