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EMBODIED CARBON ASSESSMENT OF GEOTECHNICAL WORKS

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ABSTRACT

In the light of rising construction sustainability concerns, embodied carbon assessments are often one of the main engineering tools to identify the best “green” option. Embodied carbon assessments provide a simple way to quantify and measure the summation of all the greenhouse gases generated from the built environment. It includes a whole life carbon cycle assessment of a given project from the impacts of materials production, transportation, installation, maintenance, and any waste or disposals during and at the end of design life. This paper aims to allow geotechnical engineers to quickly determine the embodied carbon of their design, and more profoundly form the basis of an innovative and efficient design approach with the consideration of intelligent and alternate material choice to achieve the same performance. In this paper, the methodology of embodied carbon calculation will first be introduced, followed by a summary of carbon emission factors (CEF) that are applicable for geotechnical designs. The discussion herein will focus on the initial portion of the embodied carbon life cycle assessment which comprises of the “before use stage” only for a particular project. Case studies on the use of embodied carbon calculations were provided for a variety of geotechnical projects including foundation for road embankment, trench excavations, and tunnel design. These case studies will show the significance of carbon calculations during the initial design stages and its value in recognition of projects’ sustainability goals. Alternative real-life solutions in achieving de-carbonization will also be presented as a concluding remark, highlighting the possibility of sustainable design in geotechnical practice.

KEYWORDS: Embodied carbon assessment, carbon emission factors, de-carbonization

1 INTRODUCTION

The Paris Agreement (COP21) signed in 2015 by 196 members of the United Nations is a legally binding treaty with a goal of limiting temperature increases to 1.5°C. In 2018, the Intergovernmental Panel on Climate Change (IPCC) reported that in order to limit temperature rise to this level, global carbon dioxide emissions needed to be reduced by 45% by 2030, and net zero by 2050. These global policies helped to change the industry’s practice by increasing the awareness of global warming, and particularly the impact of carbon. The embodied carbon (EC) assessment helps the designer quantify the amount of embodied carbon in their design and promotes sustainable strategies in the construction industry. As a result, it has become crucial to carry out quick embodied carbon calculations that align with the Sustainable Development Goals (SDGs) (United Nations, 2015). EC calculations particularly align with the following SDGs: No. 9 (Industry, Innovation, and Infrastructure), No. 12 (Responsible Consumption and Production), and No. 13 (Climate Action).

The authors are of the opinion that most Geotechnical Engineers either don’t complete or leave the embodied carbon (EC) calculations up to their Civil/Structural Engineering colleagues. Whilst Geotechnical Engineers typically refine or optimize their designs to reduce quantities and costs, most lack the understanding (or time) to undertake the EC calculations themselves. This paper aims to close the gap and provide the motivation and means for Geotechnical Engineers to quickly undertake their own calculations and hopefully fuel further discussion of sustainability in Geotechnical Engineering.

A whole life carbon assessment typically encompasses all stages and is also commonly referred to as a ‘cradle to grave’ assessment. From PAS 2080:2016 (BSI, 2016) and RICS (2017), the whole life carbon cycle is broken down into three main stages, known as ‘Before use’ (Stage A), ‘Use’ (Stage B), and ‘End of life’ (Stage C) stages, as shown in Figure 1. Stage D is typically not considered in a simple embodied carbon calculation. The carbon assessment is further categorised by the source of the emissions into capital carbon, operational carbon, and user carbon (EFFC, 2022). In the context of a whole life carbon assessment and ‘embodied carbon calculation’, the amount of greenhouse gas emissions is typically measured in the unit of carbon dioxide equivalent (CO_2e) or as a mass factor of $kg.CO_2e$. This allows quantification of the global warming potential and provides a basis for an optioneering assessment. The methodology and associated formulae for this kind of assessment is given in Section 2, followed by a summary of the selective carbon emission factors (CEFs) for different stages in section 3.

The term embodied carbon (EC) in the context of this paper is used to represent the capital carbon greenhouse gas (GHG) emissions associated with the 'Before Use' (Stage A) only, also known as a 'cradle to practical completion' assessment. It is understood that the term embodied carbon is also commonly used to represent a whole life carbon assessment. It's therefore imperative that the engineer defines the system boundaries of the 'embodied carbon' assessment. As designers, Engineers traditionally have the greatest ability to impact Stage A1-A3 (EC involved with the type and quantity of material), and construction companies Stage A4-A5 (EC involved with the transportation and installation on site). However, to meet the IPCC climate actions goals it's imperative that engineers start broadening their system boundaries to thinking whole-life and start working collaboratively with construction companies to reduce the embodied carbon of the built environment. Geotechnical specific embodied carbon case studies illustrating this type of thinking were given in section 4.

From a viewpoint of the carbon reduction hierarchy, the earlier the carbon assessment takes place the greater the ability the designer has to reduce the embodied carbon in projects and programme of work, as illustrated in Figure 2 (BSI, 2023). The adoption of low-carbon techniques are examples of 'improve' mitigations to reduce the whole life carbon in projects (refer Figure 2). Examples demonstrating 'avoid' or 'switch' techniques to reduce carbon will be given in Section 5, followed by some decarbonisation methods to 'improve'.

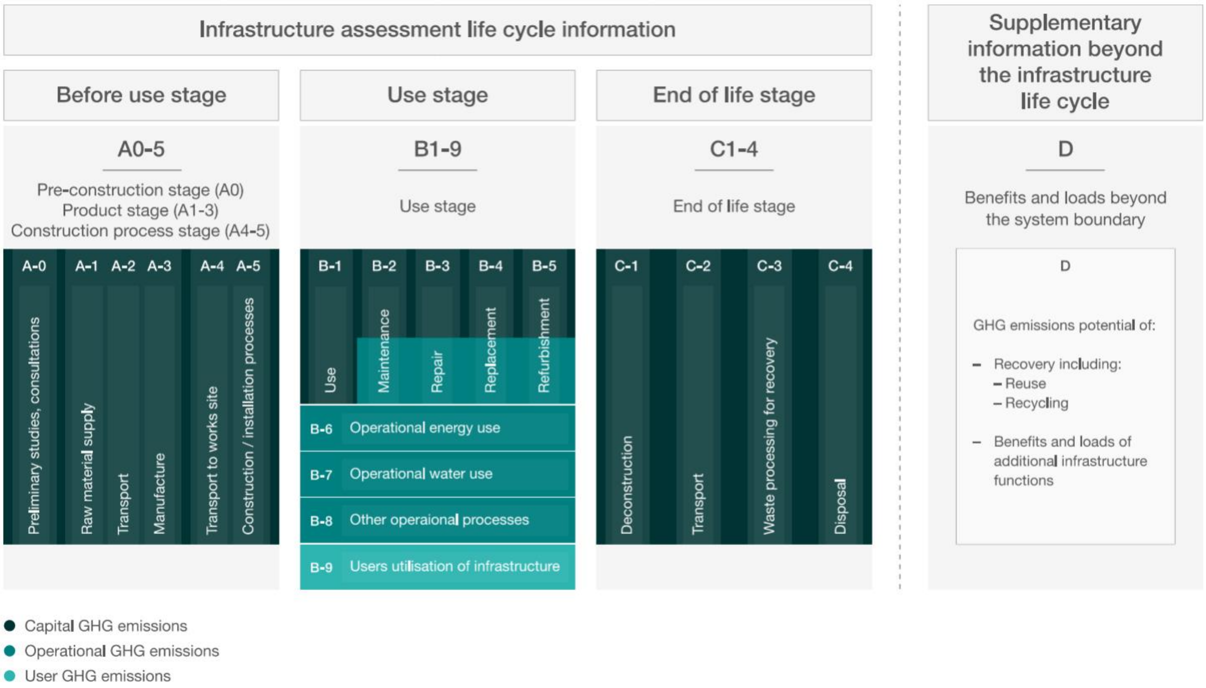


Figure 1: Whole life carbon assessment stages from PAS2080:2016 (BSI, 2016)

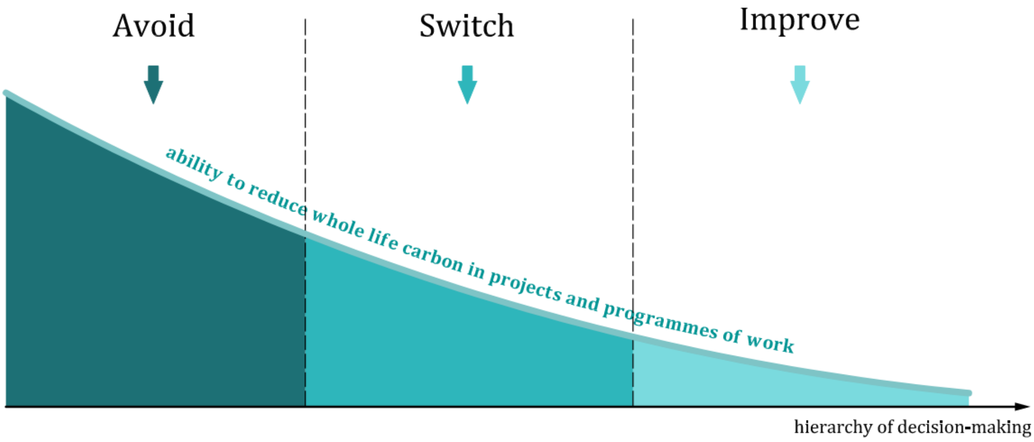


Figure 2: Carbon reduction hierarchy from PAS2080:2023 (BSI, 2023)

2 SIMPLIFIED EMBODIED CARBON CALCULATION

The word 'simplified' in the context of this paper is used to describe the extent of carbon study from Stage A1 to A5 only. The consideration of whole life carbon (Stages A-C) is not addressed herein.

The fundamental objective of embodied carbon calculations is to quantify the carbon impact from 'cradle to practical completion' of the building or infrastructure asset. This aids the engineer in comparing design options (i.e., optioneering), benchmarking, as well as target setting in carbon reduction (RICS, 2017). Benchmarking refers to the comparison between a project against itself over time ('dynamic benchmarking'), and against other similar projects ('static project') under the same basis with consistent results. Ultimately carbon targets set the goal and precedence for carbon reduction. These targets could include the sustainable development policies or planning requirements for the project.

As summarized in Table 1 after BS EN 15978 (BSI, 2011), a typical embodied carbon (EC) assessment from 'cradle to practical completion' is classified into three main categories. A simple EC calculation involves multiplying a quantity, (such as material mass or volumetric quantity of fuel or electricity) by the corresponding carbon emission factor (CEF). The specific quantity is related to resource use which is work-specific depending on the scale and size of a project, whereas the latter (CEF) is a constant determined from public research or industry published data. The authors note that most engineers have a reasonable grasp of the quantities/volumes, but seldom know the appropriate CEF to apply in the EC calculations. Guidance on the selection of CEF are given in Section 3, with industry references sourced.

Table 1: Embodied carbon formulae for Stages A1-A5

Stage	Description	Embodied carbon formula ($kg.CO_2e$) after BS EN 15978 (BSI, 2011)
A1-A3	Material/product stage	EC = Material mass (kg) × $CEF_{material}$ ($kg.CO_2e/kg$)
A4	Transportation of material stage	EC = Material mass (kg) × Transport distance (km) × $CEF_{transport}$ ($kg.CO_2e/kg$ per km)
A5	Construction process	EC = Project Cost (\$) × $CEF_{construction}$ ($kg.CO_2e/kg$ per \$) or, EC = EC_{fuel} + $EC_{electricity}$ = volume of fuel consumed (L) × CEF_{fuel} + electricity consumption (kWh) × $CEF_{electricity}$

As illustrated in Figure 3 (BSI, 2023), whilst the early work stages provide the greatest opportunity to reduce whole life carbon (as discussed in Section 1), project uncertainty is also high. Therefore, the designer must make educated assumptions in order to undertake an EC calculation. It is for this reason that EC calculations (in the early design stages) lend themselves more to comparison purposes rather exact measurement. The true carbon values may fluctuate across the project work phases and should be evaluated once more data is available.

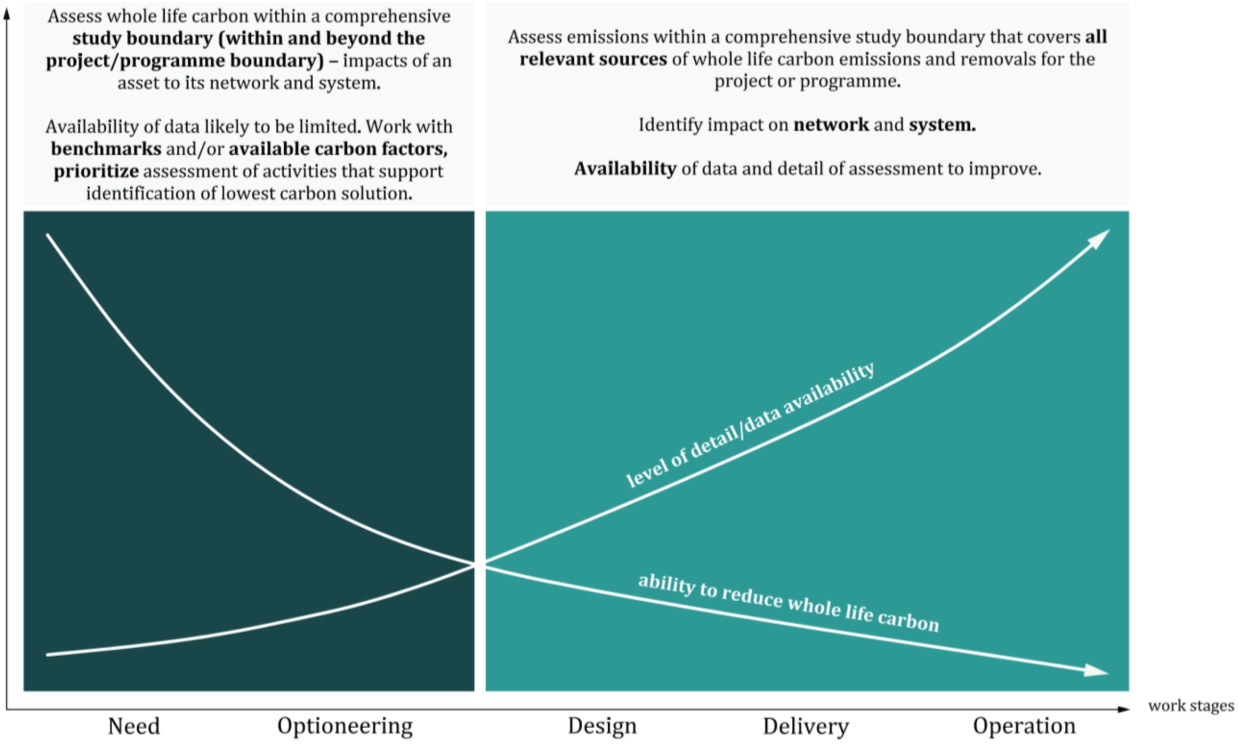


Figure 3: Plot illustrating data availability and the ability to reduce carbon in different work stages (BSI, 2023)

3 QUICK GUIDANCE ON THE SELECTION OF CARBON EMISSION FACTORS

Carbon emission factor (CEF), measured in $kg.CO_2e$ per unit, quantifies the amount of 'carbon' involved with the product or activity per unit. CO_2e, is a measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.

CEF's are material specific and typically vary across different countries for the same materials due to a variety of factors including different industrial practices and economic conditions. They are continually updated in line with current industry behaviours. Therefore, the most accurate CEF's for a material are typically provided by product specific, Environmental Product Declarations (EPDs). EPD's are an independently verified and registered document, adopted in different countries to quantify environmental impacts on the life cycle of a product (ISO, 2006). Various databases have been set up that collate local EPD's to provide country specific CEF's as well as worldwide average CEF's. Australian specific CEF's can be sourced from EPiC database (Crawford, et al., 2019) and UK and worldwide factors from the ICE database (Jones & Hammond, 2019). The full list of resources referenced in the production of this paper is provided below:

- Environmental Performance in Construction (EPiC) Database, University of Melbourne, (Crawford, et al., 2019).
- Inventory for Carbon and Energy (ICE) database (V3.0), University of Bath, (Jones & Hammond, 2019).
- Veracity (v0.1.4), Arup in-house carbon database (Arup, 2019).
- IStructE, 'How to Calculate Embodied Carbon' (Gibbons & Orr., 2020).
- Royal Institution of Chartered Surveyors, Whole life carbon assessment for the built environment (RICS, 2017).
- Product specific EPDs.

The following sections (Section 3.1 to 3.3) provide a summary of the recommended CEFs for common geotechnical project types. They were originally written from UK or European specific data and adapted for Australian factors where applicable to suit local practice. This section of CEF quick guidance was sourced from the documents of 'Geotechnical Embodied Carbon Cheat-Sheet (Aus)' (Dewar & Cheng, 2021) and 'Geotechnical embodied carbon cribsheet – Supplementary manual' (Dewar, 2021), which were prepared by Nick Dewar as part of Arup's investments and in-house resources. Factors should be selected with caution and assumptions documented, so that updates can be easily made as project uncertainty decreases.

3.1 MATERIAL STAGE (A1-A3)

The two main types of engineering materials (excluding soil) used in the construction industry (especially in geotechnical engineering) are concrete and steel. Typical CEF's for these materials are provided in the following tables, Table 2 to Table 4.

Other than the conventional form of CEF in the unit of *kg.CO₂e/kg*, it could also be represented by Carbon Factor in the unit of *kg.CO₂e/m³* with a known material density. The relation between them is given by:

EC ($kg.CO_2e$) = Material mass (kg) × $CEF_{material}$ ($kg.CO_2e/kg$) or,

EC ($kg.CO_2e$) = Volume (m^3) × Carbon Factor ($kg.CO_2e/m^3$)

Table 2: Suggested carbon factors for typical concrete mixes used in geotechnical structures

Typical uses	**Concrete strength[1,2] (*MPa*)**	**Typical cement mix[1]**	**CEF[3] (*kg.CO₂e/kg*)**	**Carbon factor (*kg.CO₂e/m³*)**
Secant piles (primary)	C8/10 [4]	CEM III/A GGBS (50%) GEN 1 [5]	0.092	219
Blinding concrete	C20	CEM II/B-S 30% GGBFS	0.113	269
Piles (Bored, CFA), Pad footings, Retaining walls, Secant Piles (secondary), Contiguous/Solider walls, Diaphragm walls etc.	C32/40	CEM II/B-S 30% GGBFS	0.142	389
Precast concrete driven piles, king post walls etc.	C40/50	CEM II/B-S 30% GGBFS	0.163	389
Ground slabs, Pile Caps, Capping beams, Ground beams	C40/50	CEM II/B-S 30% GGBFS	0.163	389

Notes:
1. Typical mix and strength based on project experience
2. Concrete strength in accordance with AS3600:2018 (Australian Standards, 2018)
3. Data extracted from EPiC database (Crawford, et al., 2019)
4. Global value is adopted with reference to data from ICEv3 database (Jones & Hammond, 2019)
5. CEF sourced from ICEv3 database (Jones & Hammond, 2019). IStructE guide (Gibbons & Orr., 2020) also typically references ICE V.3 database.

Table 3: Suggested CEF's for typical steel elements used in geotechnical structures

Typical uses	**Steel type**	**CEF (*kg.CO₂e/kg*)**
Reinforcing steel in concrete structures	Steel rebar	2.10 [1]
		1.99 [2]
Helical piles & other CHS sections	Seamless tube	4.60 [1]
Driven steel piles, pile casing (& other welded steel tubes).	Welded pipe	3.50 [1]
	Steel plate	2.46 [4]
Sheet piles - hot rolled (Z-shaped, U-shaped, straight web and H-shaped)	Steel, Section	1.55 [4]
Sheet piles - Cold formed (omega-shaped, Z-shaped, trench sheets)	Steel, Finished Cold Rolled Coil	2.73 [4]
Steel H beams (king post wall) etc.	Steel, Section	3.30 [1]

Typical uses	**Steel type**	**CEF (*kg.CO₂e/kg*)**

Notes:
1. Data extracted from EPiC database (Crawford, et al., 2019). Recycling not considered.
2. European average data from worldsteel LCI, 85% recycling rate considered.
3. Structural steel manufactured in accordance with AS/NZS 1163; manufactured through an extrusion process.
4. Global average data from ICE v.3 (Jones & Hammond, 2019) which sources its data from worldsteel LCI (Worldsteel Association, 2019). Recycling not considered

Table 4: Typical steel reinforcement rates and corresponding carbon factors for geotechnical structures

Category	**Options**	**Typical range**		**Chosen value for carbon calculation**			
		Steel rate[1] (*kg/m³*)	**% of steel range[1]**	**Steel rate (*kg/m³*)**	**% of steel**	**CEF[2] (*kg.CO2e/ kg*)**	**Carbon factor[2] (*kg.CO2e/ m³* of concrete)**
Shallow foundation	Rafts: Ground bearing/shallow	115	1.5	115	1.5	1.99	229
	Rafts: Piled rafts in heaving ground	150-200	1.9-2.5	170	2.2	1.99	338
	Pile caps	110-150	1.4-1.9	120	1.5	1.99	239
Deep foundation	Bearing piles: Fully reinforced subject to heave unloading (0.75-2.1m dia.)	80-160	1-2	120	1.5	1.99	239
	Bearing piles: Partially reinforced not subjected to heave (0.45-1.2m dia)	20-80	0.3-1	50	0.6	1.99	100
Earth retention/ Basement	RC retaining wall (L-shaped, gravity etc.)	100-300	1.3-3.8	200	2.5	1.99	398
	Secant piled wall: Hard/firm (600-750mm piles)[3]	115-190	1.5-2.4	160	2.0	1.99	318
	Secant piled wall: Hard/firm (900-1200mm piles)[3]	100-150	1.3-1.9	120	1.5	1.99	239
	Contiguous piled wall (bored, CFA): For typical basements up to 8m depth	80-160	1-2	150	1.9	1.99	299
	Diaphragm wall (incl. guide wall)	130-180	1.7-2.3	150	1.9	1.99	299
	Guide walls	40-60	0.5-0.8	50	0.6	1.99	100
	Capping beams	180-220	2.3-2.8	200	2.5	1.99	398

Notes:
1. Typical steel reinforcement rates based on industry practice (eg. Arup experience), previous projects and review of Arup Structural Concept Design Guide, Concrete Society: Concrete Buildings Scheme Design Manual (section 3.7), F.Cobbs - Structural Engineers Pocket Book (concrete section).
2. European average data from worldsteel LCI. 85% recycling rate considered given that recycling rate for scrap steel is around 80-90% in Australia (Transport Canberra & City Services, ACT Government, 2018).
3. Steel reinforcement rate for secondary pile only (primary unreinforced).

Earth fill materials are also commonly used in geotechnical works. Below (Table 5) shows the recommended CEFs values for some typical earth fill types and asphalt. Some filling types may require pre-treatment to ensure their suitability in the earthwork. It should be noted that below CEFs do not capture the embodied carbon related to the material improvement processes and additional materials. More research should be done to accommodate the impacts of 'improved' materials on carbon footprint used in EC calculations.

Table 5: CEFs for typical filling materials

Fill types	Typical uses	CEF ($kg.CO_{2}e/kg$)	Source
Gravel (aggregates)	Landscaping, drainage layer	0.036	EPiC data (Crawford, et al., 2019)
General fills (sandy materials)	General earthworks, landscaping, free draining granular fills, drainage layer	0.024	ICE v3 database (Jones & Hammond, 2019) and EPiC data (Crawford, et al., 2019)
Recycled aggregates	Landscaping, drainage layer	0.008	EPiC data (Crawford, et al., 2019)
Asphalt, 5% of bitumen as binder content (by mass)	Road surface, pavement	0.054	ICE v3 database (Jones & Hammond, 2019)
Asphalt (general mix)		0.200	EPiC data (Crawford, et al., 2019)

3.2 TRANSPORATION OF MATERIALS STAGE (A4)

In the absence of local research, the following CEFs are taken from UK guidelines, as shown in Table 6 and Table 7. It should be noted that the travel distance here refers to the distance from the material factory to the designated project site. Hence, transport distances shown in Table 7 are indicative and should be taken only if actual distance is unknown. They are sourced from RICS **(2017)**, and adjusted for Australian conditions. The source regions are categorized into the following travel 'areas': 'local', 'national', 'regional (Australasia)' and 'global'.

Table 6: Typical CEFs for different transportation modes

Mode	CEF transport ($gCO_{2}e/kg/km$)[1]
Road transport emissions, average laden	0.1065
Road transport emissions, fully laden	0.07524
Sea transport emissions	0.01614
Freight flight emissions	0.59943
Rail transport emissions	0.02556
Notes: 1. Sourced from IStructE (Gibbons & Orr., 2020)	

Table 7: Typical CEFs for transportation (A4) for construction materials

Material	Sourced from region[1]	*km* by road[1]	CEF transport ($gCO_{2}e/kg/km$)[2]
Concrete	Locally manufactured	50	0.1065
Steel	Nationally and locally manufactured	600[3]	0.1065
Controlled fill (type 6N etc)	Locally manufactured	50	0.1065
Other: lime, bentonite/polymer, stone etc.	Locally manufactured	50[4]	0.1065
Geotextiles, geomembranes plastics etc	Locally manufactured	50[4]	0.1065
Notes: When undertaking A4 calculations best practice is to consider the return journey (i.e., travel to and from site). However, it is common to only consider a one-way journey. Either method is acceptable as long as the system boundaries in the calculation are documented. 1. Sourced from RICS (2017) and adjusted for Australian conditions 2. Sourced from IStructE (Gibbons & Orr., 2020), assumed road transport with average laden 3. Average mean by assuming approximately one-third of the steel production from national sources and the rest from local manufacturers 4. Subjected to higher travelling distance if materials are not available locally			

3.3 CONSTRUCTION STAGE (A5)

The embodied carbon calculation for Stage A5 is difficult to quantify, especially at the design (or pre-design) stage when limited information is available about the construction sequences on site. The formulae given in Table 1 required the consumption usage of both electricity and fuel. Appropriate assumptions should be adopted to estimate these quantities, perhaps based on past project experience or similar project types. In addition, there are obvious limitations in taking extensive measurements of embodied carbon during construction works. The above calculation of energy consumption (also denoted by Stage A5a) did not capture the carbon emissions component due to labour resources such as the activities of concreting and formwork. The activities associated with waste disposal (Stage A5w) have also not been considered. Alternatively, the embodied carbon for waste can be captured in the A1-A3 (material production) stages by allowing for an additional quantity or volume of material. An example could be CFA piles where an overbreak of approximately 10-15% is typical for concrete consumption. Hence, more research and efforts from the contractors and design engineers to establish a proper database as an example of EC_{A5} inputs are recommended.

Another way of forecasting the EC_{A5} could be done by the estimation from project cost, suggested by RICS (2017) and IStructE (Gibbons & Orr., 2020). Caution should be made when adopting this approach, as the published correlations were for high-rise buildings and based on UK data only. Given that the studies from these institutes focus on the EC of building projects which have its project scale in proportion to project cost in most circumstances, the actual EC_{A5} for geotechnical projects computed by this method should be reviewed once more information of construction details are available. The CEF_{A5} for cost estimation approach are given in below table (Table 8) for reference only.

At the time of writing the authors are not aware of any similar published correlations for infrastructure assets or buildings in Australia.

Table 8: Embodied carbon rate for site activity emission for building construction.

Rate (*$kgCO_2e$* per £100*k*)	Project constraints
1400 [1524]	Construction cost for the whole building
700 [762]	Construction cost for the superstructure or substructure only

Note: [1524/762] 2020 rate, graded for inflation.

RICS (2017) suggests a construction carbon emission factor of 1400*$kgCO_2e$* per £100k construction cost for the whole building. IStructE (Gibbons & Orr., 2020) suggests a 50% reduction in the construction carbon emission factor to 700*$kgCO_2e$* per £100k construction cost for superstructure or substructure only. Values are based on a 2015 assessment and should be adjusted in line with inflation.

For quick computation, the authors suggest an alternative way of EC_{A5} estimation based on the assumption of fixed $EC_{A5}/EC_{A1\text{-}A5}$ ratio for each construction activity type. For instance, piling activity for one project should share similar $EC_{A5}/EC_{A1\text{-}A5}$ percentage to another project at different site despite of the resources' quantities spent, which was captured in the factor component of $EC_{A1\text{-}A3}$ and EC_{A4}. Hence, given the values from $EC_{A1\text{-}A4}$ determined in previous steps, the value of EC_{A5} could be back-calculated with reference to this fixed assumed ratio, whereas this ratio ($EC_{A5}/EC_{A1\text{-}A5}$) could be resolved by past project experience. A database of past project information is required for this approach of calculation. Example of this computation method was illustrated in Section 4.1. It should also be noted that this computed EC_{A5} is rough estimation only given the condition of data deficiency in early design stage. More profound research on EC_{A5} and updates in computed values based on more available details is recommended.

4 APPLICATIONS IN GEOTECHNICAL PRACTICES

The following section aims to provide real examples of embodied carbon calculations in geotechnical projects. The Ground Engineering team at Arup Australia Pty Ltd is gratefully acknowledged for providing the case studies presented. Contributors include Sergei Terzaghi, Alvin Chen, Evan Kaillis, Erica Guo, Dongli Zhu, Jeff Clarkeburn, Nick Dewar, and Adrian Callus. Projects details have been left out to maintain the confidentiality of the specific projects.

4.1 FOUNDATION FOR ROAD EMBANKMENT – PRELOADING VS. HEAVY ENGINEERING SOLUTIONS

This case study presents the use of preloaded ground as an alternate design solution to “heavy engineering” for the construction of a road foundation in Sydney metropolitan area (CS1), NSW. Within the site footprint, soft reclaimed and alluvial sediments are present at 12 to 20m depth. The site was previously dredged ground and used for industrial warehouses. Hence, large settlements were expected to occur over a long period of time. Arup was engaged to undertake concept and detailed design for the foundation design of road infrastructure. In contrast to raft footings or piled foundations that have been adopted in neighbouring sites, Arup’s design team investigated the option of preloading and surcharge. Additional field investigations including boreholes, cone penetration tests, dilatometers and laboratory tests were carried out to confirm the ground conditions. Appropriate geotechnical parameters could then be adopted and used in numerical analyses. This led to an alternative design solution being proposed which utilised fill materials and proper drainage techniques (such as PVDs – Prefabricated Vertical Drains) to replace the original tender design of piling and concrete supported slabs.

An embodied carbon assessment was undertaken to understand the carbon savings that occurred from the original tender design (OTD) to the final design. A couple of assumptions have been made throughout the EC calculation; the key items are listed below:

In Both Designs

- Pavement construction activities were not considered in current EC calculation, as similar extent and type of pavement works were adopted, hence, it does not contribute to the difference between baseline scheme and alternate design.
- Minor excavation activities such as landscaping and slope cutting were considered to have minimal impact to the computed EC, compared to the major filling and foundation construction works, thus neglected.
- Landscaping activities have not been taken into account for the calculation of soil volume.
- This distance travelled for the site-won fills was taken as double the length of the site, which was approximately a round trip of 800m.
- CEFs from Stage A1 to A4 were taken from the recommended values as given in Section 3.
- EC_{A5} was calculated based on the proportion of EC_{A5} against overall $EC_{A1\text{-}A5}$, which was assumed to be near constant within each particular type of construction work and was obtained from past project experience from Arup’s in-house database (Arup, 2021), the estimated forecast percentage of $EC_{A5}/EC_{A1\text{-}A5}$ is shown in Table 9. Contribution of EC_{A5} is relatively small compared to the overall EC for usual geotechnical works, as supported by the EFFC example sheet of carbon calculator (EFFC, 2022). This aligned with the assumption of $EC_{A5}/EC_{A1\text{-}A5}$ ratio, as given below.

Table 9: Forecast Ratio of EC_{A5} to overall $EC_{A1\text{-}A5}$ with respective to each work type

Construction Work Type	Work Description - assumed workflow as per Carbon Insights Platform (Arup, 2021)	Estimated $EC_{A5}/EC_{A1\text{-}A5}$ [1]
Earthworks (filling)	Earthwork Fill: assuming the use of an excavator (Cat325), a dozer (Cat D7), an ADT (Bell 30), and a compactor (Cat CS458)	14%
Piling	Rotary bored pile: considering installation of a single pile of 600mm diameter and 20m in length. Assume cast in-situ rotary bored pile, 1% steel reinforcement by volume, pile cap constructed on top of pile, and removal of soil arising from site.	8%
Construction of slab and beam	Raft foundation: unpiled, 1.5m thick reinforced concrete raft, 2% steel reinforcement, 75mm plain concrete binding layer. Soil excavation, disposal, and backfill activities are not included.	3%
Note: 1. Sourced from Arup’s in-house database, Carbon Insights Platform (Arup, 2021)		

For Baseline OTD

- Baseline OTD comprised of construction works of a reinforced concrete slab, beams, and piles, and backfilling works up to the design level as specified in Design Drawings.
- A recycling rate of 85% as suggested by ACT Transport (Transport Canberra & City Services, ACT Government, 2018) and density of 7850 kg/m^3 were taken for steel materials.
- 32MPa concrete with 30% Granulated Blast Furnace Slag (GGBFS) and a density of 2400 kg/m^3 was assumed.
- Site-won materials (or denoted as reused/recycled fills) were used for backfilling. This assumes the lowest bound of embodied carbon emission for comparison.
- Steel reinforcement in concrete slabs and beams was taken as 1%, and 2% in piles.
- Installed piles were terminated at bedrock level.
- Site activity emissions for piling and construction of concrete structures (Stage A5a) has not been captured in EC_{A5} embodied carbon calculations due to the limitations in direct measures of fuel and energy consumption for these activities, especially for those involving a large proportion of labour work such as formwork and concreting (as discussed in Section 3.3).

For Final Design

- Final design comprised of filling works in the form of preload, surcharge, and imported/reused fills.
- A thin layer of drainage materials was assumed to consist of gravel fillings (approximately 100mm thick).
- The volume of fill did not consider the effect of settlement, it was computed only from the existing level to the proposed design level plus surcharge level, if required.
- Imported fills were utilised for preload and surcharge fill during the project. Site-won spoil was available from piling of the building structure on site, however, was deemed unsuitable and unable to be reused due to having excessive moisture content as a result from prolonged exposure to inclement weather.
- Reused/recycled/site-won fills was also calculated as a sensitivity check. The true project EC for the final design, which partially utilised reused/recycled soil, would be within the range of the imported and reused fill results.

A summary of the embodied carbon results is given below (Table 10). Figure 4 presents a comparison between baseline OTD and final design. Figure 5 to Figure 7 shows the computed EC at each stage within the same design option. A few key findings from the EC results study are listed below:

1. The final design (with imported fills) equated to 30% or less of the total embodied carbon for baseline OTD solution (lowest bound of EC considered in OTD).
2. The use of site-won materials (reused fills) imposed ~50% reduction in the design scheme, when comparing Final Design option 1 (imported fills) and option 2 (reused fills).
3. The materials production factor contributed to more than 90% of the total embodied carbon in the construction of concrete structure, however, significantly reduced to 70-80% when earthworks (i.e., ground improvement solution) replaced rigid engineering foundations.

Table 10: Results of embodied carbon emissions for design options of CS1

Baseline Scheme (OTD)		**Final Design (Option 1 – Imported fills)**		**Final Design (Option 2 – Reused fills)**	
comprises of construction works for slab, beams and piles		*comprises of ground improvement works including preload and surcharge*			
Stage	**EC (*kg.CO₂e*)**	**Stage**	**EC (*kg.CO₂e*)**	**Stage**	**EC (*kg.CO₂e*)**
A1-A3	3,385,859	**A1-A3**	744,880	**A1-A3**	382,341
A4	100,483	**A4**	150,399	**A4**	31,672
A5	148,119	**A5**	145,743	**A5**	67,397
Sum	3,634,461	**Sum**	1,041,022	**Sum**	481,410
-		$\frac{EC_{A1-A5,FD}}{EC_{A1-A5,OTD}}$	29%	$\frac{EC_{A1-A5,FD}}{EC_{A1-A5,OTD}}$	13%

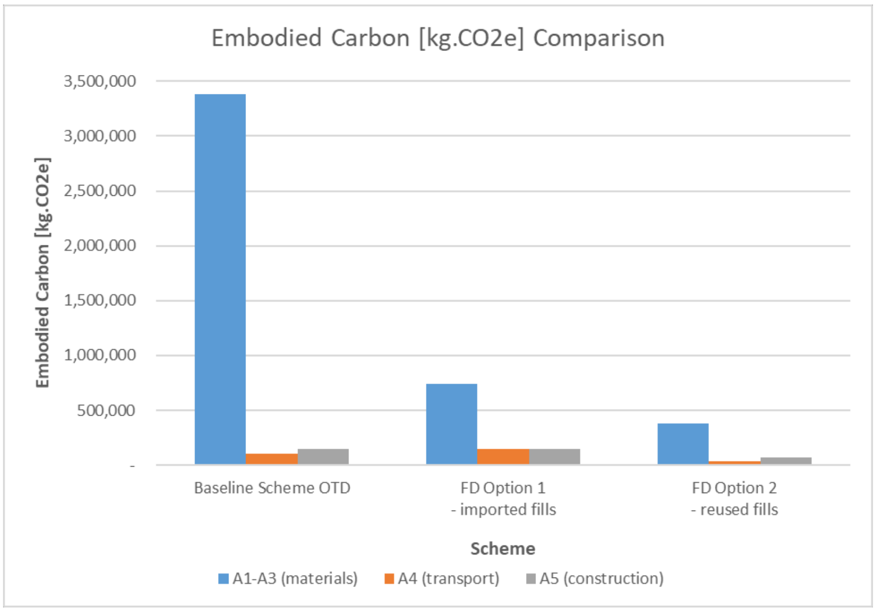


Figure 4: Embodied carbon comparisons between OTD and final design

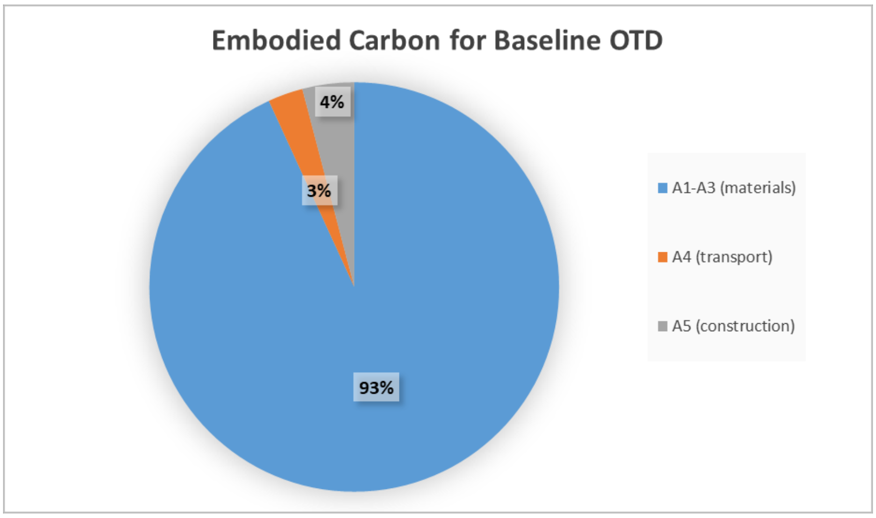


Figure 5: Embodied carbon distributions for OTD

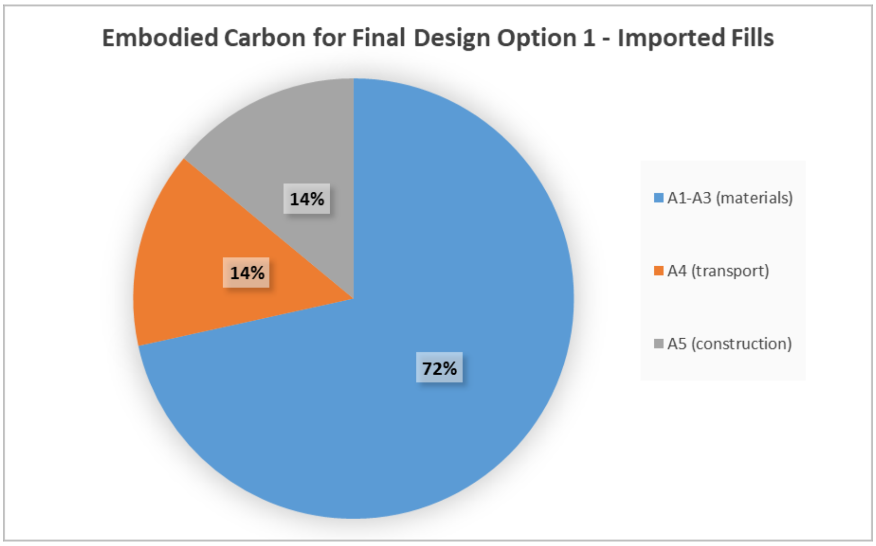


Figure 6: Embodied carbon distributions for FD option 1 – imported fills

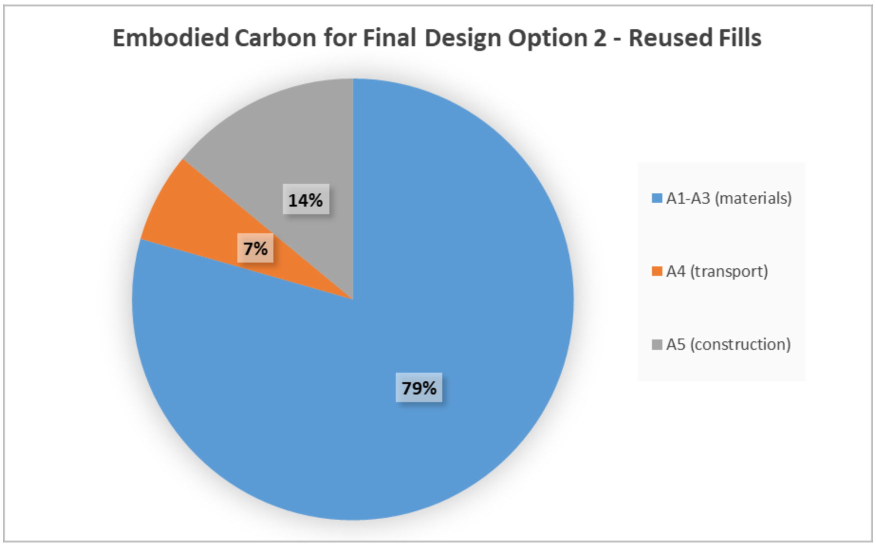
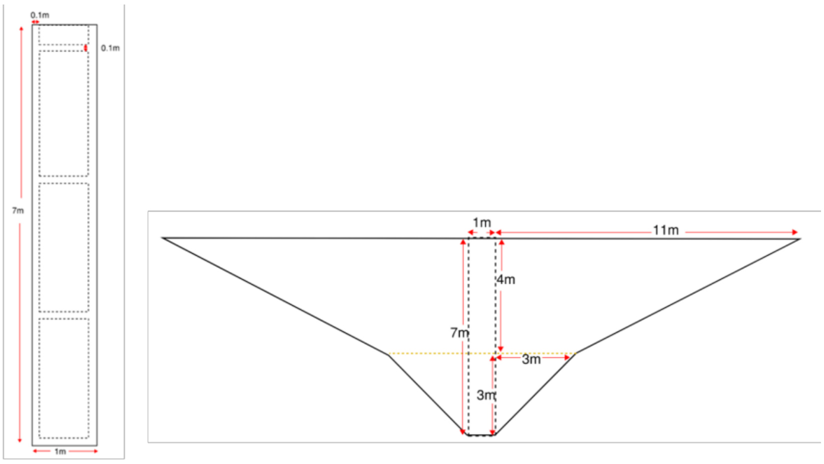


Figure 7: Embodied carbon distributions for FD option 2 – reused fills

4.2 UTILITIES INFRASTRUCTURE – TRENCH EXCAVATION

This case study focuses on a utility infrastructure project located in the Greater Western Sydney region. As part of the concept design, a geotechnical desktop study was carried out to inform the key constraints and opportunities for the design. This included a simple embodied carbon calculation comparing the two most common methods of open trench excavation: battered excavation of 1V:2H slope and a supported shoring trench. The following assumptions have been made to facilitate the EC calculations:

- The major activity involved in the battered option is excavation; the major activity involved in the shoring option is concreting plus excavation. The work of excavation includes both soil and rock cutting.
- EC per unit meter of trenching was evaluated for optioneering purpose, instead of a full EC study. This was considered more useful as the detailed design inputs are often subject to change (e.g. alignment).
- A general trench depth of 7m was adopted for excavation extent (with 1m width), assumed 4m depth of soil overlaying the rock stratum. Slope gradient of 1V:1H in rock, and 1V:2H in soil were assumed, sample section details as shown in Figure 8.



Supporting shoring trench:

Battered open trench:

Figure 8: Trench cross-section showing possible excavation options for EC evaluation

- Unit mass of 20 kN/m^3 and 24 kN/m^3 were adopted for soil and rock respectively.
- $CEF_{materials}$ and $CEF_{transport}$ were taken from the recommended values, as given in Section 3.
- No engineering materials were created/produced due to battered open trench option, hence, $EC_{A1\text{-}A3} = 0$ for the battered open trench.
- Road transport (on land) with average laden was assumed for excavated materials delivery.

- A total distance of material transportation was taken as 25*km*, based on site constraints.
- For EC_{A5} calculations, only the embodied carbon emissions that contribute to the machinery activities were considered given that they were measurable. As the excavation activity being the dominant type of work, an excavator with an assumed working performance of 20 *L/hr* and 75 m^3/hr of fill removal was adopted, based on site practices and product catalogues.
- Only EC_{fuel} was considered here as part of EC_{A5} due to the constraints of insufficient research and data in collating the amount of electricity used on site, hence, the component of $EC_{electricity}$ was omitted in this simple exercise (recalling $EC_{A5} = EC_{fuel} + EC_{electricity}$ from Section 2).
- The CEF_{fuel} for an excavator was taken as the carbon emission factor for unit diesel used (i.e., 2.7 $kg.CO_2e/L$), with reference to the open source from the National Transport Commission (NTC, 2019).
- For the supported shoring trench, a minimum steel reinforcement of 0.8% was assumed, without considering recycling.
- Based on experience and usual practices, time required to install a single shoring box and each battered open trench sectional length (per box) was assumed to be 0.5*hr*/section and 6*m* respectively.

The results from the EC assessment (per meter alignment) are summarised below (Table 11), the battered trench option was found to outperform the shoring box option by approximately 20%. However, this assumes that the shoring structure is built along the whole chainage. Reusing the shoring box reduces the mass of engineering materials (i.e., $EC_{A1\text{-}A3}$), which contributes to nearly 90% of the calculated EC. Hence, it is suggested that the option of reusing these shoring boxes should be considered in practical application, noting that this is dependent on particular project constraints. Figure 9 to Figure 11 illustrated the computed EC of the project options, as well as their distributions per different stages.

Table 11: Results of embodied carbon emissions for trench excavation options

Stage	**Embodied carbon for battered open excavation ($kg.CO_2e/m$)**	**Embodied carbon for supported shoring trench ($kg.CO_2e/m$)**
A1-A3	0	900
A4	808	105
A5	16	10
Total	**824**	**1014**

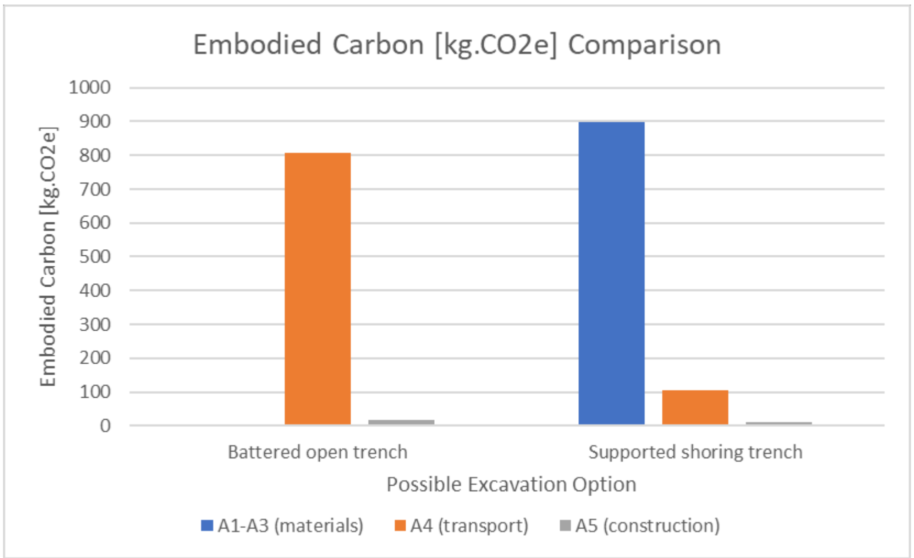


Figure 9: Embodied carbon comparisons between two trench excavation options

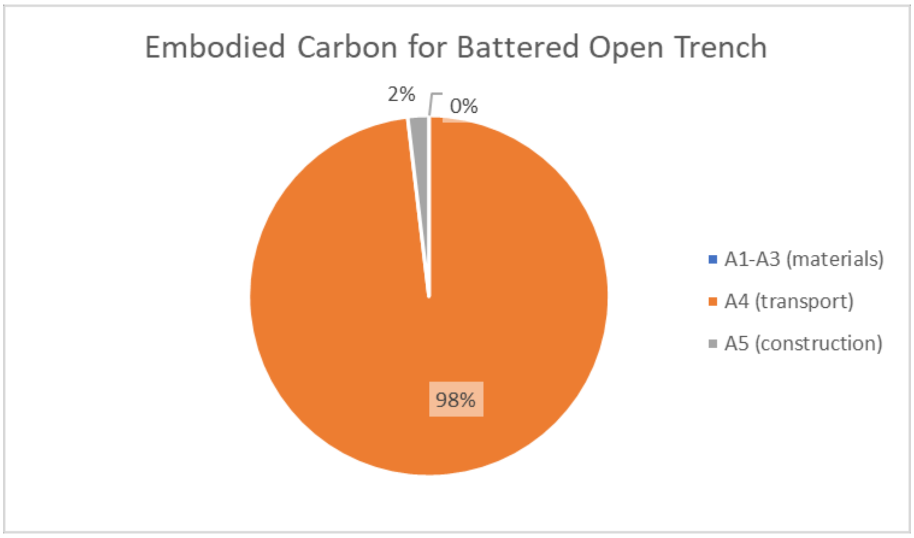


Figure 10: Embodied carbon distributions for battered open trench excavations

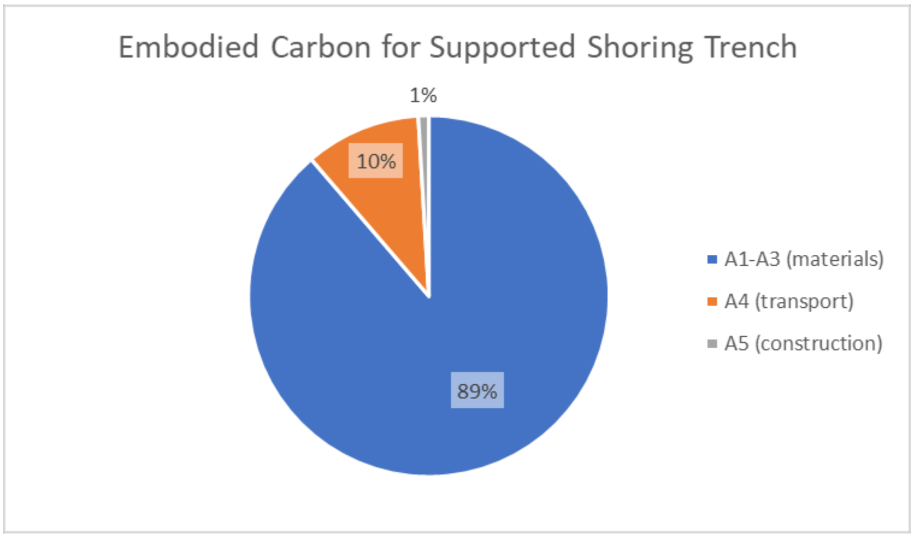


Figure 11: Embodied carbon distributions for supported shoring trench excavations

4.3 PERMANENT TUNNEL LINING – TENDER DESIGN

As part of a recent tunnel tender design, the embodied carbon of four stations was calculated. The assessment allowed the designer and client to understand the 'carbon heavy' components of the design and allowed further optimisation. The following key assumptions and limitations were made as part of the embodied carbon assessment:

- Computed embodied carbon was measured in tonne of carbon dioxide emissions (*t.CO2e*).
- Only Stage A1-A3, and A4 were considered. Stage A5 EC calculation was excluded due to the high level of engineering study required and data inadequacy at this early phase of project consultation.
- For the purpose of simplicity, the carbon factor for PL2 – C40/50 was applied to all concrete in the tunnel station design. Whilst the vast majority of concrete grade/mix was PL2 – C40/50, there was also minor amounts of PL4 – C50, and PL3 – C50, CEM III/B.
- The volume of steel within the concrete varied between approximately 0 to 6% depending on the structural component.
- Reinforcing steel assumed to be virgin (i.e., contain 0% recycled content).
- The embodied carbon from rock bolts and waterproofing components were ignored for simplicity.
- Average laden was assumed for road transport emissions in Stage A4 calculations.
- Spoil removal was captured in Stage A4 instead of Stage A5.
- Disposal of spoil did not consider the bulking factor of soil.

The results of the EC assessment are provided below (Figure 13 to Figure 15). The majority of EC is from the material source (Stage A1-A3) rather than the transportation (Stage A4). Figure 15 showed that the majority of EC_{A4} was related to spoil removal, which is expected for a tunnel project type. However, this result should prompt the designer to consider recycling the spoil (with proper treatment if required). This could surpass the efficiency of any decarbonisation technique on concrete or steel when it comes to the consideration of EC_{A4}. The carbon "credits" for recycling the spoil are typically considered in Stage D, which is outside the system boundaries of this simple A1-A4 calculation.

Results from Figure 14 show that even though steel contributed to only a small amount of volume/mass (generally less than 6% of the concrete volume), their computed $EC_{materials,A1\text{-}A3}$ are comparable to each other. In other words, the reduction of steel consumption, or use of recycled steel may be more advantageous in reducing carbon emissions than reducing the use of concrete at the same scale.

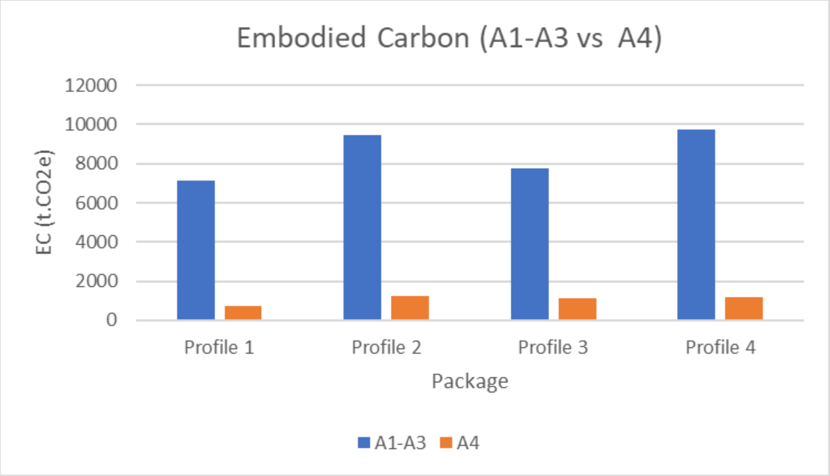


Figure 12: Embodied carbon distribution of Stage A1-A3 and Stage A4

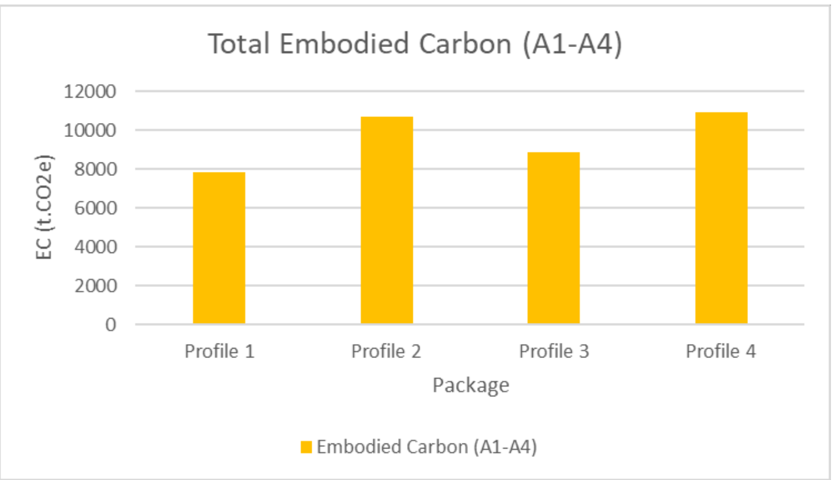


Figure 13: Total embodied carbon for Stage A1-A4.

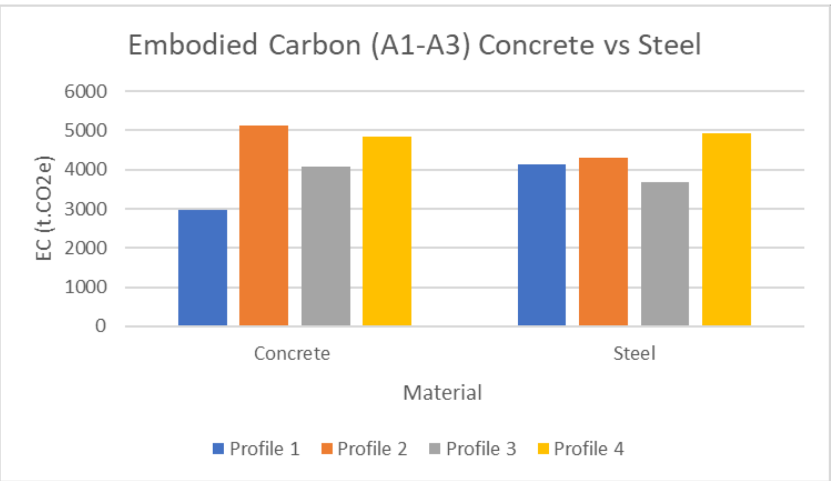


Figure 14: Embodied carbon distribution of materials Stage A1-A3.

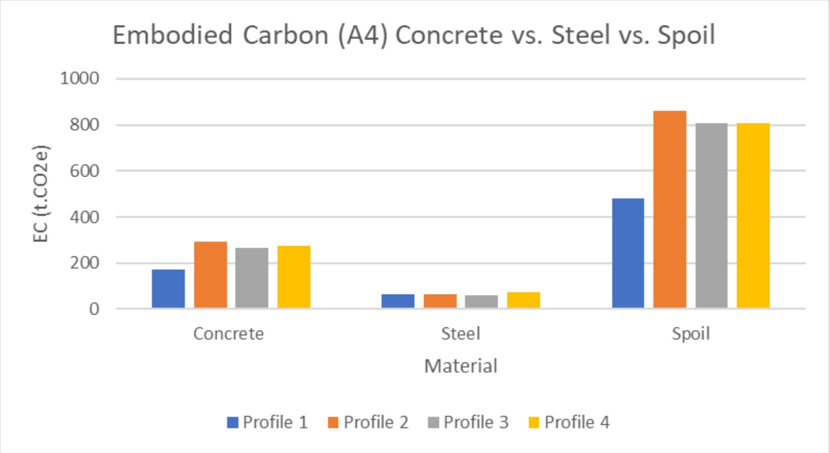


Figure 15: Embodied carbon distribution of materials at Stage A4 including soil removal

5 METHODS OF DECARBONISATION

Sustainable development is defined as the growth of human living standards that 'meet the needs of present without compromising the ability of future generations to meet their own needs' (Brundtland, 1987). Fundamentally, it would obligate to satisfy the three main pillars of environmental, social, and economic objectives. The methods discussed here are targeted to tackle the industrial practices of reducing carbon emissions from a viewpoint of geotechnics and to fulfill the three main perspectives of sustainability goals.

The following waste hierarchy is introduced in Figure 16. It showcases the priority for the most efficient ways to minimise waste and energy consumption, hence, carbon emissions. The subsequent chapters should be read according to the order of this 'reverse pyramid', with the most preferable methods for decarbonisation at the top, through to the least at the bottom of the pyramid.

Figure 16: Waste hierarchy 'reversed pyramid' (NSW EPA, 2022)

5.1 LEAN DESIGN APPROACH

The need of establishing a 'lean design approach' has escalated in recent times. It is typically the most preferable choice to 'avoid and reduce' carbon emission. The principles of lean design were evolved by Womack and Jones in 1996 that consolidated the concept into the following (Womack & Jones, 1996):

1. Identify value – client's needs, project scope and target function of the engineering asset.
2. Map and create the 'work-flow diagram' – to ensure the allocated resources and work tasks are essential to the target goals and are constructible.
3. Establish pull – deliver the product/option scheme in a 'work-on-demand' basis that avoids excessive resource usage and/or overdesign. For instance, it could be achieved by a more calibrated estimates of Building Quantities to reduce inaccuracy assigned. These calculations may not need to be more detailed but should be calibrated with data collected from as-built material volumes and comparing with estimated design volumes to establish design to reality ratios. Similarly, 3D modelling and consideration of the appropriate level of detail at a given project stage may be used to more accurately estimate volumes from an early project stage.
4. Seek perfection – repeat step 1-3 until significant drop-in work delivery time and high efficiency in resource usage could be achieved.

Implementing the above lean design thinking into geotechnical practice, engineers should undertake appropriate optioneering assessments to outline the project aims and create designs that make best use of materials, whilst limiting embodied carbon expended in transport and construction. Considerations could include: the use of project specific ground investigations to optimise design parameters; installation of instrumentation and monitoring to verify design predictions with real-life observations, following the "observational method" (as stipulated in Eurocode 7) where designs are monitored on site and engineering solutions undertaken on a per need basis, and considering ground improvements as an alternative to 'hard engineering' solutions. This was clearly demonstrated in the CS1 study, presented in Section 4.1. The choice of using ground improvement methods (surcharge and preloading) allowed the minimization or even elimination of concrete and steel utilisation. This substantially reduced the amount of waste generated and associated carbon emissions. Sufficient ground investigation data in early design stage also enabled appropriate design parameters, justification of reduced partial factors and overall, a more efficient design. Furthermore, settlement monitoring provided understanding of the time required and degree of surcharge and preloading required for the design.

5.2 MATERIAL SELECTION

Better choice of engineering materials also helps to 'reduce', 'reuse' or 'recycle' resources. As shown in Section 3.1, the $CEF_{materials}$ vary for different types of concrete and steel. Therefore, it is imperative that the designer specifies the appropriate material for construction that meets both; the minimum design standards (avoiding overdesign i.e., lean design approach) and selects the lower carbon material where possible.

Examples of this include: The use of different cement mixes that contain lower embodied carbon additives (i.e. GGBS Ground Granulated Blast Furnace Slag or fly ash) to replace traditional (carbon 'heavy') cement clinker. Other examples include using alkali-activated materials to substitute Portland Cement and replace steel with micro-macro synthetic (EFFC, 2022).

Using steel products manufactured with higher recycling rate or recycled fills/aggregates instead of imported fills could also help to reduce carbon footprint. EcoSheetPile and EcoSheetPile Plus from ArcelorMittal is an example of better material selection. They benefit from a manufactured recycling scrap rate of 100%, and the use of 100% renewable energy to power the electric arc furnace as part of steel production (ArcelorMittal, 2023). Other local examples of 'green' manufacturing is the implementation of renewable hydrogen electrolyser in blast furnaces by BlueScope Steel (Peacock, 2022). The 'green steel' industry is rapidly growing across the industry and should be more widely promoted by engineers and developers to strategically include the use of recycled or 'green' products as part of the contractual terms. The choice of local suppliers and yards also minimises the transport distance of materials to and from the project site, which may play an important role when EC_{A4} is crucial to the project overall EC (for instance, in the example of battered open trench excavation option given in Section 4.2).

5.3 REDUCTION OF WASTE DISPOSAL

As illustrated in the example of Tunnel Tender design (in Section 4.3), the contribution of soil removal (either EC_{A4} or EC_{A5}) can be a significant contribution to the overall embodied carbon assessment. While waste disposal can often be reduced, it cannot always be removed entirely. An example of reusing site-won materials is provided in Section 4.1 (CS1). With reference to the waste hierarchy diagram, this would elevate the mitigation method from the bottom (disposal of waste) to 'reuse'. Examples and case studies of waste disposal include:

- The case study discussed in Section 4.1, showed an overall EC reduction of nearly 50% could be achieved by reusing soil aggregates as fills. This outcome emphasised the significance of waste reuse, especially in the context of earthworks. Another study to be considered, reviews the reuse of tyre bales as lightweight fill (Kidd, et al., 2009).
- Treating spoil is another potential way to significantly reduce waste disposal, as outlined in the Tender Design case study (Section 4.3). Whilst the treated soil may not be able to be reused on the project it was sourced from, it could be used as filling works on other projects. The industry is becoming increasing more aware of the opportunity of sharing resources or wastes to minimize soil resources being sent to landfill.
- Reusing temporary work structures could also help to save excessive carbon emissions. The case study (Section 4.2) shows how a reusable (pre-cast) shoring structure can significantly reduce the quantities of material production along the alignment if the structural performance of the temporary frame has been certified and confirmed by the field engineer.
  Soil stabilisation is another geotechnical area that could make use of waste-transformation. Examples of reused products that have been used to aid in soil stabilisation include ground granulated blast furnace slag, furnace bottom ash, and pulverised fuel ash that could be reused in a concrete mix (Pantelidou, et al., 2012).

6 CONCLUSIONS AND RECOMMENDATIONS

The methodology and simplified formulae for embodied carbon (EC) assessments is discussed in this paper, consisting of material production (A1-A3), transport of materials (A4) and construction (A5) stages. A quick guidance on the selection of carbon emissions factors with respect to the most commonly adopted engineering material types is presented. The application of these calculations was given in Section 4, which took the examples from real projects and demonstrated the significance of having the EC assessment done in early design stages to ensure best EC reduction strategies were implemented. Based on the example projects, the key findings on performing EC evaluations were summarized as follows:

- An earthworks foundation typically contains lower embodied carbon than a traditional 'hard' engineering structure (such as the reinforced concrete piling foundation in CS1, Section 4.1 and shoring design in trench excavations, Section 4.2).
- The use of reused or recycled aggregates as fill materials could impose a large reduction in EC (nearly ~50% in the presented case study). Therefore, best practice would be to always consider if on-site won materials are suitable for re-use or filling purposes (Section 4.1).
- Similarly, reducing the travel distance of soil or rock from spoil removal activities may play an important role in tunnelling projects (as per Section 4.3). This could be done by reusing the excavated materials by means of proper treatment methods, acquiring a local manufacturer for materials production, and local receiver as waste disposal.
- Although a ‘hard’ engineering structure (such as a reinforced concrete slab) typically has a higher EC footprint than an equivalent earthwork activity. If the ‘hard’ engineering structure could be reused, the EC may be significantly reduced. For example, the trench excavation case study (Section 4.2) revealed that if the contractor was able to reuse shoring boxes along the alignment, this could reduce the $EC_{A1\text{-}A3}$ by up to 90%.
- Early involvement of EC calculation in tender design stage (Section 4.3) helps identify the key areas of concern in later development stages. This can assist in decision making for site selection and target the focus of implementing carbon reduction strategies.
- Overuse of steel reinforcement (as per finding in Section 4.3) should be avoided where possible, or ‘green steel’ and steel manufactured with higher recycling rate should be adopted by the industry.

Some decarbonisation methods have also been introduced, which should be prioritised in the order of ‘reduce’, ‘reuse’, ‘recycle’, and ‘disposal’. Three main approaches have been addressed, they include lean design thinking, material selection, and reduction of waste disposal. The value of EC calculations has also been reinstated such that it enables the designer to understand the carbon ‘heavy’ components of the design and allow further refinement for decarbonisation as per the strategies listed. More research and further investigations are recommended to better quantify the embodied carbon calculation of Stage A5 (construction). It is recommended that either alternate formulation of EC_{A5} should be developed based on more measurable quantities in early design stages or collation of more extensive databases for CEF_{A5}. Therefore, the overall EC and global warming potential of each individual engineering option could be more easily and accurately assessed to inform key decision making.

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