

# CASE STUDY COMPARING EMBODIED CARBON EMISSIONS IN TWO ROAD-OVER-RAIL BRIDGE FOUNDATION DESIGNS

Jessica Dalton<sup>1</sup> and Stephen Barrett<sup>2</sup>

<sup>1</sup>Principal Geotechnical Engineer, Geotechnical and Tunnels at WSP

<sup>2</sup>Lead Technical Director, Geotechnical and Tunnels at WSP

## ABSTRACT

This paper examines and compares the embodied carbon emissions in the earthworks and foundation design for two road-over-rail integral bridges as part of a project in Western Australia. The first bridge is supported on gravity footings and constructed using bottom-up methods, the second on load-bearing contiguous piles and constructed using top-down methods. The abutments support a cut profile of sand and limestone up to 10 m high.

A Life Cycle Assessment (LCA) for embodied carbon emissions was carried out for each bridge using the framework of PAS 2080. Construction-stage design information was used in the assessment, representing a bottom-up LCA approach to retrospectively identify carbon hotspots to inform future designs.

The assessment incorporated geotechnical site investigations; temporary works; bulk excavation for gravity footings and other minor excavations; and the raw materials for construction of the two foundation types. Transportation of materials to site, construction processes and final deconstruction and disposal of the structures were also considered. The bridge superstructure was outside the scope of the assessment.

The results are presented in total tonne CO<sub>2e</sub> per bridge and tonne CO<sub>2e</sub> per bridge deck area to allow direct comparison of the embodied carbon emissions of the two bridge foundation systems. The carbon hotspots in each design are identified, and the authors discuss how the results can be communicated to clients and contractors to be weighed alongside the various other drivers that influence construction method and design.

The paper closes with the authors' assessment of opportunities across the design process where geotechnical designers have most influence on embodied carbon over the design life of these bridge types.

## 1 INTRODUCTION

A rail extension project in Western Australia includes construction of bridges, stations and retaining walls along the alignment using a combination of top-down (such as contiguous piled walls) and bottom-up (gravity footings) methods. Due to the constraints of existing road levels and proposed development levels the rail alignment is founded in sections of cut.

The site is located within a coastal dune system, with subsurface units mainly comprising Tamala Sand and Tamala Limestone. The Tamala Limestone weathering profile has varying degrees of cementation and strength occurring within short lateral and vertical distances. Groundwater is approximately 20 m below foundation level, and the risk of karstic features varies from low to medium across the alignment. Karstic features such as solution features and cavities have been encountered during construction.

The overall cut to fill balance across the site is approximately 10:1. Excess fill is distributed to local developers and a nearby motorway upgrade project which intersects the site.

A Life Cycle Assessment (LCA) for embodied carbon emissions has been undertaken for two bridge sites within the project, one constructed top-down (Bridge No.1) and the other bottom-up (Bridge No.2), for comparison of embodied carbon emissions generated by the two foundation design solutions. The software One Click LCA was used for the assessment.

A design life of 120 years is applicable to both bridges. The bridges were also designed to require minimal maintenance, for example by adopting abutments integral with the superstructure to omit the requirement for maintenance of bearings.

It is the authors' opinion that LCAs for bridge design options typically focus heavily on superstructure components, whereas embodied emissions from earthworks and foundations systems are less well understood. Tools and software created for these assessments do not well represent geotechnical input requirements. Input data quality can also have a significant effect on the outcome of the LCA.

For the current case study, an initial assessment was carried out using construction stage information such as pile schedules, concrete and reinforcement drawings, and earthworks quantities estimated from drone imagery. The results of

this initial assessment were compared against an LCA carried out using inputs obtained from a Bill of Quantities (BoQ). The outcome demonstrates some sensitivity to data input assumptions, which presents a challenge to geotechnical engineers working through these assessments who may not typically influence the structural components and may not always have ready access to the BoQ and 3D models. Further discussion is provided below.

## 2 BRIDGE NO.1 (TOP-DOWN CONSTRUCTION)

Bridge No.1 is a single span, two lane integral bridge constructed using top-down methods. The span is approximately 24 m wide and length 20 m (width is 35 m including approach slabs). The bridge abutments comprise load bearing contiguous piles socketed into limestone. The superstructure is integral with the abutment walls, and the wing walls are structurally independent contiguous piled walls. The bridge deck is an in situ concrete post-tensioned beam. Retained heights are in the order of 9.5 m, and original ground level is near the final road level.

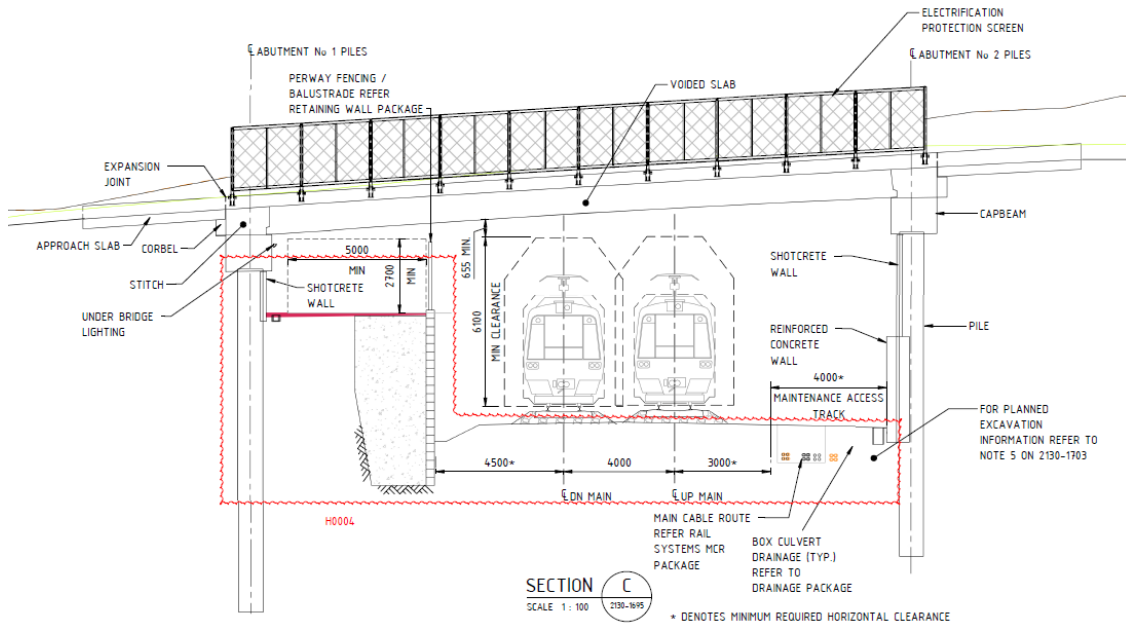


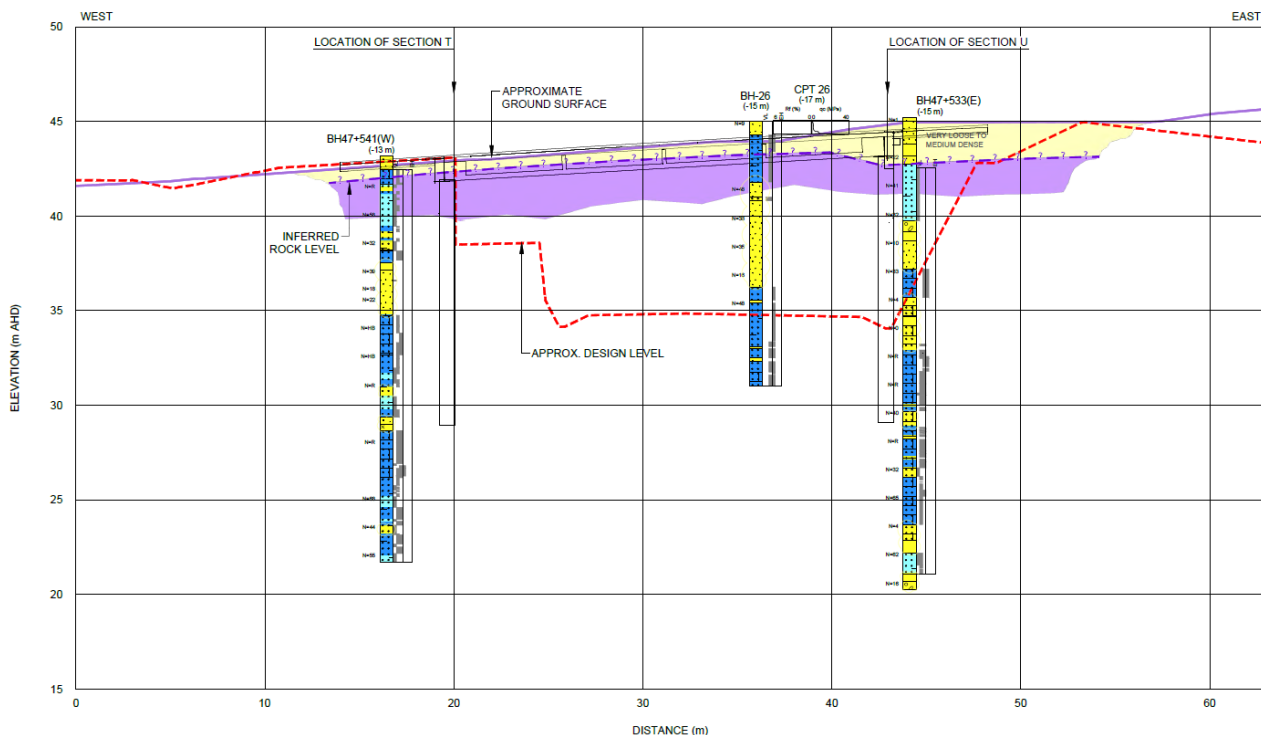
Figure 1: Bridge No.1 profile



Figure 2: Bridge No.1 during bulk excavation works

Bridge No.1 is founded on 900 mm diameter bored concrete piles, up to 20 m length and forming a contiguous piled wall. Pile design was carried out in accordance with Australian Standard AS 2159 and PD 6694-1:2011. An observational approach to piling was adopted using decision-trees to inform pile length based on materials encountered during piling, and some piles extended below design depth by up to 2 m where poor ground conditions (including inferred karstic features) were encountered. The total meterage of piling was in the order of 1,650 m.

Geotechnical investigations for the bridge comprised boreholes to about 20 m depth with Standard Penetrometer Testing (SPT) in sand and weak rock layers, and rock samples obtained for testing. The drilling method included a combination of rotary mud, diameter core drilling and air core drilling. Cone Penetrometer tests (CPTs) encountered shallow refusal on inferred rock. A geological cross-section through the bridge profile is provided below.



**Figure 3: Geological profile at Bridge No. 1**

During construction, a geotechnical engineer travelled to site for piling pad assessment and piling supervision. Pile Dynamic Analysis (PDA) with CAPWAP analysis was carried out on pre-production sacrificial piles to confirm load bearing capacity of the abutment piles. Several piles were subject to Thermal Integrity Testing (TIP). Concrete loss in three piles, inferred due to karstic cavities, triggered the requirement for targeted grouting works and Ground Penetrating Radar in the passive resistance zone to mitigate against voids affecting wall performance. Movement monitoring during bulk excavation was carried out using In-Place-Inclinometers installed within representative wing wall pile cages and steel survey pins installed along the capping beam.

Double pile geometry (rear piles spaced intermittently behind front piles) was required at wing walls to reduce wall deflections during bulk excavation works, necessitating a widened capping beam as shown in Figure 4 and 5 below. Reinforcement requirements differed between abutments and wing walls.

Temporary works included the requirement for additional piles at the wing wall extents to form return walls for construction of adjacent bottom-up structures. The piling platform and laydown pad comprised sub-base quality crushed limestone fill over site-won engineered sand fill compacted and tested in accordance with the project earthworks specification.

The permanent wall facing along the rail corridor will comprise a mesh reinforced shotcrete finish. In accordance with Australian Standard AS 5100, a reinforced concrete deflection wall is required along the eastern abutment within 10 m of the rail.

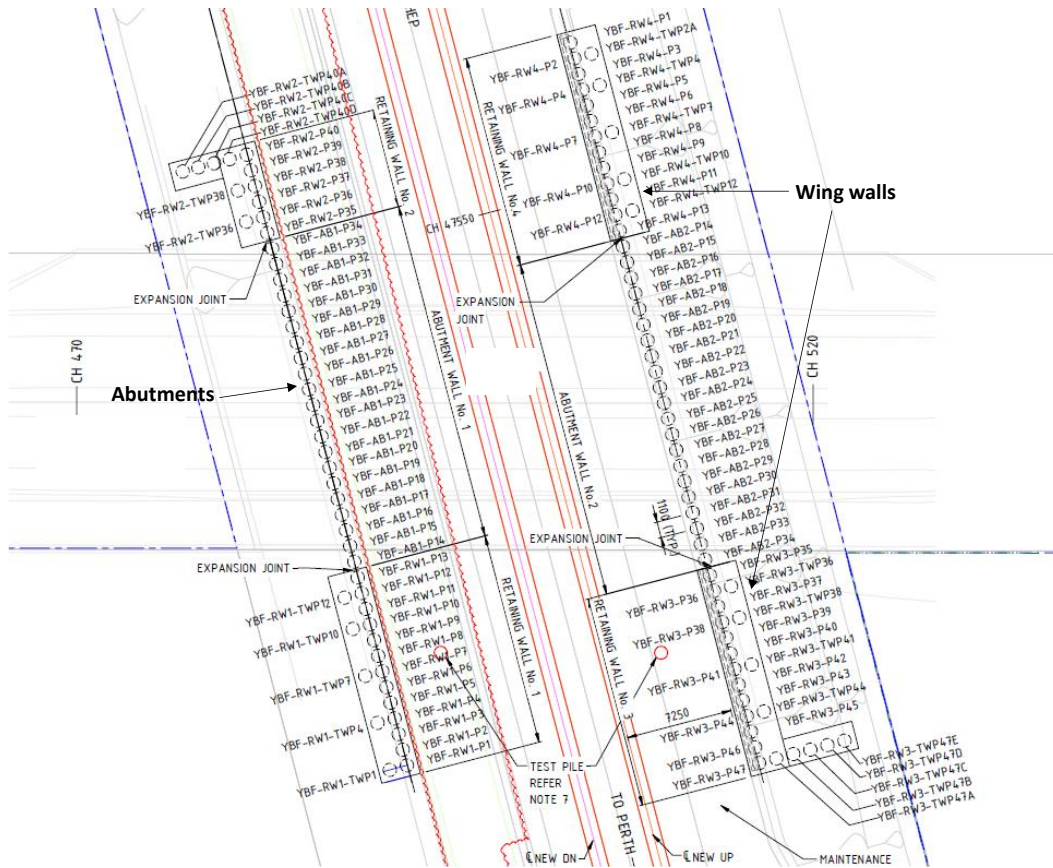


Figure 4: Bridge No.1 pile layout



Figure 5: Bridge No.1 pile capping beam excavation

### 3 BRIDGE NO.2 (BOTTOM-UP CONSTRUCTION)

Bridge No.2 is a single span, two lane bridge constructed using bottom-up methods. The bridge superstructure comprises precast beams with an in-situ topping slab made integral with full height reinforced concrete abutments, founded on shallow footings. The retained heights are in the order of 10 m, and footing widths up to 8 m. The span is approximately 20 m wide and the length 40 m (width is 35 m including approach slabs). The original ground level is above footing level.

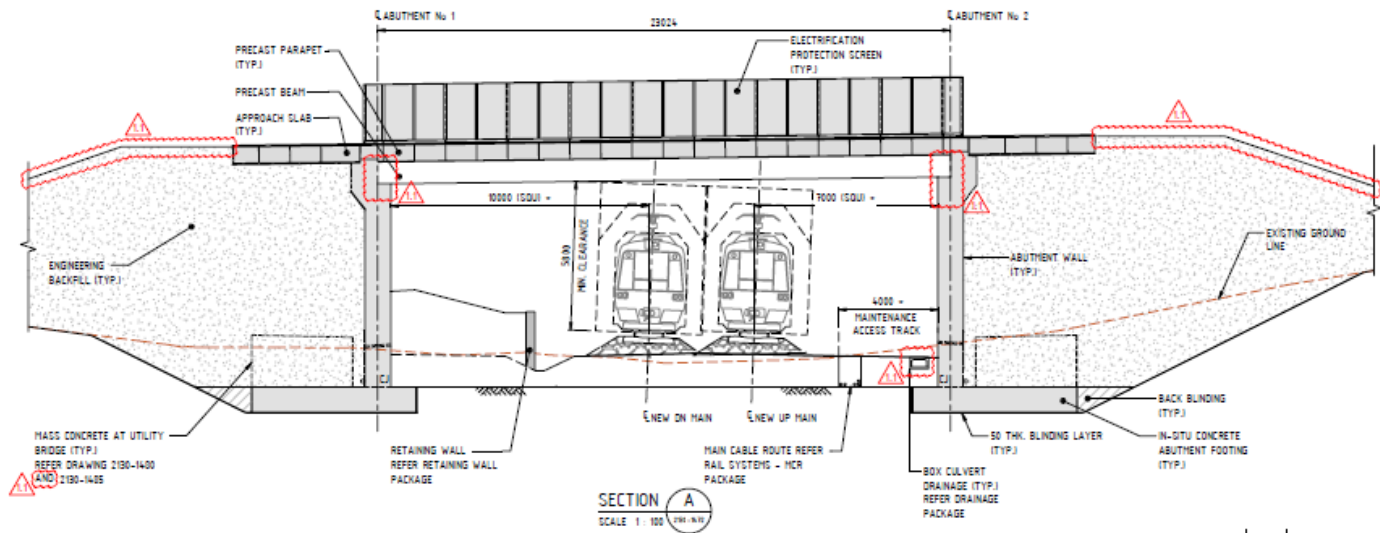


Figure 6: Bridge No.2 profile



Figure 7: Bridge No.2 during construction

The bridge foundations comprise reinforced concrete cast-in-situ L-shape wall footings varying in width. Wing wall footings are generally wider than abutment footings.

Geotechnical investigations comprised boreholes to an average depth of 25 m with SPT using rotary mud and diamond core drilling, with soil and rock samples obtained at regular intervals for testing. Vertical seismic profiling was carried out in two of the boreholes. A suite of soil and rock laboratory tests was carried out. CPTs were carried out to an average depth of 4 m. A geological long-section through the bridge profile is provided below.

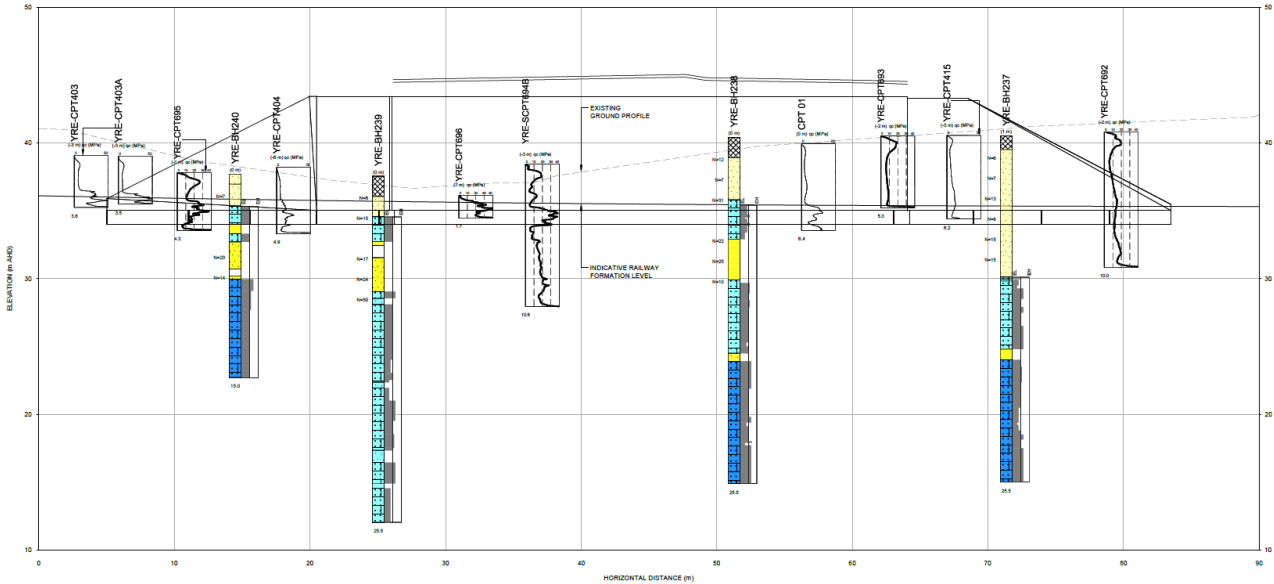


Figure 8: Geological profile at Bridge No. 2

Engineered backfill material behind the wall comprises site-sourced Tamala Sand, compacted and tested in accordance with the project earthworks specification. A geotechnical engineer travelled to site during construction for foundation inspections.

To reduce differential settlements across the footing over the sand /limestone interface, a compacted subbase quality crushed limestone foundation treatment layer was placed across the full length of the footing below blinding level. Steel survey pins were used for movement monitoring during bulk excavation works.



Figure 9: Bridge No.2 footing excavation (across sand / limestone interface)

## 4 CONSTRUCTION CONSIDERATIONS

Some of the key drivers for the choice of top-down or bottom-up construction methods are summarised in the table below. To the authors' knowledge, the embodied emissions of the different bridge options were not an explicit driver in the choice of construction methodology.

**Table 1: Construction methodology considerations**

Construction method	Advantages	Constraints / Disadvantages
Top-down	<ul style="list-style-type: none"> <li>— Smaller excavation footprint, can accommodate boundary constraints</li> <li>— Road able to be opened prior to bulk excavation under the bridge</li> </ul>	<ul style="list-style-type: none"> <li>— Only practical where ground level is near final level</li> <li>— Piling rig and cage availability</li> <li>— Access to rail formation level available end of construction</li> </ul>
Bottom-up	<ul style="list-style-type: none"> <li>— Appropriate where ground level to be raised up from existing</li> <li>— Early access to rail formation level for installation of utilities, rail capping and ballast etc</li> </ul>	<ul style="list-style-type: none"> <li>— Larger excavation footprint, may not be possible (without temporary works) depending on boundary constraints</li> <li>— Earthworks requirement for excavation of material and placement and compaction of approved fill behind walls</li> </ul>

Mechanically stabilised earth bridge abutments were considered as an alternative to bottom-up reinforced concrete L-shape walls, however, were not selected on the basis of durability considerations over the 120-year design life of the bridge. Reinforced earth structures can have lower embodied carbon emissions; however, the relative benefit should be assessed over the life of the structure as the design life may be less.

## 5 LIFE CYCLE ASSESSMENT METHODOLOGY

### 5.1 METHODOLOGY AND ASSUMPTIONS

An LCA for the two bridges was carried out using the guidance of PAS 2080. Modules A0-5 (Before Use Stage) and C1-4 (End of life stage) were assessed. It was assumed because of the integral nature of the sub and superstructures, the maintenance requirements for both structures would be minimal and therefore were not assessed. Items assessed for each stage are summarised in Table 2 below.

Construction-stage design information was used in the assessment, representing a bottom-up LCA approach to retrospectively identify carbon hotspots to inform future designs. Ideally these assessments are done early in the project to be able to influence design decisions (a top-down LCA approach).

Emission factors were obtained from verified Environmental Product Declarations (EPDs) only, provided through One Click LCA software. An exception is fuel consumption rates and fuel emissions factors for geotechnical site investigations and inspections, which were obtained from the SiteWise™ Tool for Green and Sustainable Remediation.

**Table 2: Items assessed for different PAS 2080 stages**

PAS 2080 Module	Description	Items assessed
A-0	Preliminary studies, consultations	Geotechnical site investigations (both bridges), and geotechnical site inspections. Laboratory testing excluded
A-1	Raw material supply	<b>Bridge No. 1</b> (top-down) substructure:
A-2	Transport	

A-3	Manufacture	<ul style="list-style-type: none"> <li>- Concrete for piles (abutments and wing walls), including test piles</li> <li>- Steel reinforcement for piles (abutments and wing walls)</li> <li>- Concrete and steel for shotcrete facing including deflection wall</li> <li>- Engineered fill for piling pad construction and laydown area</li> </ul>
A-4	Transport to work site	<ul style="list-style-type: none"> <li>- Engineered fill backfill for capping beam excavation</li> <li>- Bulk excavation for rail formation</li> <li>- Grout for infill of karstic cavities in front of piles</li> </ul> <p><b>Bridge No. 2</b> (bottom-up) substructure:</p> <ul style="list-style-type: none"> <li>- Concrete for gravity footing</li> <li>- Steel reinforcement for gravity footing</li> <li>- Bulk excavation for gravity footing and rail formation</li> <li>- Engineered backfill behind the abutment and wing walls</li> <li>- Foundation treatment</li> </ul>
A-5	Construction /installation processes	Calculated within One Click LCA software based on m <sup>3</sup> of removed / imported masses
B1-9	Use stage	Not assessed
C1-4	End of life stage	Calculated within One Click LCA software as follows: “This includes impacts for processing recyclable construction waste or ...processing waste streams that cannot be recycled. Additionally deconstruction includes emissions caused by waste energy recovery”

The assessment excluded the following items: embodied carbon of the bridge superstructure; greenhouse gases other than carbon dioxide; formwork and falsework required for construction; minor elements such as drainage, movement monitoring instrumentation and geotechnical investigation consumables; geotechnical laboratory testing, and pile integrity testing items. Travel to and from site by personnel other than geotechnical engineers was also excluded.

Transportation distances were calculated on the basis that pile reinforcement cages were shipped from eastern to western Australia, whereas other steel and concrete were sourced locally. Excavated soils were assumed to be transported for use by local projects, whereas imported soils were assumed to travel a greater distance to site. Based on the overall cut to fill balance for the site, it was assumed that 10% of excavated materials were re-used on site, with the remaining transported offsite. A bulking factor of 15% was applied to excavated sands and gravels.

## 6 RESULTS OF ASSESSMENT

Outcomes of the assessment are summarised in Tables 3 and 4.

**Table 3: Embodied carbon emissions, Bridge No.1 (top down) substructure**

PAS 2080 Module	Description	Design items assessed	Total CO <sub>2e</sub> (t)	% of total	
A-0	Preliminary studies, consultations	Geotechnical site investigations	20	1.5%	
		Geotechnical site inspections/ pile supervision	0.9	<1%	
A-1	Raw material supply	Design inputs			
A-2	Transport	- Abutment piles	258	<b>20.6%</b>	
A-3	Manufacture	- Abutment capping beam	43	3.4%	
A-4	Transport to work site	- Abutment shotcrete facing	54	4%	
		- Wing wall piles (60% steel/ 40% concrete)	463	<b>37%</b>	
		- Wing wall capping beam	95	7.6%	
		- Wing wall shotcrete facing	34	2.7%	
		Construction inputs			
		- Abutment pile extensions, overbreak etc	35	2.8%	
		- Wing Wall pile extensions, overbreak etc	100	8%	
		- Wing wall capping beam extension	10	<1%	
		- Grout for karst backfill	4.2	<1%	
		Soils removed and sourced for project	75	6%	
A-5	Construction processes	Earthworks operations for 21,210 m <sup>3</sup> of soils removed or placed on site	30	2.3%	
B1-9	Use stage	Not assessed			
C1-4	End of life stage	Waste processing and emissions during demolition	30	2.4%	
			<b>TOTAL = 1,252</b>	<b>(~1.25 t/m<sup>2</sup> of deck area)</b>	

**Table 4: Embodied carbon emissions, Bridge No.2 (bottom up) substructure**

PAS 2080 Module	Description	Design items assessed	Total CO <sub>2e</sub> (t)	% of total
A-0	Preliminary studies, consultations	Geotechnical site investigations	33	1.8%
		Geotechnical site inspections	0.1	<1%
A-1	Raw material supply	Steel and concrete for gravity footings (60% steel/ 40% concrete)	1,410	<b>80%</b>
A-2	Transport			
A-3	Manufacture	Soils removed and sourced for project	210	12%
A-4	Transport to work site			
A-5	Construction processes	Earthworks operations for 46,285 m <sup>3</sup> of soils removed or placed on site	65	3.7%
B1-9	Use stage	Not assessed		
C1-4	End of life stage	Waste processing and emissions during demolition	41	2.3%
<b>TOTAL = 1,759</b> (1.37 t/m <sup>2</sup> of deck area)				

The quantities in Tables 3 and 4 were assessed first using construction stage information such as pile schedules, concrete and reinforcement drawings, and earthworks quantities estimated from drone imagery (within the battery limit of the project and extending only within the bridge footprint). The results were then refined based on more accurate assessment from BoQ for steel quantities at both bridges, which resulted in reduction in estimated steel quantities in the order of 10% to 20% and overall reduction in assessed emissions for both bridges in the order of 4% to 7%. This correction did not change the assessed relative emission intensity of the two bridge types or the overall insights from this study.

## 7 INSIGHTS GAINED

The results of the assessment indicate the bridge substructure constructed using top-down piling methods (Bridge No.1) generated in the order of 30% less embodied carbon emissions than the bridge constructed using bottom-up construction methods (Bridge No.2). Emissions per m<sup>2</sup> of deck area were also lower for this option.

The highest embodied carbon emissions for both bridges were generated by the raw materials supply and manufacture for the main foundation elements (abutment and wing wall piles, and reinforced concrete footings). Steel reinforcement was the most emission intensive material used in construction of the bridges, followed by concrete.

Geotechnical investigations accounted for up to 2% of bridge substructure emissions. However, had investigation not been undertaken at Bridge No.1, a rock socket could not have been assumed in design (given ground variability across the project) and piles may have been lengthened by an estimated 4 to 5 m each to accommodate a sandy rock socket design. This would have added approximately 500 m of pile length, equating to about 260 tonnes or an additional 20% of carbon emissions to the life cycle of the bridge. For Bridge No.2, sandy foundation conditions were confirmed by site investigation and assumed in design, so in this case site investigations did not materially affect the carbon emissions over the life cycle of the bridge (though were required for design input). Overall, the study demonstrates that site investigations can significantly reduce carbon emissions by providing greater design confidence to allow optimisation.

An observational approach to pile design at Bridge No.1 in the variable sand/rock conditions also prevented the design from being overly cautious and allowed piles to be lengthened only as required where sand pockets were encountered. In this instance, geotechnical design optimisation based on site investigation data and an observational approach to piling represented the best opportunities for the geotechnical engineers to influence embodied carbon over the design life of Bridge No.1. There was limited opportunity to optimise the design of Bridge No.2 and reduce embodied carbon emissions based on geotechnical conditions.

Construction processes (earthworks) accounted for only 2% to 4% of the bridge substructure emissions, where travel to source or remove soil offsite accounted for another 6% to 12%. Construction stage changes to the design (such as additional piles for temporary stability, pile extensions for poor conditions, pile overbreak etc.) accounted for an additional 15% of carbon emissions at Bridge No.1. Construction stage changes at Bridge No.2 did not materially affect carbon emissions to the authors' knowledge.

Transportation of raw materials (other than soils) accounted for up to 10% of emissions. Had the pile steel reinforcement cages for Bridge No.1 been able to be sourced locally within Western Australia, carbon emission could have been reduced by about 2% to 3% for the bridge substructure. There was an awareness among the design team of steel cage length limitation to fit on one truck bed, however the design requirements did not allow the pile lengths to be reduced below this length. This understanding was used elsewhere on the project however for design optimisation of alignment retaining walls. Travel distances for imported soils had limited effect on the overall assessment, as the bulk of the backfill was sourced on site. However, Bridge No. 2 assessment was sensitive to assumed truck movements within the site for backfilling works, where every 1 km of additional distance to/from soil stockpile areas represents 1.5% of the embodied emissions for the bridge (over the total number of truck movements).

Items not considered to be of material significant to the assessment included geotechnical inspections and small items such as the grouting program for karstic features.

From these insights it is apparent that familiarity with LCA for different bridge foundation solutions will allow geotechnical and structural engineers to optimise their designs, and where possible, move towards lower embodied emissions solutions over time. Development of a consistent LCA assessment methodology across the geotechnical industry is however needed to facilitate easy comparison of different project examples. The current case study also indicates that foundation solutions that allow for an observational approach during construction and where construction constraints are well understood provide more opportunities for geotechnical engineers to optimise the design and ultimately reduce embodied emissions of the bridge structure, when compared to more conservative design approaches.

## 8 ACKNOWLEDGEMENTS

The authors wish to thank the WSP project team and Christian Guerrero for his support in providing information on the bridge construction.

## 9 REFERENCES

Australian Standard 2159 (2009). Piling Design and Installation.

Australian Standard 5100, (2017). Bridge Design.

BSI Standard Publication (2020), PD 6694-1:2011+A1: Recommendations for the design of structures subject to traffic loading to BS EN 1997-1:2004+A1:2013.

One Click LCA Software by One click LCA LTD, Version 0.18.0.

PAS 2080, (2016), *Carbon Management in Infrastructure*, British Standards Institution.

SiteWise™ Tool for Green and Sustainable Remediation by the United States Navy, United States Army Corps of Engineers (USACE), and Battelle, Version 3.2.