Comparing the Embodied Carbon of Foundation Support solutions

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ABSTRACT
Foundations of buildings can be supported with a wide range of solutions. The foundation support options that are considered for a given development project depend on the structure to be built, as well as the ground conditions and the access conditions to the future jobsite. Total embodied carbon has recently emerged as another important criterion for evaluating foundation strategies. Some municipal regulators in Canada have started to add limits to embodied carbon in new construction projects.

The article highlights projects where more than one foundation support solution is considered and provides a clear comparison of the carbon impact of the alternative strategies. The comparisons are based not only on the ground-related works but also on the structural implications of the foundation strategy. The aim of the article is to provide metrics to evaluate the carbon impact of foundation support solutions at the project conception phase.

RÉSUMÉ
Les fondations de bâtiments peuvent être supportées par un large panel de solutions. Les options considérées pour un projet de développement donné dépendent de la structure à construire, ainsi que des conditions du sol et des conditions d'accès au futur chantier. Cet article examine un autre paramètre déterminant de plus en plus important dans le processus de prise de décision : l'empreinte carbone totale. Certaines municipalités au Canada ont déjà commencé à plafonner l'empreinte carbone des nouveaux projets de construction.

L'article met en évidence des projets dans lesquels plus d'une solution de support de fondations a été envisagée et fournit une comparaison claire de l'impact carbone de ces solutions. Les comparaisons portent non seulement sur les travaux géotechniques mais également sur les implications structurelles de ces solutions. L'objectif de l'article est de fournir des métriques pour évaluer l'impact carbone des solutions de support de fondations lors de la phase de conception.

1 INTRODUCTION

Community recreation centres promote public health through physical fitness and social connection. Their design also signals community values. Increasingly, these values include sustainability initiatives and carbon efficient design. Furthermore, limits on embodied carbon are commonly piloted for city-owned or public projects in the early stages of implementation. As a result, the requirement for quantifying and reducing the Global Warming Potential (GWP) of buildings is realized initially in public projects including recreation centres.

The City of Toronto has enacted embodied carbon limits on city-owned buildings in terms of GWP per square meter. It is anticipated that limits will also be applied more broadly in future versions of the Toronto Green Standard (Mantle Developments, 2023). Additionally, the National Building Code of Canada is expected to consider embodied carbon by 2030 (Engineers and Geoscientists British Columbia, 2023).

1.1 Embodied Carbon in Community Recreation Centres

Recreation centres in Canada tend to be carbon-dense buildings that feature long-span roof structures and contain high-value concrete components such as arena slabs and pool tanks – like shown in Figure 1. It is a challenge to benchmark embodied carbon for these buildings because their structure is influenced to an outsized extent by site considerations such as snow loading, seismic forces and soils conditions.

Sites with poor soils requiring deep foundation systems increase the cost and embodied carbon relative to a site with competent soils where conventional shallow foundations can be used. In some cases, however, conventional foundations may be viable on poor soils by using Ground Improvement techniques. This paper investigates the embodied carbon implications of deep foundation systems compared to conventional foundations on improved soil. This is done by comparing structural models for each condition while maintaining identical above grade structure. This process allows for direct comparison to provide insight for making well informed decisions on foundation solutions for future projects.

1.2 Quantifying Embodied Carbon

The built environment is responsible for 11% of carbon emissions globally (World Green Building Council, 2019). The conversation around environmental impacts of buildings in the past has focused more on the greenhouse gas emissions associated with the operation of a building, resulting in more sophisticated and efficient mechanical systems and envelope design. Recently, however, the conversation has expanded to include a building's upfront embodied carbon; that is, the greenhouse gas emissions resulting from the extraction, production, transport and manufacturing of the materials that comprise a building.

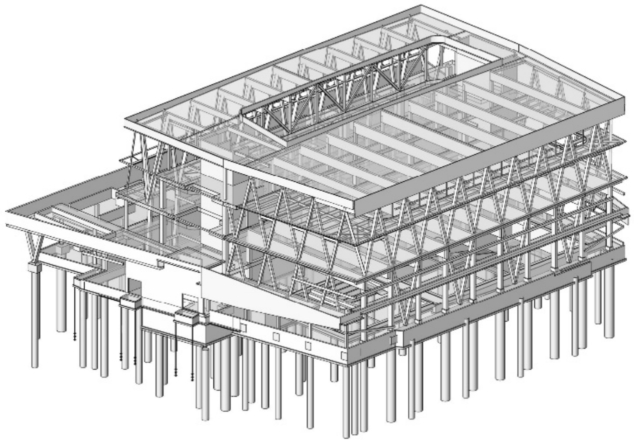

Figure 1. 3D View of a recreation centre supported by deep foundations

2 FOUNDATION SUPPORT SOLUTIONS

This article compares various foundation support systems for the same projects. The foundation supports considered for a project usually depend on the soil conditions, the structural loads and the settlement requirements (differential and maximum). Some systems are recommended by the Geotechnical Engineer in the project geotechnical report.

Where the ground is competent enough to support the structural loads, a conventional shallow foundation option is always preferred as it simplifies the project constructability and minimizes both the embodied carbon and the cost of the project.

Where the settlement criteria or the estimated native soil bearing capacity does not allow for a shallow foundation solution, at least three other options are available to the project team for foundations support:

- Excavate the shallow soft soil layer(s) responsible for the excessive settlements and replace them with engineered fill that meets the bearing capacity requirements to allow for use of shallow foundations. This option was not viable for the projects analyzed in this study.
- Install deep foundations that bear on a competent deeper soil layer and/or make use of friction resistance in the soils in contact. Using deep foundations require adjustments to structure that will be discussed in Section 2.1.
- Opt for a Ground Improvement technique that increases the bearing capacity of the native ground and helps control settlements to the specified level. Some techniques require the addition of material into the ground (stones, concrete, etc.) and others do not. Shallow foundations can then be constructed.

2.1 Deep Foundations

The most common type of deep foundations are piles. Piles have very different methods of installation (driven or drilled, with or without displacement), they can be made of a range of materials (concrete, steel, wood) and all these factors impact the performance of the pile.

The design method of a pile system depends on the soils in which it is founded and whether or not the pile tip bears on rock (Canadian Foundation Engineering Manual, 2023). The focus of the pile design is to safely transfer structural loads to the pile system. The native soil conditions below and around the piles are used to calculate a pile capacity in kilo Newton (kN) that is used to design a system capable of resisting loads from the building above.

Using a deep foundation option often requires the addition of a structural slab at the ground level along with grade beams for lateral stability. These additions are considered in this analysis.

On the embodied carbon side, most of the carbon footprint of these solutions come from the material used and the equipment involved during the pile construction (fuel/energy burnt to install them). Given that the piles tend to have large diameters and/or stiff soil layers to penetrate through, the installation of such elements is often more time consuming than conventional methods. This impacts the project timeline, which due to mobilization and demobilization of equipment and people, can add to the carbon footprint of the building.

For the projects described in this article, three different deep foundation solutions were recommended in the initial stages of the project:

- *Steel H-piles*: driven steel piles, installed by a driving hammer (D19 Delmag or equivalent) mounted on a drilling rig. They are usually 12-21m long (requires welded splices for greater lengths) and have a capacity from 350 to 1800 kN. In this specific case, the H-piles were assumed to be HP 310 x 110.
- *Caissons*: usually drilled and cast-in-place to ensure a greater contact with the rock they are anchored in. The capacity of a caisson depends mostly on the end-bearing resistance on competent rock; the shaft resistance also increases the caisson capacity. They are reinforced with steel cages. Caissons are installed using a drilling rig; a large excavator (35-45t) is needed on site to load the dump trucks that manage the drill spoils. In this study, the diameter of the caissons was 600mm.
- *Micropiles*: small diameter (<305mm) piles that can support both axial and lateral loads. Micropiles are installed with a smaller rig than caissons or H-piles and require a grout batch plant on site. Reinforcing steel in this study was with a Grade 75 threaded rod.

2.2 Ground Improvement

Ground Improvement focuses on soil properties below the structure; these properties are improved differently depending on the technique chosen. Ground Improvement techniques vary based on the type of soils encountered and on the targeted improvements – which can be one or several of the following:

- settlement control
- increased bearing capacity

- liquefaction mitigation

Some techniques require the addition of materials such as concrete for rigid inclusions (e.g. Controlled Modulus Columns), stones (e.g. Stone Columns, Rammed Aggregate Piers) or PVC pipes for Vertical Drains.

The primary structural benefit of choosing Ground Improvement for foundation support is that the foundation layout will be the same as a shallow foundation system – meaning no structural slab, pile cap etc.

Ground Improvement "complements" (more than "replaces") the native soil characteristics and therefore usually requires less material than deep foundations for the same required support. When looking at the project embodied carbon, the pieces of equipment needed on site as well as the duration of installation should also be considered as more equipment and more time on site means more energy burnt.

This study focuses on three Ground Improvement techniques:

- *Controlled Modulus Columns (CMC)*: concrete rigid inclusions executed with a drilling rig and in most cases with a soil displacement auger that generates minimal to no spoils. CMC's produce increased bearing capacity by using the existing soil capacity and the stiffer rigid inclusions as a load sharing system.
- *Stones Columns (SC) / Aggregate Piers*: well suited for the improvement of soft or loose soils. SCs are vertical inclusions that provide high stiffness, shear strength and draining characteristics.
- *Prefabricated Vertical Drains (PVD):* drains that provide a preferred path for water to assist in consolidation which improves soil characteristics. The combination of vertical drains with the placement of preloading or a surcharge program accelerates the consolidation period.

These techniques have different working platform requirements depending on the main equipment type. The installation of the working platform was not considered in this study. Most Ground Improvement techniques and Deep Foundation techniques have the same requirements.

It should also be noted that rigid inclusions (CMCs and SCs) require a Load Transfer Platform (LTP) made of concrete or granular material. This LTP was assumed to be constructed from the existing working platform for this study. The impact of the construction of the LTP on the total Embodied Carbon was considered negligeable.

Now that Deep Foundation and Ground Improvement techniques are well defined, the scope of the study can be outlined.

3 SCOPE AND CALCULATIONS TOOLS

To calculate and compare projects embodied carbon, it is key to clearly define the Physical Scope of the study (which structural elements are included in the comparison, and which are not) and the Embodied Carbon Scope.

3.1 Physical Scope

To provide a direct comparison, the embodied carbon counted in this article includes slabs on grade and any structural elements below grade. The structural system above grade is identical for each case. Figures 2 and 3 below define the scope of which elements are considered in this analysis.

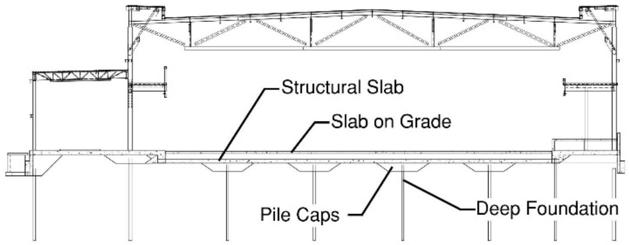

Figure 2. Cross section of a community recreation centre on deep foundations

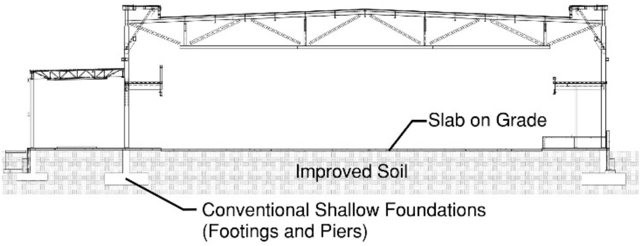

Figure 3. Cross section of a community recreation centre using ground improvement.

3.2 Embodied Carbon Scope

Embodied carbon is often represented in terms of carbon dioxide equivalent (CO_2e). The unit CO_2e represents all greenhouse gas emissions as their equivalent global warming potential in carbon dioxide. This study represents the embodied carbon of a building in terms of a mass of carbon dioxide equivalent (tCO_2e) and in terms of mass of carbon dioxide per square meter of Gross Floor Area - GFA ($kgCO_2e/m^2$).

Two methods were used to calculate the total embodied carbon of the projects in this study. Both tools, discussed below, provide Emission Factors or Global Warming Potential (GWP) values from Industry Environmental Product Declarations (EPDs), Product EPDs or global Emission Factors databases. Whenever available, Type III EPD (third-party verified) that are compliant with the ISO 14025 standard were used.

The International standard for whole building embodied Carbon includes five main categories; the product stage; the construction process stage; the use stage; the end-of-life stage; as well as the benefits and loads beyond the system boundary (Carbon Leadership Forum, 2019).

The embodied carbon values for the structural components in this article consider only the A1-A3 phase of the Life Cycle Analysis (LCA) – see Table 1. This includes all elements from the product stage (raw material supply, transport and manufacturing). The scope was limited to A1-A3 for structural components since the materials were assumed to be the only significant varying source of embodied carbon for the different building models.

The A4-A5 phases of the LCA include the transport of equipment, crew and materials to site as well as the construction installation process itself (labour, energy used on site etc.). For the foundation solutions (deep foundations and ground improvement) the energy required to install the different types of foundation solutions can vary and would be interesting to include in this study. The authors are able to provide these values for the Ground Improvement systems they install. For the Deep Foundation options, a lot of assumptions would be needed as the authors do not have the technical expertise to accurately calculate these numbers. Therefore, the A4-A5 phase numbers will only be provided in this study for the Ground Improvement options in section 3.2. It was assumed that any differences in the A4-A5 phase is negligible for structural components.

Now that the embodied carbon scope is clearly defined, we look at the tools used to perform these calculations.

2.1.1 Structural Quantity Takeoff Tool

The structural quantity takeoff was completed by modelling the structural elements in Revit, then using Blackwell's quantity takeoff tool to export material volumes. These volumes are then converted into GWP values in terms of kg/CO2e by using Type III EPD's from the available material market.

To maintain accurate comparison, the EPD's used to convert material quantities to global warming potential were maintained consistent for each project in this article. The GWP estimated in this analysis will vary from GWP values executed during construction since the exact materials to be used and their sources cannot be anticipated, nor do all the potential sources have verified EPDs available. However, the intention for these estimates is to provide comparable values, which has been accomplished by maintaining a consistent approach across each building case.

2.1.2 Foundation Support Tool: EFFC/DFI Carbon Calculator

Computations for the foundation support solutions were performed with the EFFC DFI Carbon Calculator Tool (Wilmotte and al., 2023).

The EFFC DFI Carbon Calculator Tool considers seven categories for carbon emissions, each requires different key information summarized in Table 1. These categories cover the A1-A5 phase as per the International standard (World Green Building Council, 2019).

Table 1. DFI categories (Bunieski and al., 2023)

Category	**Content**	**LCA Phase**
Materials	Type of material (aggregates origin, concrete mix, etc.), material amount	A1-A3
Freight	Type of truck, distance travelled for the transport of the material	A4
Energy	Amount of fuel or electricity used on the project	A5
Mob/Demob	Type of truck, distance travelled, days on site for the mobilization and demobilization of the equipment (main and ancillary)	A4
People Transport	Type of transport (train, plane, car), distance to site travelled by the project crew	A4
Assets	Weight of asset, lifetime expectancy for the equipment used on site	A5
Waste	Weight of waste generated on site	A5

Each foundation support solution has a different embodied carbon breakdown using these seven categories as shown in Figure 4. To calculate the GWP of materials (concrete, stone) – which is the most carbon-intensive category for most foundation support solutions – EPDs available 50km around the project location were used in the EC3 database (Building Transparency, 2020).

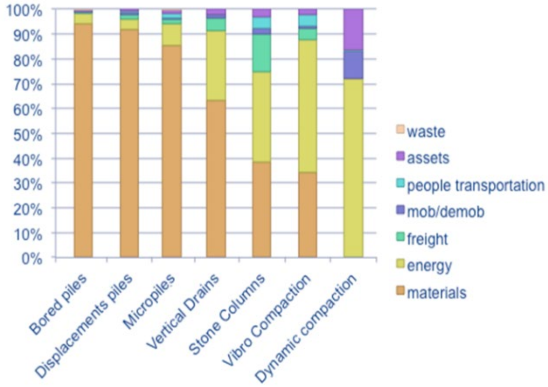

Figure 4. Embodied Carbon breakdown per EFFC-DFI category for various Deep Foundation and Ground Improvement techniques (Wilmotte and al., 2023)

Now that we have a clear scope for the structural elements and for the embodied carbon calculation, we are able to run the calculations for each project analysed and compare the results.

4 RESULTS

The embodied carbon calculations were completed on three recreation centers development projects in Ontario. All three projects had poor soil conditions and Deep Foundations were recommended initially; they also had different sizes:

- *Case Study 1*: soft compressible clay layer down to about 30m with N SPT values between 0 and 6. The Gross Floor Area (GFA) of this recreation centre was about 10,400 m2
- *Case Study 2*: relatively loose fill (clay and silt) layer down to 8m with N SPT values ranging between 4 and 7. This centre had a GFA of about 3,800 m2
- *Case Study 3*: 30m of very soft clay with N SPT values less than 5. The GFA of this third centre was about 3,500 m2.

Table 3 summarizes the foundation support solutions that were considered by the project teams for each Case Project.

Table 3. Foundation support scope and solutions considered for each Case Project.

Case	Foundation support	Deep Foundation solution	Ground Improvement solution
1	Slab and footings	Steel H-piles	Controlled Modulus Columns and Vertical Drains
2	Footings only	Caissons	Controlled Modulus Columns
3	Slab and footings	Micropiles	Controlled Modulus Columns

4.1 A1-A3 Phase Results

The results of this study have been organized into three categories to highlight the largest implications of the data:

- The first category is the *slabs and structural slabs*. This includes the slab on grade, as well as any additional structural slab required as part of the deep foundation system.
- The second category is the *foundation system*. For ground improvement cases, this category includes the embodied carbon of the ground improvement itself as well as the conventional foundation system. For deep foundations, this category includes the deep foundations themselves (H-piles, micropiles, or caissons) as well as the pile caps associated.
- The third category includes *all other below grade elements* not associated with the categories above such as foundation walls, grade beams and frost slab elements.

Table 4 below summarizes the results obtained. One comparison column was added to show the percentage of change for each category for the Ground Improvement option (GI) compared to the Deep Foundation (DF) option. The Table also provides the total embodied carbon for A1-A3 for the "below-grade" structure and the overall A1-A3 embodied carbon of the building.

Table 4. A1-A3 Embodied Carbon Results for 3 Case Projects.

Embodied Carbon (tCO_2e)	Ground Improvement (GI)	Deep Foundation (DF)	GI vs DF
Case 1			
Slabs & Structural Slabs	323	976	+67%
Foundation System	395	177[2]	-123%
Other Below Grade Elements	217	231	+6%
Total Below Grade	**935**	**1,384**	**+32%**
Total Building[1]	**2,008**	**2,374**	**+15%**
Case 2			
Slabs & Structural Slabs	162	167	+3%
Foundation System	137	312[3]	+26%
Other Below Grade Elements	142	164	+13%
Total Below Grade	**536**	**643**	**+17%**
Total Building[1]	**1,268**	**1,384**	**+8%**
Case 3			
Slabs & Structural Slabs	131	339	+61%
Foundation System	155	136[4]	-14%
Other Below Grade Elements	47	73	+36%
Total Below Grade	**333**	**548**	**+39%**
Total Building[1]	**757**	**949**	**+20%**

[1] includes all ground improvement, foundation, and building structural elements (above and below grade) for phase A1-A3.

[2] Foundation system: Steel H-piles

[3] Foundation system: Caissons

[4] Foundation system: Micropiles

It is consistent across these three case studies that ground improvement methods resulted in the lowest embodied carbon – which is in line with what a cost comparison would provide. The biggest carbon savings with the Ground Improvement option are found with Case 1 and Case 3 where both slab and footing support was needed for the project. The carbon savings below grade are consistent and provide an average saving of approximately 35%. The soil conditions were similar for both projects. Case 2 still shows carbon savings (17%) with the Ground Improvement option but half what could be obtained with Case 1 or 3.

Case 2 only required footing support – no structural slab was needed.

When comparing absolute values between cases, it is clear that the total Embodied Carbon of the works below grade (as well as the whole construction) are impacted by the size of the building and the Gross Floor Area (GFA). Between Case 1 and Case 3, the carbon impact of Case 1 is almost three times that of Case 3. This difference is approximately the same as the percentage difference in GFA between these projects.

Furthermore, these case studies have highlighted how crucial it is to consider the entire building when comparing foundation systems. For example, Case 1 and Case 3 - which are supported by H-Piles and Micropiles respectively - required the addition of a structural slab to receive the support from the deep foundations. This additional slab is responsible for 47% of total below grade embodied carbon for Case 1, and 37% for Case 2.

Comparatively, Case 2 did not require a structural slab, yet the ground improvement solution remained the least carbon intensive. The deep foundation system recommended for Case 2 was a caisson system. This caisson system, though it did not require a structural slab, did account for 48% of the embodied carbon in the structure below grade. When compared to the 13% and 25% in Cases 1 and 3 with other foundation methods this raises the question of whether an alternative deep foundation method may be more efficient.

Comparing buildings that have different architectures and use different materials is not straightforward, but this study enables us to extract some orders of magnitude for the carbon intensity (kgCO2e/m2 of GFA) of recreation centers and the portion of the below grade works in the total carbon intensity of the building. Table 5 summarizes the results in carbon intensity for both Ground Improvement (GI) and Deep Foundation (DF) solutions.

Table 5. Summary of Carbon intensities for all cases

kgCO2e/m^2	**Total Building**	**Below Grade**	**Total Building**	**Below Grade**
Case	**GI**	**GI**	**DF**	**DF**
1	192	89	228	133
2	333	141	364	169
3	216	95	271	157

These numbers are to be compared with the upfront embodied carbon caps recently published by the City of Toronto and the City of Vancouver. The City of Toronto set up a cap of the upfront embodied carbon intensity at 350 kgCO2e/m2 for the new city-owned buildings (Mantle Developments, 2023) while the City of Vancouver set theirs at 400 kgCO2e/m2 (City of Vancouver, 2023). These caps cover upfront carbon emissions from life cycle stages A1-A5. The numbers in Table 5 only account for stages A1-A3. For now, the cap in the Toronto Green Standards is "limited to major structure and envelope materials" (Mantle Developments, 2023) and it is not clear if Below Grade works should be included. This being said, from a structural point of view, the Below Grade Works represent 40% to 50% of the Total Building upfront embodied carbon – which makes foundation support design choices quite impactful on the total upfront embodied carbon of the building. Had these recreations centres been in Toronto and had the caps been defined on stages A1-A3 like the analysis in this study, going for a Deep Foundation solution instead of a Ground Improvement alternate for Case 2 would have implied a fail for the Toronto Green Standards v4 cap (364 kgCO2e/m2 > 350 kgcO2e/m2).

4.2 A4-A5 Results

The A1-A5 stages were mentioned above. Table 6 below provides a breakdown of the A4-A5 categories defined in the EFFC-DFI Carbon Calculator for the Ground Improvement options. To be able to run a full A1-A5 embodied carbon comparison of Ground Improvement system vs Deep Foundation system, similar numbers should be obtained for the Deep Foundation system. Such numbers would also be needed on the slab construction and on footings excavation and installation. With the level of information publicly available at the moment, a complete absolute comparison is not possible. More environment-related case studies on Deep Foundation projects will help refining the comparison.

Table 6. Breakdown of embodied carbon per EFFC-DFI category for each Case Project for the Ground Improvement options for stages A4 and A5

Embodied Carbon (tCO_2e)			
EFFC-DFI Category	**Case 1**	**Case 2**	**Case 3**
Energy	98	35	42
People Transport	1.5	0.2	0.6
Assets	2.1	0.7	0.9
Waste	0.1	0.0	0.0
Mob/Demob	16	5	13
Freight	3.5	1.1	1.2

For these three Case Studies, the Ground Improvement option for stages A4-A5 represents about 30%-35% of the upfront carbon emitted during stages A1-A5. The A4-A5 stages impact the total carbon footprint however the calculation relies heavily on sharing key operational information by multiple trades (deep foundation, excavating and forming, slab constructors etc.). Without the operation knowledge of each trade, the embodied carbon values are difficult gather and confirm.

Embodied carbon calculations on stages A1-A3 on the other hand can be evaluated by the project team using BIM during the design stage which makes the comparison of several scenarios possible – like we did here with the Ground Improvement option vs the Deep Foundation initial solution. The fact that current embodied carbon caps rely on stages A1-A5 (and not A1-A3 only) means more transparency is needed in the industry on every trade's carbon contribution.

5 CONCLUSION

While the initial scope of this study is modest, two conclusions can be drawn.

First, in each of the cases studied, the ground improvement foundation strategy resulted in lower total embodied carbon relative to the deep foundation strategy when looking at the A1-A3 phase of the Life cycle Assessment.

Second, for buildings that require support of high value concrete slabs such as pools and ice arena slabs, the savings in embodied carbon when choosing ground improvement over deep foundation systems is large: 32% for Case Study 1 and 39% for Case Study 3. Where slabs can be supported on native soils (Case Study 2), our study indicates a more modest saving of 17% for the ground improvement over a deep foundation strategy.

Future research will expand the scope of our investigation to include other project types such as commercial midrise buildings, condominiums and cultural centres such as art galleries. These projects vary in terms of foundation demand and have smaller footprints relative to recreation centres.

It is expected that such carbon budgets will become compulsory to gain approvals for new projects in the near future. While it is not entirely clear where the consideration of foundation support would fall within the whole building Life Cycle Analysis (LCA), the intent here was to understand the embodied carbon implications of some design decisions which is entirely consistent with the global goal of reducing upfront carbon emissions for new buildings. Relying on carbon budgets or caps that cover stages A1-A5 (and not only A1-A3) will require trades to provide baselines to allow for upfront embodied carbon values to be calculated early in the design cycle. As this article showed, some design choices can impact the compliance of a new building to the local embodied carbon regulations.

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