

Comparing the embodied carbon and local environmental impact of common geotechnical foundation solutions for the Australian market

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ABSTRACT

In the Australian geotechnical market, foundation solutions for construction projects are commonly assessed against three key criteria; cost, program and quality. Safety and environmental aspects are often not assessed in the process until a geotechnical foundation technique has been selected based on the aforementioned criteria. As climate change has progressed to become one of the largest and most pertinent environmental issues in society today, it has in turn brought sustainability to the forefront of post construction assessments and is now a greater focus for government bodies, private developers and wider stakeholders. Using Keller's inhouse carbon calculator and a series of environmental metrics, this paper aims to inform decision makers of the carbon emission and social impacts of various geotechnical foundation solutions prior to their selection. Two theoretical projects are used to compare a range of geotechnical solutions: a 60-storey high-rise building requiring heavy foundations, and a low load warehouse building where ground improvement solutions can be used. Each geotechnical solution designed for the two Australian projects is then assessed using a standard cradle-to-gate carbon calculator. In addition, the impact on the local community is assessed according to the noise, traffic and emissions generated by each solution.

Keywords: Foundations, Piling, Ground Improvement, Carbon, CO₂e, Emissions

1 INTRODUCTION

The construction sector has many impacts on local environmental sustainability, from piling machinery generating noise and dust to the traffic congestion caused by bringing materials on to site. The construction sector also produces 39% of Global Greenhouse Gas (GHG) emissions (IEA, 2020 & UNEP 2019); foundations and other substructures can be responsible for between 13% to 30% of these construction emissions (WRAP 2019, Menzies, 2011). This makes geotechnical contractors and their supply chains key to meeting global emissions goals, such as the Paris Accord and Climate Action (Goal 13) of the UN Sustainable Development Goals.

Nationally, the creation of the Green Building Council of Australia (GBCA) in 2002 aims to incentivise delivering projects with severely reduced, or even positive, environmental impacts. The GBCA is driving this change with a vision "to lead the sustainable transformation of Australia's built environment" and targeting a net zero emissions outcome for new buildings by 2030 and for existing buildings by 2050.

GBCA assigns green star ratings to buildings based on their design, construction and operation meeting sustainability criteria. The GBCA assessment also assigns credits for a whole of site life cycle assessment. Much like BREEAM (Building Research Establishment Environmental Assessment Method) in Europe or LEED (Leadership in Energy and Environmental Design) in America, these green star ratings are increasingly valued by developers, customers, investors and clients alike.

One of the best ways geotechnical contractors can reduce their sustainability impacts and achieve these green building accreditations is by changing the geotechnical solutions they offer clients. Yet currently, geotechnical foundation solutions are

often assessed by three major categories: cost, time and quality. Safety is usually assessed and managed in detail after selection of a solution. Typically, little to no consideration is given to environmental impact of proposed geotechnical foundation solutions during appraisal of proposals.

This paper explores the prediction of carbon emissions and local environmental impact of these solutions; through the use of realistic, Australian-focused examples, aiming to highlight the impacts of different geotechnical solutions. Ultimately, geotechnical companies can then integrate carbon calculations and social sustainability into client's project assessment and decision-making as standard. In turn, this can act as a driver for the adoption of low carbon, low impact geotechnical solutions, where there is client demand. Foundation contractors can also then be measured against these predictions, as they are against other categories.

2 METHODS

2.1 Emissions Calculator Overview

The calculation of geotechnical solution carbon emissions uses Keller's inhouse carbon calculator. This uses the same system boundaries and carbon intensity multipliers as published industry standards, such as the European Federation of Foundation Contractors - Deep Foundation Institute (EFFC-DFI) calculator, which is in-keeping with the GHG protocol of the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). However, this Keller calculator uses direct machinery efficiency and supply chain data from Keller Australia and their supply chain. This 'cradle-to-gate' assessment incorporates everything from the extraction and manufacture of the raw materials through to the final installation of the foundations (Figure 1) and ensures all three carbon emission scopes are considered (WRI & WBCSD, 2004), as set out below:



Figure 1. 'Cradle-to-gate' life cycle of the carbon calculator.

- Scope 1 – Direct (or point source) emissions, such as fuels burnt and oils used on site.
- Scope 2 – Indirect emissions from electricity obtained from the utilities power grid for the site concerned.
- Scope 3 – Other indirect emissions embodied in the materials use and commuting of materials, equipment and personnel to site.

Activity data (such as consumed fuels and materials) are the primary input for determining GHG emissions. These activity data are multiplied by known factors for a given product, vehicle, equipment or machinery to determine the GHG emissions. GHG emissions are dealt with collectively using CO₂ equivalent (CO₂e) capturing effects of CO₂, CH₄ and N₂O, according to the GHG protocol global warming potential multipliers for CO₂e.

For most geotechnical projects overall emissions are primarily dictated by Scope 1 and Scope 3 whilst Scope 2 emissions represent a minimal contribution to the overall emissions.

Primary emission sources assessed are material manufacturing and transport, consumed energy, equipment transport, equipment manufacturing waste treatment and transport, personnel transport.

Secondary emission sources (such as depreciation/life span of machinery, steel transport) is generally assessed using a standard database of ratios for secondary emissions, unless activity data can be accurately and confidently estimated for the project. For the purposes of the comparisons within Section 4, life span of machinery has not been assessed.

Most factors have been adopted from Australian Government National Green House Accounts (NGA) Factors (2018). A full list of databases referenced for emissions factors can be presented upon request to the author.

2.2 Local Environmental Impact

Local environmental impact is assessed subjectively and comparatively via a combination of metrics. These metrics are intended to allow assessment of project foundation solution impact upon the community local to the project site. These metrics include:

- Emissions generated on site.
- Spoil or material waste sent to landfill.
- Noise generated on site, measured via equivalent continuous sound pressure (LA_{eq}) and 90th percentile noise level (L90).
- Vehicle movements/arrivals on site, total and daily, providing an indication of effect on local traffic conditions. Assumed distances for data calculations in Section 4 were between 20 to 50km based on recent project data.

LA_{eq} and L90 give an indication of noise levels on site for a standard workday. For consistency all noise levels are measured at 30m from source. 30m has been selected on the assumption this distance for most sites in Australia is a good representation of average distance from noise source to site boundary or sensitive neighbours.

The amount, reuse of and contamination of any waste generated will be influenced by site variables such as existing contamination, soil density/porosity and previous site use. For the purposes of the comparison in Section 4, it has been assumed that 50% of the cement-based and steel waste is recycled with carbon emissions from the recycling attributed to the project those recycled materials are to be used on, i.e. not captured within this modelling presented in Section 4. The remaining 50% is assumed to be inert waste sent to landfill.

Drilled soil and rock can also be reused for certain ground conditions. However, for the scenarios assessed in Section 4 it is assumed the ground

conditions are not suitable for spoil reuse and all spoil is sent to land fill.

3 THEORETICAL PROJECT DETAILS

3.1 High-Rise Building Foundations

Assumed high-rise building details are 60 storey, footprint of 2,500m², building load 1,650MN or an equivalent pressure of 660kPa.

The high-rise building foundations were all designed to support the same floor and core loadings to represent equivalent schemes. Details of each foundation scheme considered are provided in Table 1. The details of each scheme, including concrete grades, reinforcement tonnages, site deliveries and machinery on site was input into the calculator.

Table 1. High-rise building foundation details

Foundation Scheme	No. of piles	Volume of works (m ³)	Days on Site
A - CFA Piles	147	2,909	58
B - Bored Piles	91	2,583	75
C - Precast Piles	691	2,762	50

3.2 Warehouse Building Foundations

Assumed industrial warehouse details are footprint of 300m x 100m = 30,000m², floor load of 80kPa with four rows of concentrated column loads:

Details of each foundation scheme considered are provided in Table 2. It should be noted that many of the solutions presented in Table 2 are not mutually compatible in all soil ground conditions and each provide a different settlement performance for the structure from 5mm through to 150mm. For the purposes of this comparison it has been assumed that each technique is applicable for the hypothetical ground conditions. It should be noted that scheme H would rarely be considered as a viable solution unless there are significant onsite restrictions.

Table 2. Warehouse building foundation details

Foundation Scheme	Number of elements	Volume of works (m ³)	Days on Site
D – CFA Piles	1,450	8,200	107
E – Bored Piles	1,450	8,200	100
F – Precast Piles	1,450	4,571	107
G - Rigid Inclusions	5,800	7,617	45
H - Jet Grouting	3,734	54,900	134
I – DSM [#]	3,734	54,900	85
J – VSC [*]	5,800	37,901	111

^{*}Vibro Stone Columns, [#]Deep Soil Mixing

Schemes were assessed based on most realistic resourcing typically provided in the Australian market whilst targeting programs regularly required by clients.

4 RESULTS

4.1 High-Rise Building Foundations

Calculation results presented in Table 3 demonstrate Scheme B generated the lowest amount of CO₂e emissions with schemes A and C each generating 85t and 367t more emissions respectively.

Table 3. CO₂e Emissions for high-rise building foundation schemes

Metric	CO ₂ e Emissions (kg/MN)	Total CO ₂ e Emissions (tonnes)
A – CFA Piles	1,017	1,679
B – Bored Piles	966	1,594
C – Precast Piles	1,189	1,961

The source of emissions is presented in Figure 2, demonstrating that the overwhelming majority of CO₂e emissions is due to materials manufacture. The next highest CO₂e emissions are a result of onsite equipment whilst the remaining categories make up less than 5% of the CO₂e emissions.

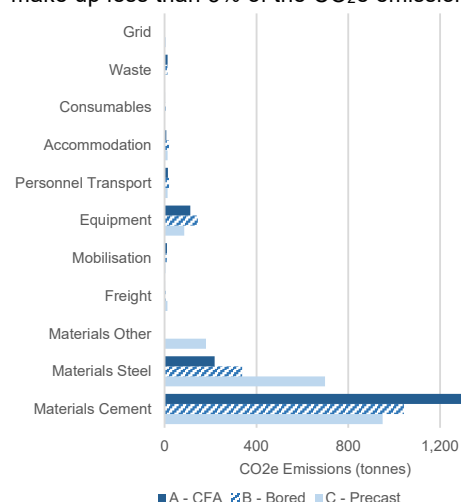


Figure 2. CO₂e Emissions by category for high-rise building foundation schemes

Table 4 presents the local environmental impact metrics for the three schemes investigated. The author acknowledges that the priority placed on each environmental metric will vary with the site setting. Therefore, it is not practical to draw a definitive preference out of the results presented given most sites are unique when consideration is given to neighbouring structures, community, traffic network and background noise. Nonetheless, this comparison still allows us to highlight key differences between solutions, which can then be considered in each local environment.

As expected, noise generated is higher for scheme C, 88dB compared with 84dB for the other two schemes. Time on site is significantly less for scheme C, demonstrating an 8 and 25 day advantage over schemes A and B respectively.

Table 4. Local Environmental Impact Metrics for high-rise building foundation schemes

Metric	A CFA Piles	B Bored Piles	C Precast Piles
CO ₂ e Emissions on Site (tonnes)	112.9	145.6	86.2
Total site vehicle arrivals	1,233	1,226	817
Total site vehicle arrivals per day	21	16	16
LA _{eq} @ 30m from machinery (dB)	84dB	84dB	88dB
L90 @ 30m from machinery (dB)	77dB	77dB	79dB
Days on site	58	75	50
Waste, spoil (tonnes)	5,236	4,649	0
Waste, materials inert (tonnes)	437	388	117

Schemes A and B require the dumping or reuse of a significant amount of extracted spoil waste. However, scheme C, as a driven precast pile scheme, displaces the ground and therefore does not typically require any spoil removal. The environmental impact of this waste is significantly affected by the contamination of the spoil waste, but this is dictated by initial ground conditions rather than the geotechnical solution.

Inert waste for the schemes is significantly more for the in-situ concrete Schemes A and B. This is due to uncertainty around constructed pile volumes due to over drilling and over ordering of concrete. With Scheme C, precast material quantities are known, hence there is significantly less waste.

4.2 Warehouse building foundations

Table 5 shows schemes H and I had the greatest overall CO₂e emissions, eclipsing other schemes by more than 20,000t and 5,000t respectively. This is due to high volume of treatment zones and high cement consumption for each scheme. Interestingly scheme J resulted in significant CO₂e emissions due to a large use of aggregate despite lack of cement or steel content.

Of the remaining schemes, G had the lowest estimated CO₂e emissions with 2,610t. This is attributed to low relative treatment volumes, low cement consumption and efficient onsite plant, though it should be noted a greater tolerance of overall structure settlement is required.

For the 3 piled schemes assessed, scheme F had approximately 1,000t less CO₂e emissions than schemes D and E, primarily due to lower volume of materials required. This is contrary to the high-rise schemes A, B and C. The reason for this is in this scenario geotechnical capacity governed the design details and accordingly for schemes D and E pile structural capacity is not fully utilised whilst for scheme F, the piles utilised most of their structural capacity.

Table 5. CO₂e Emissions for warehouse foundation schemes

Foundation Scheme	CO ₂ e Emissions (kg/MN)	Total CO ₂ e Emissions (tonnes)
D – CFA Piles	1,745	4,189
E – Bored Piles	1,923	4,615
F – Precast Piles	1,367	3,281
G - Rigid Inclusions	1,088	2,610
H - Jet Grouting	11,398	27,356
I – DSM	4,224	10,138
J – VSC	1,870	4,489

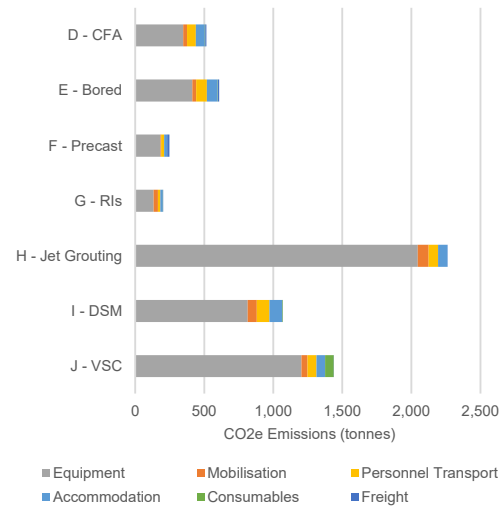


Figure 4. Scope 1 CO₂e Emissions for warehouse foundation schemes.

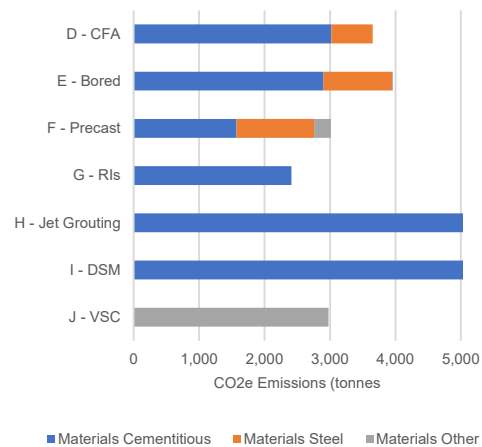


Figure 5. Scope 3 CO₂e Emissions for warehouse foundation schemes.

Graph truncated for clarity, extent of I – DSM (9,053t) and H – Jet grouting (25,039t) not shown.

The warehouse schemes cannot be solely assessed by CO₂e emissions for geotechnical works. The schemes require varying solutions for superstructure, primarily ground slab, ground

Table 6: Local Environmental Impact Metrics for warehouse foundation schemes.

Metric	D CFA Piles	E Bored Piles	F Precast Piles	G Rigid Inclusions	H Jet Grouting	I DSM	J VSC
CO ₂ e Emitted on Site (t)	351	418	184	135	2050	818	1210
Total vehicle arrivals	4,278	4,786	952	2,395	10,824	5,981	6,849
Vehicle arrivals per day	40	48	9	53	81	70	62
LA _{eq} @ 30m (dB)	85	86	88	89	89	92	88
L90 @ 30m (dB)	79	79	79	79	79	82	79
Days on site	107	100	107	45	134	85	111
Waste, soil/rock (t)	14,760	14,760	-	686	49,410	19,764	3,411
Waste, cement/steel (t)	1,232	1,183	552	914	6,588	6,588	4,548

beams and pile caps. Scheme G, for instance, will result in an on-ground slab with placement of a load transfer platform whilst schemes D through F will require a suspended slab with ground beams. To robustly calculate CO₂e emissions, for each scheme, superstructure through to top of ground slab level should be assessed in combination with the presented Figures 4 and 5. However, this is beyond the scope of the cradle-to-gate carbon calculator methodology and therefore rests with the main contractors, project managers or consultants to assess.

Scheme G was the lowest onsite CO₂e emissions of 135t due to efficient onsite equipment and low number of days on site. Scheme F is next with 184t of CO₂e emitted onsite primarily due to fabrication of piles off site. The highest onsite CO₂e emissions were from schemes H and J due to a large amount of equipment onsite for a lengthy period compared to the other schemes.

The L90 noise levels for each scheme is relatively consistent between 79 to 82 dB each. LA_{eq} levels were lowest for schemes D and E with 85dB and 86dB respectively. Scheme I had the highest LA_{eq} at 92dB, surprisingly, larger than the driven precast pile scheme F at 88dB. This was primarily due to many compressors, rigs and other ancillary equipment onsite compared to scheme F, precast piles, which utilised louder but a significantly lower number of equipment.

The waste generated for scheme H was by far the greatest due to large treatment volumes whilst schemes D, E and I also generated significant waste requiring to be managed.

5 DISCUSSION

It can be inferred from the calculations that best reduction of CO₂e emissions for foundation schemes can be achieved by targeting reduction in material tonnage and time on site. Auspiciously, reduction of these categories directly reduces project costs, accordingly projects are already incentivised to reduce them as far as is practical.

Australian design codes for reinforced concrete structures and piling design utilise a limit state design approach. Adopting a higher factor of safety

for design directly results in use of additional materials, either by increased cement content, steel content or longer period spent on site. Unnecessary conservatism in design can therefore lead to increased CO₂e emissions, particularly where structural capacity of the solution is not being fully utilised.

It should be noted the recent release of the Australian Concrete Structures code AS3600-2018 has increased reduction factors by 5% to 8%, accordingly a similar, if not slightly lower, reduction on CO₂e emissions will be realised as implementation of this code becomes widespread.

In general, the longer the time spent on site, the higher the Scope 2 CO₂e emissions of the project. A significant reduction in vehicle arrivals/deliveries is achieved via prefabrication of foundations offsite. It should be noted this may not equate to a reduction in overall emissions subject to details of off-site manufacture. Off-site manufacturing also leads to significantly less disruption to local traffic throughout project durations and reduction in local air pollution reducing nuisance to people local to the site.

For many projects, stakeholders such as councils, clients and neighbours view construction noise as a key concern which can drive implementation of restrictions around construction hours and techniques leading to increased costs. Accordingly, consideration must also be given to the duration of the works as it relates to the period of disruption to neighbouring persons which must be assessed with the intensity (LA_{eq}/L90) of the disruption.

For the schemes compared within this study, the average CO₂e contribution for materials is 87.4%. Calculating CO₂e emissions for materials involves the lowest margin for error as a result of significant work done by the Australian government for National Greenhouse factors and work done by Australian materials suppliers.

Assessing the total amount of materials to be used on site is generally quite robust. As improper estimation of material use has a direct and significant impact upon cost overruns, for the majority of projects materials are estimated within 5 to 10% of actual final quantities.

The largest margins of error in the predictions likely lie within the onsite CO₂e emissions assessment. It is unlikely to be possible to accurately predict specific plant, fuel consumption and time on site for all equipment at design phase. Post construction however this information can be easily vetted by inspection of fuel consumption on site and compared to initial estimates.

The remaining categories comprise minor percentages of overall CO₂e emissions and accordingly assessing margins of error for them is not significant for assessment of the schemes.

It is estimated the accuracy of the estimations is approximately +/-12%. This is driven largely by estimated 10% and 30% margin of error for predicted vs actual material and onsite CO₂e emissions respectively.

6 CONCLUSIONS, SUMMARY AND FURTHER WORK

The carbon calculator aspect of these case studies demonstrates that material procurement and consumption have by far the greatest impact on CO₂e emissions for a given foundation scheme. For example, 5m³ to 8m³ of concrete waste represents 1,700kg CO₂e, the equivalent of a car travelling 7,000 km (an approx. distance travelled by an employee commuting 30km/day in a work year). This emphasises the size of scope 3 emissions compared to scope 1. Therefore, unsurprisingly in both case studies, those geotechnical solutions that reduce cement and steel content, or rely solely on ground improvement, have a lower carbon footprint and will assist in higher green star ratings from the GBCA.

Development of standards and specifications and factors of safety therein has a direct impact on material use. Unnecessary conservatism in design will substantially increase carbon emissions. Load testing of foundations often leads to more efficient designs and this should be favoured both for verification and emissions purposes.

In some cases, the avoidance of concrete to reduce embodied carbon is not feasible. In the high-rise case study, for example, all the potential solutions require concrete. This highlights the need for further development, research and application of low carbon cement technologies. Within Australia, this technology faces a number of barriers, such as a lack of historical data, a lack of supply and availability of low carbon cement materials and a lack of relevant standards, all of which could result in hesitance to adopt low carbon technologies.

Similarly, it is worth reiterating that not every ground improvement or heavy piling solution is suitable for all ground conditions. When coupled with local environmental factors, especially for urban areas where avoiding congestion and noise pollution is particularly important, this emphasises the need for a framework to determine what is the most sustainable geotechnical solution for each

project. In understanding and comparing the carbon and local environmental impact of these solutions, this paper aims to pave the way for this development.

In terms of further work, this paper does not touch upon the carbon or environmental impact of foundation reuse from previous buildings. In Australia, the end of life phase for foundations is typically waste, being left in-situ, often partially demolished over the top few meters to enable subsequent redevelopment of the site with new foundations installed. Although currently inhibited by compliance with new codes and standards, such as "AS2159 – Piling design and Installation", the reuse of foundations is worth exploring, both as a way to reduce carbon and reduce the impact on the local environment. Expanding AS2159 to provide guidance on foundation reuse would be a key step towards this.

This paper and the calculator do not assess the positive impact of energy piles. The next step for full assessment of foundation solutions is to incorporate this positive contribution to provide a more robust assessment of a foundation scheme carbon emissions.

The limits of this paper are acknowledged in terms of quantifying the environmental impacts of different geotechnical solutions. Nonetheless, it is hoped this comparison illustrates the relative embodied carbon and local environmental impact for various techniques commonly adopted for high-rise and warehouse foundations within Australia.

7 ACKNOWLEDGEMENTS

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