Methodology to calculate and compare Embodied Carbon associated with Ground Improvement techniques

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ABSTRACT

As some cities in Canada start to set total embodied carbon targets on construction projects, architects, structural engineers, and contractors must innovate and find alternate construction solutions with a lower carbon footprint. Although some baselines have been published for residential developments, the calculation methodologies and the metrics are still evolving - which makes project-by-project comparisons difficult. For example, evaluating the CO_2 savings for a given project poses challenges when defining the baseline.

Ground improvement techniques are by design an optimized alternate to traditional deep foundations or dig and replace options. The economical advantage of such solutions can also be found on the carbon footprint side. To be able to reduce the carbon impact on its projects, MENARD has conducted some extensive work on its construction projects in Canada to obtain a reliable methodology to calculate the ton equivalent CO_2 associated with ground improvement techniques.

This article describes a step-by-step methodology to calculate the embodied carbon associated with ground improvement. It also provides carbon footprint comparisons between ground improvement techniques on past construction sites and suggests a metric to evaluate the embodied carbon of these techniques for a given project at the feasibility phase.

RÉSUMÉ

Alors que certaines villes au Canada commencent à fixer des objectifs absolus de carbone incorporé pour les projets de construction, architectes, ingénieurs structure et entreprises générales se doivent d’innover pour trouver des techniques de construction alternatives ayant une empreinte carbone réduite. Bien que des valeurs de référence aient été publiées pour les projets résidentiels, les méthodes de calcul et les métriques sont toujours en cours d’évolution – ce qui rend la comparaison entre projets délicate. Par exemple, évaluer les gains d’émissions CO_2 pour un projet donné se révèle être compliqué quand il s’agit de définir une valeur de référence.

Les techniques d’amélioration de sol sont, par nature, une alternative optimisée aux solutions traditionnelles telles que les fondations profondes ou le remplacement pur et simple des couches de sol problématiques. L’avantage économique de telles alternatives se retrouve coté empreinte carbone. Pour réduire l’impact carbone de ses travaux, MENARD a lancé un travail de fond sur ses chantiers au Canada afin d’obtenir une méthode fiable de calcul du tonnage équivalent CO_2 des techniques d’amélioration de sol.

Cet article détaille une méthode pas à pas pour calculer la part de carbone incorporé due à l’amélioration de sol. On compare aussi les différentes techniques d’amélioration de sol avec un point de vue empreinte carbone sur des chantiers passés et on propose une métrique pour évaluer l’impact carbone de l’amélioration de sol pour un projet donné dès la phase de faisabilité.

1 INTRODUCTION

Being a contractor that utilizes materials such as concrete and consumes energy such as diesel fuel, carbon dioxide emissions are inherently apart of MENARD’s everyday activities. Starting in 2015 with the Paris Agreement during COP21, countries, municipalities, and private companies, like MENARD, have begun to implement strategies to reduce carbon dioxide emissions. Canada itself declared a national climate emergency in June of 2019 (Jackson, 2019). The climate emergency launched cities such as Toronto to implement new “Green Building Standards” that challenge and require developers to better understand and limit their operational and embodied carbon emissions to near zero by 2030 (King et al., 2022).

During the last decade, most of the discussions on environmental impact in the construction industry were focused on the *operational* carbon (carbon impact of the building after it is built); but more recently discussions shifted towards the notion of *Embodied Carbon* (carbon impact of the construction of the building itself). The embodied emissions from buildings represent 11% of the worldwide carbon emissions (World Green Building Council, 2019).

For the purpose of this article, the methodology of calculating the embodied carbon emissions of various Ground Improvement techniques and comparing the results obtained will be discussed. The last section will present a metric that could be used to evaluate the Embodied Carbon of a future development project involving a Ground Improvement technique.

With regards to the tools used for this article, version 4 of the DFI Carbon Calculator Tool’s emission factors was utilized (EFFC, 2020). It should be noted that version 5 of the calculator was released in January of 2023.

1.1 Embodied Carbon applied to Ground Improvement

Embodied carbon is the carbon emissions associated with the production of materials, construction of the building, and its end of life recycle/demolition as seen in Figure 1 below (i.e: a cradle-to-grave life cycle analysis) (World Green Building Council, 2019). With regards to ground improvement techniques, upfront carbon emission calculations were the focus which includes CO2 emissions from raw material extraction to the installation and construction process (World Green Building Council, 2019).

When the simplified term *CO2 emissions* is used in this article, it is considered synonymous with Global Warming Potential (GWP), Greenhouse Gas Emissions (GHG), and Embodied Carbon. All these terms are calculated in ton equivalent CO2 (tCO2e).

Calculating the upfront embodied carbon for ground improvement techniques, involved completing three key steps:

- Identifying the various sources of carbon emissions and categorizing them for ease of calculations.
- Collecting the appropriate data which was mostly already done at MENARD for quality control purposes.
- Utilizing a standard set of emission factors for the carbon dioxide sources.

To determine the categories of carbon emissions, MENARD investigated various existing third-party and internal tools and decided to utilize the tool called *EFFC/DFI Carbon Calculator* created by both the Deep Foundation Institute (DFI) with the help of the European Federation of Foundation Contractors (EFFC) (EFFC, 2020). Its first version was released in 2020 and its latest version was just released in 2023.

The tool has the advantage of being:

- Custom-made for deep foundations and ground improvement techniques.
- Developed by an industry third-party.
- Utilizes well-specified emission factors databases that enable the use of regional databases.
- Environmental Product Declarations (EPD) can be incorporated in the tool when available.
- Free to use/download.

The EFFC DFI Carbon Calculator Tool considers seven categories for its carbon emissions, each requires different key information summarized in Table 1.

Table 1. DFI categories

Category	Content
Materials	Type of material (aggregates origin, concrete mix…), material amount
Freight	Type of truck, distance travelled for the transport of the material
Energy	Amount of fuel or electricity used on the project
Mob/Demob	Type of truck, distance travelled, days on site for the mobilization and demobilization of the equipment (main and ancillary)
People Transport	Type of transport (train, plane, car), distance to site travelled by the project crew
Assets	Weight of asset, lifetime expectancy for the equipment used on site
Waste	Weight of waste generated on site

The ton equivalent CO2 (tCO2e) for a given project is then calculated by summing each category.

MENARD determined the Assets category to be out of scope for its activity. Assets, such as a drill rig or crawler crane, require energy to both manufacture, maintain, and recycle and this is the reason why they appear in the tool.

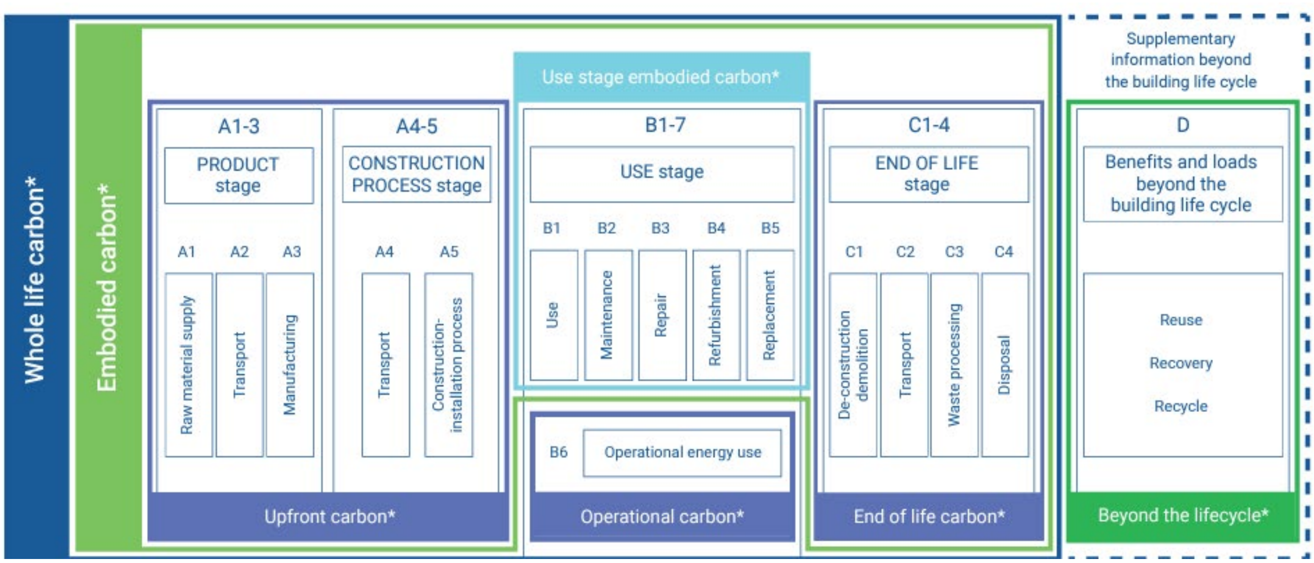

Figure 1. Embodied Carbon Scope (from World Green Building Council, 2019)

Assets have a limited impact on a MENARD project given the lifetime of the machines being counted in decades and the short durations of most projects.

It impacts the total Embodied Carbon of the project between 1 to 7% on the projects that were analyzed in Figure 2.

Waste is also minimal on MENARD sites due to its no spoil techniques, therefore, only household waste from the workforce is generated. For example, assuming a conservative 1 ton of waste is generated and is transported 50km for a 3-week duration job, <0.5% of the project's total emissions is generated through waste. The example project chosen was the Vertical Drain project illustrated in section 2.2.

Therefore, calculating the Embodied Carbon of the project can be simplified in Equation 1 below. M is for Materials, F for Freight, E for Energy, MD for Mob/demob, PT for People Transport, A for Assets.

$$\text{Total tCO2e.} = \sum \begin{matrix} \text{tCO2eM.} + \text{tCO2eF.} + \text{tCO2eE.} \\ + \text{tCO2eMD} + \text{tCO2ePT} + \text{tCO2eA.} \end{matrix} \quad [1]$$

To determine the CO2 equivalent value per category, an Emission Factor chosen from a regional Emission Factor database is used in combination with the quantity of the category (i.e: cubic meters of concrete). Equation 2 below summarizes this calculation.

$$\text{tCO2e} = \text{Quantity} \times \text{Regional Emission Factor} \quad [2]$$

Categories can either be determined as indirect or direct emissions, however, when reporting Embodied Carbon, the distinction between direct and indirect emissions is rarely used. The *Scope* approach (Scope 1/2/3) is mostly used by entities to report their carbon emissions rather than reporting emissions per project.

With the frame of the Embodied Carbon calculation explored, the next section will discuss the data collection process for past projects to define trends in Carbon Emissions.

1.2 Data collection Process and Requirements

This article focused on the five more widely used ground improvement techniques throughout Canada to ensure enough data could be collected to determine any possible correlations and trends of CO2 emissions per technique.
Each technique produces Greenhouse Gas Emissions (GHG). The variation between the techniques is significant as it involves very different installation processes and machinery, and they are used to improve a wide variety of ground conditions. Furthermore, the "intensity" of ground improvement to be done on a given project is also linked to the characteristics of the surface structure to be supported.

On the materials aspect, ground improvement techniques that involve compaction (Dynamic Compaction (DC) and Rapid Impact Compaction RIC) use no materials, and the techniques that involve insertion of inclusions (Controlled Modulus Columns CMC, Vibro-Replacement / Stone Columns SC, and Vertical Drains VD) involve the usage of raw materials such as concrete, stones, and polypropylene wick drains.

MENARD utilized its quality control procedures to extract the required information for calculating the Embodied Carbon. With regards to materials, the daily tonnage of stones or volume of concrete used are tracked along with the linear metreage of wick drains. Freight of materials was obtained per project. Also, energy/diesel consumption on site along with people kilometers travelled were tracked per site. Fuel delivery kilometers was ignored. For some historical projects analyzed, the trucking distance for the Mob/demob category was not available. Therefore, the distance was deduced from dividing an hourly trucking rate obtained from MENARD trucking companies by the total mobilization and demobilization cost. The type of truck for both freight and Mob/demob was determined from experience.

A total of 114 past projects between the years 2020 and 2022 were utilized for this study. All project locations were spread throughout Canada. The DFI tool logic was used to both categorize and calculate the CO2 emissions for the projects considered, depending on the applied ground improvement technique.

1.3 Emission Factors

Section 1.2 discussed the data collection process for extracting the "quantities" per category. Therefore, the last piece of the puzzle is obtaining a standard Emission Factor for the categories outlined. These emission factors would then be displayed in units of kgCO2e (kilogram of equivalent CO2) over the quantity's unit (i.e; km travelled, or tonnage of material).

MENARD prioritized local Emission Factors for each categorical item. For example, concrete of the same compressive strength and similar overall mix design can have a different CO2 emission factor due to varying distances in transportation of raw materials, or the energy required to process materials and batch the final mix. Therefore, CO2 emission factors can vary by country, by province, or even by municipality.

The emission factors used from the DFI tool include polypropylene for wick drains, aggregate for stone columns, freight emission rates per vehicle kilometer travelled, and people transportation by car, train, or passenger air. The EFFC DFI tool extracts carbon emission factors from international public and private databases (Wilmotte, 2023).

Local emission factors for diesel and concrete can be obtained from local supplier Environmental Product Declarations (EPD). EPDs are compliant with ISO 14025 standard making it an internationally accepted procedure. A type III EPD is fully compliant with ISO 14025 and is a product-specific Life Cycle Analysis (LCA) (EPD International, 2023). The environmental impact which is outlined via the product's total GWP is measured through the product's full life cycle from cradle to grave.

Also, emission factors can be obtained from regional reports, such as Concrete Ontario's EPD report (Concrete Ontario, 2022). These EPDs are industry-wide averages across each province for ready-mix concrete and can be used as baselines in CO2 emission calculations. Furthermore, the Carbon Leadership Forum (CLF) released 2023 North American material baselines for general materials used in construction (Waldman et al, 2023). These regional/national EPD scopes tend to be from cradle-to-gate (A1-A3 in Figure 1) which includes raw material extraction to manufacturing.

For this study, the Emission Factors were considered constant between 2020 and 2022.

With both Emission Factors and quantities obtained, analysis of the total Embodied Carbon can be completed on a given project for a given technique.

2 RELATIVE EMISSIONS PER TECHNIQUE

Comparing absolute values of Embodied Carbon from one ground improvement technique to the other brings little information as we know the calculation is based on multiple factors: the use of material or not, the size of the project, the ground conditions to be improved, and the surface structure to be supported.

The paragraphs below focus on the proportion (percentage) of each DFI category on the total Embodied Carbon amount for a given technique as shown on Figure 2. Note that the values below 5% were not displayed on the graph. The aim of such approach is to prioritize efforts when minimizing the overall carbon impact.

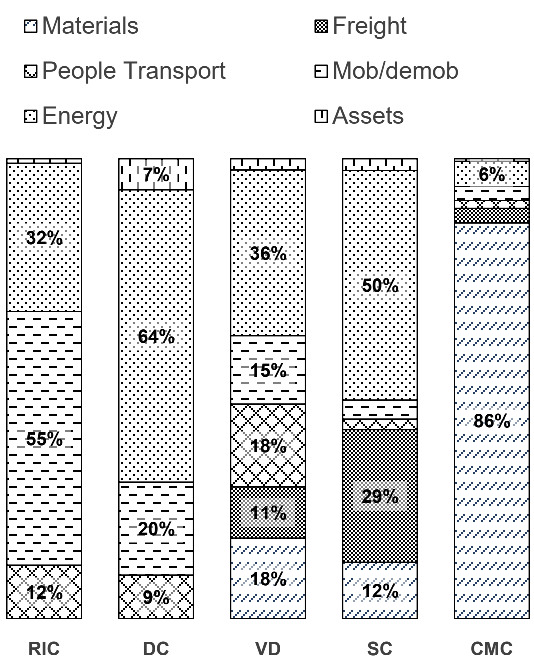

Figure 2. Embodied Carbon Breakdown per Ground Improvement Technique

2.1 Rapid Impact Compaction and Dynamic Compaction

The two projects analyzed were performed in 2022; the Rapid Impact Compaction (RIC) project is a non-industrial project and lasted about a week; the Dynamic Compaction (DC) project is a major industrial project where MENARD crews have been working for over a month. These methods were used to improve the ground up to 10m.

As mentioned in section 1.2, compaction methods such as DC and RIC do not use materials rendering no CO2 output for materials nor for freight of materials.

DC and RIC methods main composition of Embodied Carbon arrives from the use of fuel and the transport of machines to/from site (Mob/demob). For RIC, 56% of its emissions originate from the Mob/demob and 32% from consumption of fuel with the remaining 12% originating from people transport. For DC, 65% originates from the fuel usage, 21% from Mob/demob, and 10% from people transport.

The notable differences between DC and RIC include the variations of CO2 impact with regards to fuel and Mob/demob. The smaller size of the RIC machine (excavator) versus the DC crane makes a lesser fuel impact on the project. The high proportion of Mob/demob for the RIC project is a direct impact from the duration of the project. A short project will show a much bigger relative impact of the equipment transport (Mob/demob) on the total CO2 footprint than a longer one where fuel consumption will prevail.

It seems fair to agree that RIC and DC techniques show similar Embodied Carbon breakdown. Acting on the equipment fuel efficiency and on the idling time will have an impact on the total carbon footprint of the project for these two compaction techniques.

2.2 Vertical drains

The Vertical Drain (VD) project analyzed in this study was completed in 2021 for a public building. The installation of the vertical drains went to 20m in depth.

It can be noted that wick drain installation has a nearly even distribution for all five categories. This is due to the smaller machine (excavator) set up being used which requires less fuel and fewer total transport distance for its mob/demob versus DC or Controlled Modulus Columns (CMC).

The material used for wick drains (polypropylene) has an emission factor of 2,293 kgCO2e per metric ton of material according to the DFI tool (Wilmotte, 2023). Typically, the material is shipped from overseas which slightly impacts the material freight value.

Acting to lower the carbon impact on Vertical Drains projects implies considering fuel-efficient machinery, have local crews whenever possible and attempting to source the wick drain material regionally.

2.3 Stone Columns / Vibro-Replacement / Aggregate Piers

The Stone Column (SC) project that was used for the detailed analysis was completed in 2022. The technique was used to mitigate liquefaction on a road embankment and the ground conditions have been treated to a depth of 25m.

Stone Columns or Aggregate Piers installation can be done with a wide diversity of machinery, and this of course impacts the total carbon footprint of the project: 50% on this specific example.

What is noticeable as well – and very specific to the *aggregate* techniques – is the proportion of Freight of material compared to the other techniques. Even though the raw aggregate extraction and processing is much less CO2 intensive than concrete, the shipment of the aggregate from quarries typically is much further than concrete batch plants. On this specific example the quarry was 70km away from the site – which is not uncommon to find on projects. The impact Freight has on stone columns is 30% versus 4% for the CMC project as shown in *Figure 2*. Compared to concrete, aggregates also usually involve a higher number of truck trips for a similar depth of treatment primarily due to the installation method.

Therefore, to reduce the CO2 impact of a Vibro-Replacement project, finding a local quarry is key; using recycled aggregates also reduces the Materials part (the DFI tool has a dedicated Emission Factor for it).

2.4 Controlled Modulus Columns

The project involving the last technique shown on *Figure 2*, Controlled Modulus Columns (CMC), was for an industrial building. It was completed in 2022 and it involved installation depths up to 19m in very soft clay conditions.

Material and Energy represent a total of 93% of the project carbon impact. Ready-mix concrete has undeniably a high energy manufacturing process which makes it highly carbon intensive. Fuel consumption on site (drilling rigs and ancillary equipment) is the second largest source of CO2 emission on such projects.

Provincial EPD baselines have been published in 2022 for concrete read-mix designs, like the one published by Concrete Ontario (Concrete Ontario, 2022). They provide local Emission Factors which are helpful to assess the real impact of concrete on a project. Concrete suppliers have more openly begun providing project-specific Type III EPDs to improve the accuracy of the emission factor. The concrete industry is working on low carbon options for several mix designs and with increasing demand of low carbon concrete, the supply of such mixes will increase. Supplementary Cementitious Mixtures (SCM) like slag or fly ash are used to replace the cement in concrete mixes to achieve a 20-40% reduction on the kgCO2e/m3 of concrete, compared to the provincial baselines. These SCMs are usually by-products from other industries and their availability varies throughout Canada. Research on alternates to cement will need to continue as the supply of current SCMs such as slag will diminish as other industries (i.e: steel) aim to reduce their carbon footprint.

Reducing the CO2 emissions for CMC projects primarily involves utilizing low carbon concrete and optimizing design to minimize material required whilst ensuring a safe final product. After discussions with local concrete suppliers, MENARD launched a country-wide initiative to use low-carbon concrete mixes on most projects by 2025.

Although the above describes the relative CO2 emissions per Ground Improvement technique, it may be of interest to determine a range of absolute values of Embodied Carbon at the development stage.

3 IDENTIFYING A COMMON EMBODIED CARBON METRIC

When designing a structure (industrial or non-industrial), understanding the Upfront Embodied Carbon is becoming more prevalent. Cities such as Toronto have most recently developed an Embodied Carbon pre-requisite cap for public developments and recommended for private developments (Mantle Developments, 2023).

This last section of the study will determine orders of magnitude of Embodied Carbon from the five Ground Improvement techniques listed in Section 2. The goal will be to guide users, such as Architects, to fulfill their carbon budget for the project.

3.1 First Approach: Embodied Carbon by Treatment Area

As mentioned above, the carbon footprint of a Ground Improvement project can be determined knowing:

- The ground conditions – often linked to the depth of treatment;
- The Ground Improvement technique used;
- The size of the project (linked to the loads involved).

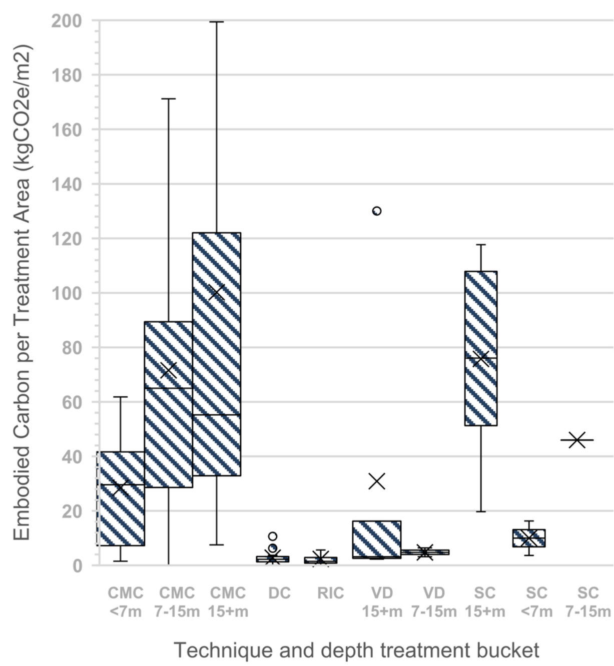

Figure 3. Embodied carbon per m2 (based on Treatment Area) ranges per technique per depth of treatment

With this logic in mind, Figure 3 presents the ranges of Embodied Carbon values calculated on the MENARD past projects for a given technique and a range of depth of treatment (called *depth treatment bucket*). Note that RIC and DC techniques do not have a range of depths of treatment as they do not vary much from one project to the other. The Embodied Carbon value is given per m2 of Treated Area. *Treatment Area* is defined as the area where

Ground Improvement has been performed. Typically, it can be simplified into the building footprint with some buffer zone around it.

Figure 3 clearly shows that the Embodied Carbon values vary significantly from one technique to the other which can be attributed to whether materials are used for the technique and the emission factor of that material. The deeper the treatment depth, the more Embodied Carbon especially for techniques that involve the usage of materials as more volume of that material is required. It is also striking that for Stone Columns (SC) or Controlled Modulus Columns (CMC) techniques, there is a wide range of values for a given treatment depth bucket. This could be potentially a consequence of the building type or of the loads induced on the surface structure. Dividing the total Embodied Carbon of the project by the Treatment Area does not consider the height of the building for instance.

The analysis on the 114 past projects is coherent with the relative analysis performed in section 2. Table 2 summarizes the Embodied Carbon per Treatment Area for typical projects and the values are in line with the ranges presented in Figure 3.

Table 2. Example of Embodied Carbon per Treatment Area for five typical projects

Technique	Type of project	Depth of treatment	GWP per treatment area (kgCO2e/m2)
RIC	Non-industrial	<10m	1.2
DC	Industrial	<10m	1.8
VD	Non-industrial	15+m	3.7
SC	Non-industrial	15+m	64.8
CMC	Industrial	15+m	61.2

Figure 4 shows that industrial buildings have a lower Embodied Carbon per Treatment Area than the non-industrial buildings such as residential for CMC rigid inclusions projects. Industrial buildings are usually single storey building whereas residential projects go higher. Therefore, dividing the total embodied carbon of the ground improvement works by the Treatment Area misses the "storeys" variable which makes comparisons between buildings pretty unreliable. For similar soil conditions, more storeys usually means more load and more ground improvement support, hence the higher carbon footprint per m2.

It is to be noted that projects that did not involve buildings (roads) were removed from this analysis.

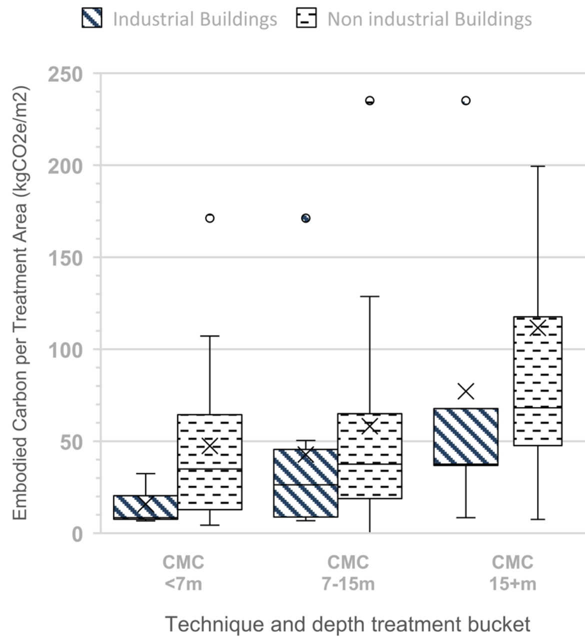

Figure 4. Embodied carbon for CMC projects per m2 (based on Treatment Area) ranges per type of building per depth of treatment

The next approach discussed in section 3.2 looks at utilizing the Gross Floor Area instead of the Treatment Area. The target is to remove the bias observed when comparing ground improvement embodied carbon performances between building types.

3.2 Second Approach: Embodied Carbon by Gross Floor Area

The Gross Floor Area (GFA) can be defined as the total floor area inside the building envelope, excluding the roof. Therefore, the GFA takes into consideration the number of storeys of the building which could influence the final loading condition and also change the level of treatment required.

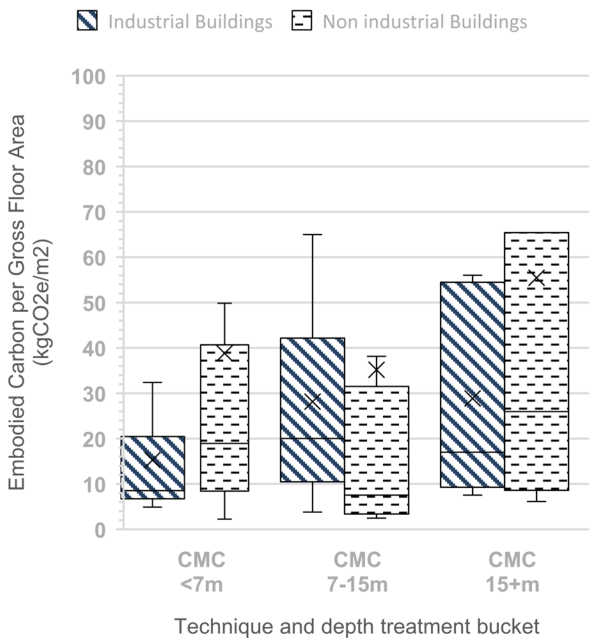

Figure 5. Embodied carbon for CMC projects per m2 (based on GFA) ranges per type of building per depth of treatment

The results of the division of the total Embodied Carbon by the GFA are shown in Figure *5*. The ranges between Industrial and Non-industrial buildings are now similar for a given depth treatment bucket. This new metric seems to be more robust regarding the type of building considered.

Figure *6* displays the ranges of CO2 emissions per technique using GFA as the normalized factor. Also, municipalities such as Toronto, utilize GFA as the unitary kgCO2e to cap Embodied Carbon for the surface structure. Therefore, Figure 6 can be used to help determine the *carbon budget* for the Ground Improvement portion of the project.

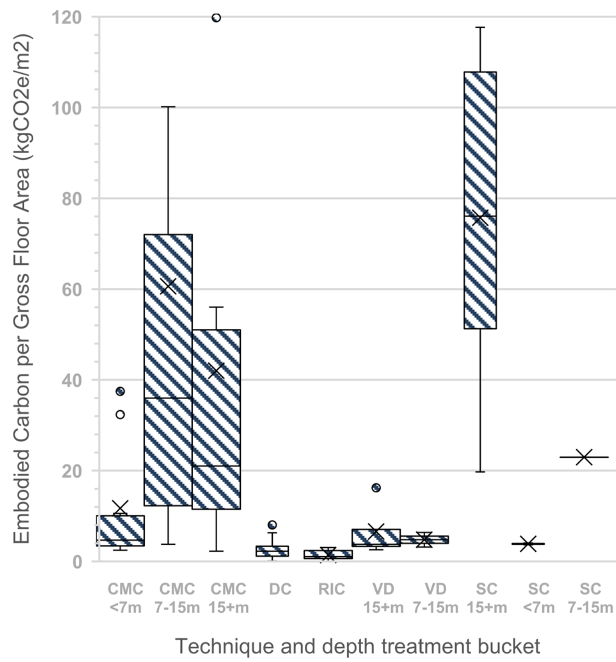

Figure 6. Embodied carbon per m2 (based on GFA) ranges per technique per depth of treatment

4 CONCLUSION

The Deep Foundation Institute tool is very convenient to assess the Embodied Carbon of a Ground Improvement project. Once the logic is understood, it can be integrated to internal processes to automatically calculate carbon emissions throughout the project's production, or during the bidding stage.

Comparing Embodied Carbon absolute values from one Ground Improvement technique to the other was discovered to not be informative as each technique has its own domain of application depending on the soil conditions. The lowest carbon intensive techniques like Dynamic Compaction or Rapid Impact Compaction should be considered whenever possible (usually soil conditions dependent). The type of building that will be supported also has an impact on the choice of Ground Improvement technique. It is interesting to note that aggregate-based methods like Stone Columns (SC) can have a higher carbon impact than concrete-based methods like Controlled Modulus Columns (CMC) due to the freight from the quarry and the higher installation rates with concrete.

Once the building envelope is defined and the Gross Floor Area is known, using MENARD's historical data from past projects along with knowledge of the depth to be *improved*, a development team would be able to estimate the Embodied Carbon relative to the Ground Improvement technique. This can then be included in their *carbon budget* for the project. This study does not provide a CO2 emission comparison between traditional options like dig and replace or deep foundation solutions with Ground Improvement techniques. However, with the data shown above, development teams can now compare options and decide for the one with the lesser carbon impact.

The numbers that were shared are considered as baselines for the MENARD team in Canada. There are options to reduce the carbon impact of Ground Improvement: optimize quantities, use low-carbon options, avoid machine idling, use more fuel-efficient machinery etc. The internal objective in the coming years will involve reducing the Embodied Carbon per m2 of Gross Floor Area for all techniques to be ready for the next generation of Embodied Carbon capping regulations. Such regulations push the industry to innovate and deliver more sustainable construction projects.

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