

Original Article

Comparative Assessment of Embodied Carbon in Cantilever Concrete Retaining Walls and Sheet Pile Walls

Riza Suwondo^{1*}, Andryan Suhendra¹, Traad Alzhirani², Yustian Suprpto³

¹Department of Civil Engineering, Faculty of Engineering, Bina Nusantara University, Jakarta 11480, Indonesia.

²Department of Civil and Geospatial, School of Engineering, Newcastle University, UK.

³PT Keller Group Indonesia, Jakarta, Indonesia.

*Corresponding Author : riza.suwondo@binus.ac.id

Received: 07 May 2026

Revised: 22 September 2026

Accepted: 24 September 2026

Published: 28 October 2026

Abstract - Retaining walls store significant amounts of embodied carbon, yet this aspect is often overlooked due to high material requirements. Although awareness regarding carbon assessment in the built environment sector is growing, comparative studies across different retaining wall systems remain scarce. This study presents a comparative analysis of embodied carbon—within the cradle-to-site scope (Modules A1–A5, BS EN 15978:2011)—for Cantilever Concrete Retaining Walls (CCRW) and Concrete Sheet Piles (CSP), ranging from 1 to 4 m in height. Unlike previous studies that focused on a single system or specific life-cycle stage, this research quantifies emissions arising from material production, transportation, and on-site construction activities. The results indicate that total embodied carbon increases with wall height for both systems. However, CSP consistently generates higher emissions—ranging from 20%–30% higher at lower heights to nearly 90% higher at a height of 4 meters—primarily due to production emissions and a heavier transportation burden. A proportional analysis reveals that material production (A1–A3) accounts for over 85% of total emissions in both systems, whereas transportation (A4) represents a significant additional burden for CSP. This study also identifies emission hotspots and opportunities for carbon reduction for each system. The findings highlight the importance of incorporating embodied carbon considerations into the early design stages and emphasise the need for material optimisation for CCRW and supply chain optimisation for CSP to achieve retaining wall solutions with lower carbon footprints.

Keywords - Embodied carbon, Retaining wall, Cantilever concrete wall, Concrete sheet pile, Sustainable design, Climate action.

1. Introduction

The construction sector has a disproportionately large impact on global energy consumption and CO₂ emissions, positioning the built environment as a critical focal point in efforts to mitigate climate change [1, 2]. This impact is intensified by energy-intensive processes such as raw material extraction, manufacturing, and the substantial generation of construction and demolition waste, all of which contribute significantly to greenhouse gas emissions across the life cycle of built assets [3, 4]. Although recent advances in building performance modelling and the widespread adoption of low-energy, climate-responsive designs have led to notable reductions in operational emissions [5–7], embodied carbon, defined as the CO₂ equivalent emissions released during the extraction, processing, transportation, and assembly of construction materials, remains comparatively under-addressed.

Representing emissions from cradle to practical completion (Modules A1–A5), embodied carbon now constitutes an increasingly significant share of total building-

related emissions as operational energy demands decline [8–10].

Concrete, the most widely used construction material in terms of volume, illustrates the embodied carbon challenge in stark terms. Its widespread use stems from its exceptional mechanical properties and abundance of raw materials. However, the production of Portland cement, the primary binder in concrete, is responsible for approximately 8% of global CO₂ emissions [11–13]. Concrete Cantilever Retaining Walls (CCRW) and Concrete Sheet Piles (CSP) are among the most commonly adopted solutions for stabilising hillsides, roadway embankments, riverbanks, and agricultural terraces [14–18].

The dominance of cement-based materials and reinforcement in construction gives CCRW and CSP significant potential to reduce embodied carbon emissions in civil infrastructure. Understanding how design decisions influence material requirements—and the resulting emissions—serves as a crucial foundation for designing more



sustainable retaining walls without compromising geotechnical performance.

The demand for sustainable construction has driven research into quantifying the environmental impact of structural systems, spurring the development of standardised carbon footprint assessment methods and comprehensive carbon coefficient databases to support environmentally conscious design decisions [19].

However, most studies focus on the superstructure, particularly on reducing embodied carbon through cutting-edge material technologies and low-carbon alternative materials [20-24]. In parallel, structural optimisation strategies are being implemented to minimise material usage through innovative load-bearing systems and advanced computational approaches that enhance stress efficiency without compromising safety or serviceability [25-27].

Despite various advancements, substructures, such as foundations and retaining walls, have received insufficient attention in embodied carbon research. Yet, substructures can possess high material and carbon intensities, sometimes matching or even exceeding the environmental impact of the superstructure.

Abushama et al. [28] found that optimising the geometry and material strength of reinforced concrete piles could significantly reduce emissions, while Georgiou et al. [29] highlighted the substantial contribution of underground infrastructure to the carbon footprint of water sector projects. Other studies on wind turbine foundations and high-rise buildings have also demonstrated the significant share of emissions attributable to foundations [30, 31]. However, existing research generally focuses on specific foundation systems; consequently, comparative studies across different retaining wall alternatives-particularly those encompassing material production, transportation, and construction activities (cradle-to-site)-remain scarce.

Although the environmental aspects of earth-retaining structures are gaining recognition, comparative studies evaluating the embodied carbon performance of various alternative retaining wall systems remain limited. Existing research on embodied carbon largely addresses superstructures, foundation systems, and earth-retaining solutions in isolation, whereas comprehensive comparisons of commonly used retaining-wall systems are scarce.

Furthermore, previous studies have generally focused on material-related emissions, rarely considering the combined impact of material production, transportation logistics, and on-site construction activities on the overall embodied carbon performance. In current engineering practice, the selection of retaining walls is primarily based on geotechnical performance, ease of construction, and economic

considerations, with embodied carbon rarely being included as a decision-making criterion. Consequently, engineers and decision-makers lack comprehensive quantitative information on the relative environmental performance of commonly used earth-retaining systems.

In particular, research comparing embodied carbon assessments between Cantilever Concrete Retaining Walls (CCRW) and Concrete Sheet Piles (CSP) remains limited, despite these two systems being the most widely used earth-retaining solutions in civil infrastructure projects. To bridge this gap, this study highlights and compares the embodied carbon performance of CCRW and CSP systems across various representative design scenarios using a cradle-to-site life cycle assessment framework (Modules A1–A5, BS EN 15978). The unique contributions of this study are as follows: (1) a comprehensive assessment of the embodied carbon performance of CCRW and CSP based on consistent design assumptions; (2) quantification of the contribution of each stage-material production, transportation, and construction activities-throughout the cradle-to-site life cycle; and (3) identification of emission hotspots and carbon reduction opportunities for each system. These findings are expected to support low-carbon decision-making during the conceptual design stage and contribute to sustainable civil engineering practices.

2. Methodology

This study comparatively evaluates the embodied carbon of CCRW and CSP systems under uniform geotechnical conditions and design parameters. The methodology begins with the establishment of representative design scenarios, followed by structural analysis to estimate the material requirements for each system. Carbon emissions were estimated using a cradle-to-site life-cycle approach (Modules A1–A5: material production, transportation, and construction) in accordance with BS EN 15978:2011 [32]. By integrating structural design procedures, carbon coefficient databases, and on-site construction emission data, this analysis presents a comprehensive and reliable comparison of the carbon intensities of these two retaining wall systems.

Table 1. Summary of key assumptions and design parameters

Parameter	Value
Wall height	1 – 4 m
Soil density	19 kN/m ³
Soil friction angle	35
Concrete strength CCRW	28 MPa
Concrete strength CSP	42 MPa
Transport distance CCRW	50 km
Transport distance CSP	300 km

Figure 1 illustrates the retaining wall configurations analysed in this study. To evaluate the effect of wall height, H was varied incrementally from 1 m to 4 m. Both the CCRW

and CSP systems were designed to support a granular soil embankment with a unit weight of 19 kN/m^3 and an internal friction angle of 35° , and the underlying native soil was assumed to have properties identical to those of the embankment. Table 1 presents the assumptions and design parameters used in this study.

The material specifications used in this study were established based on common construction practices in Indonesia. For the CCRW system, concrete with a specific gravity of 24 kN/m^3 and a characteristic compressive strength (f'_c) of 28 MPa was used, along with grade 60 reinforcement with a yield strength (f_y) of 420 MPa .

Meanwhile, the CSP system adopted precast concrete with a higher quality, namely $f'_c 42 \text{ MPa}$, to meet the structural demands of a slimmer sheet-pile section. The precast sheet pile profiles used (Table 2) were selected based on their availability in the local market, thus reflecting the actual conditions and applicability of the design in the field.

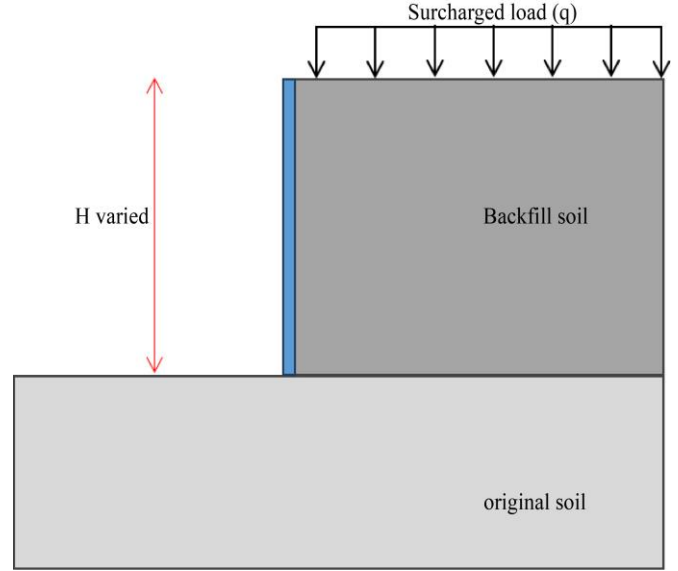


Fig. 1 Retaining wall configurations

Table 2. Precast concrete sheet pile profile used in CSP design

Type	Width (mm)	Cross section (cm ²)	Section Inertia (cm ⁴)	Class	Service moment (T-m)
FPC-220	500	1085	43802	6S-A	1.54
				8S-A	2.01
				10S-A	2.46
				6S-B	2.64
				8S-B	3.38
				6S-C	3.55
				10S-B	4.05
				8S-C	4.47
FPC-320	500	1585	135455	6S-A	2.32
				8S-A	3.06
				10S-A	3.78
				6S-B	4.06
				12S-A	4.47
				14S-A	5.15
				8S-B	5.29
				6S-C	5.59
				16S-A	5.81
				10S-B	6.45
				8S-C	7.2
				12S-B	7.56
				14S-B	8.61

2.1. Design Calculations

Design calculations were performed using classical earth pressure theory to determine the lateral loads acting on the CCRW system. The active lateral earth pressure (P_a) of the non-cohesive soil embankment was calculated based on Rankine's assumptions [33] as follows:

$$P_a = \frac{1}{2} K_a \gamma H^2 + q H K_a \quad (1)$$

$$K_a = \tan^2 \left(45^\circ - \frac{\phi}{2} \right) \quad (2)$$

Where γ is the unit weight of the backfill soil, H is the

retained height, K_a is the Rankine active earth pressure coefficient for the soil friction angle ϕ , and q is the uniform surcharge load.

Stability checks were performed to ensure safety against overturning, sliding, and bearing capacity failure, with the Factors of Safety (FS) evaluated as follows:

Factor of safety against sliding

$$FS_{SL} = \frac{\mu W}{P_a} \quad (3)$$

Where μ is the coefficient of friction at the base of the wall, and W is the total weight of the wall system.

Factor of safety against overturning

$$FS_{OT} = \frac{M_R}{M_O} \quad (4)$$

Where M_R is the resisting moment provided by the wall weight and base geometry, and M_O is the overturning moment induced by the lateral earth and surcharge pressure.

The maximum and minimum bearing pressures (σ_{max} and σ_{min} , respectively) under the base were calculated as follows:

$$\sigma_{max,min} = \frac{W}{B} \pm \frac{6M}{B^2} \quad (5)$$

Where B is the base width, and M is the resultant overturning moment.

For the CSP system, the required embedment depth (D_e) was determined to ensure rotational stability and adequate soil fixation. The maximum bending moment along the sheet pile was calculated using pressure diagrams derived from the Rankine active earth pressure combined with the surcharge loading as follows:

$$M_{max} = \frac{P_a H}{2} \quad (6)$$

The moment capacity of the selected precast sheet pile profile listed in Table 1 was checked to confirm that it exceeded the calculated demands with appropriate safety margins.

Both systems were analysed for each height ($H = 1-4$ m). The concrete volume and steel reinforcement weight were calculated based on the detailed section design, which formed the basis for the embodied carbon calculations and allowed a direct comparison between the CCRW and CSP.

2.2. Embodied Carbon Assessment

The embodied carbon assessment was conducted using a

process-based Life Cycle Assessment (LCA) approach in accordance with BS EN 15978:2011 [32]. The functional unit adopted was a retaining wall of 1 m length, and all results are expressed in kgCO₂e/m. The system boundary covered Modules A1–A5, as illustrated in Figure. 2, representing cradle-to-site assessment. Structural design and embodied carbon calculations were performed using spreadsheet-based calculations in Microsoft Excel to ensure transparency and reproducibility of the results.

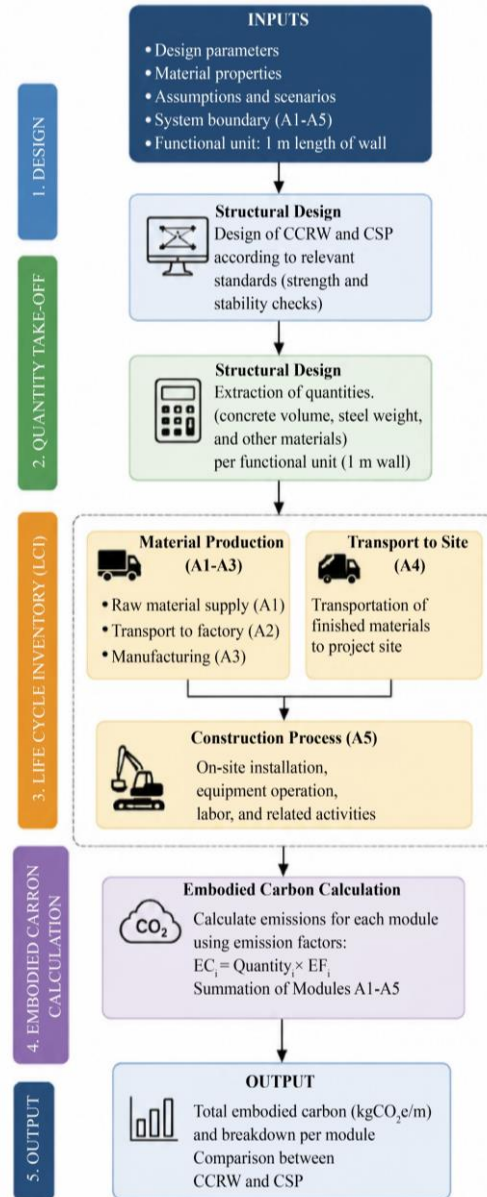


Fig. 2 Workflow of the embodied carbon assessment methodology

The embodied carbon for the product stage (Modules A1–A3) was calculated using the following equation:

$$EC_{A1-A3} = \sum(Q_i \times CF_{A1-A3}) \quad (7)$$

Where Q_i represents the quantity of material i (in kg or m^3) and CF_{A1-A3} denotes the carbon emission factor specific to the product stage, expressed in $kgCO_2e$ per unit of material. Emission factors were sourced from the Inventory of Carbon and Energy (ICE v3.0) [34], which is widely utilised in life cycle assessment studies and is consistent with the principles of the circular economy. The carbon factors used in this analysis are presented in Table 3.

Table 3. Embodied carbon factor of materials

Material	Embodied carbon factor
Concrete 28 MPa	330 $kgCO_2e/m^3$
Concrete 42 MPa	380 $kgCO_2e/m^3$
Rebar/PC strand	1.99 $kgCO_2e/kg$

For the transportation stage (Module A4), the embodied carbon was determined using the following equation:

$$EC_{A4} = \sum Q_i \times CF_{A4} \quad (8)$$

The transportation emission factor (CF_{A4}) for each material was calculated as follows:

$$CF_{A4} = \sum TD \times TEF \quad (9)$$

Where TD is the distance the materials are transported to the construction site (km), and TEF is the transport emission factor, assumed to be 0.10749 gCO_2e per kg per km. For CCRW, cast-in-place concrete was assumed to be produced locally, with an average transport distance of 50 km from the concrete batching plant to the project site. For the CSP system, precast elements were manufactured at national production facilities with an average haul distance of 300 km to reflect realistic supply chain conditions in Indonesia.

These transport scenarios were incorporated into the calculations to accurately capture the emissions associated with the delivery of materials to the construction sites.

For the construction process stage (Module A5), the calculation was divided into two parts: emissions from on-site material waste (EC_{A5w}) and emissions from the overall construction activities (EC_{A5o}). The embodied carbon attributed to material waste was calculated using

$$EC_{A5w} = WF_i \times (CF_{A1-A3} + CF_{A4}) \quad (10)$$

Where WF_i is the waste factor for each material derived from the Waste Rate (WR_i) by

$$WF_i = \frac{1}{1-WR_i} - 1 \quad (11)$$

The WR_i for each material was obtained from the literature and is presented in Table 4.

Table 4. Waste rate of material

Material	Waste rate
Concrete in situ	5 %
Concrete precast	1 %
Rebar	5 %

For general construction activities, embodied carbon was estimated using a cost-based approach.

$$EC_{A5a} = CAEF \times \frac{PC}{100,000} \quad (12)$$

Where $CAEF$ is the emission factor for construction activities, adopted as 700 $kgCO_2e$ per £100,000 of the project cost, and PC is the total project cost in £.

A sensitivity analysis was performed to evaluate the influence of uncertainties in embodied carbon factors and transportation distances on total embodied carbon. Concrete and steel carbon factors were varied by $\pm 20\%$, whereas transportation distances were varied by $\pm 50\%$, representing realistic variations in material production and supply chain conditions.

3. Results and Discussion

This section presents and interprets the embodied carbon analysis results for CCRW and CSP systems at wall heights ranging from 1 to 4 meters. Carbon contributions are calculated separately for the product stage (Modules A1–A3), transportation to the site (Module A4), and on-site construction (Module A5) to provide an in-depth understanding of emission sources at each stage of the life cycle.

The study reveals significant differences in the magnitude and trends of embodied carbon emissions between the two systems. These findings indicate that material quantities, transportation logistics, and construction processes collectively determine the environmental performance of both retaining wall systems.

3.1. Product Stage (A1–A3)

The embodied carbon emission results for the product stage (modules A1–A3) are presented in Figure 3. As shown, the emissions increased consistently with increasing wall height for both the CCRW and CSP systems.

For example, in the CCRW, A1–A3 emissions jumped from 200 $kgCO_2e/m$ at 1 m height to 750 $kgCO_2e/m$ at 4 m height.

This increase reflects the direct relationship between the wall height and the volume of material (concrete and steel reinforcement) required to withstand greater lateral pressures.

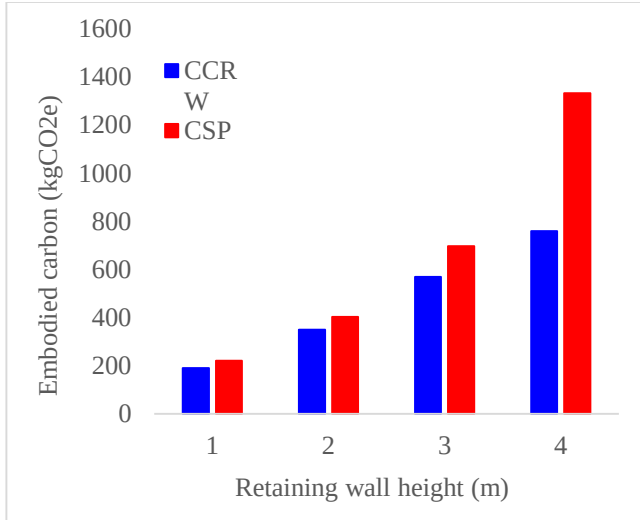


Fig. 3 Embodied carbon from product stage (A1-A3)

In the CSP system, the embodied carbon emissions of A1=A3 were slightly higher than those of CCRW at a height of 1 m, at 250 kgCO₂e/m vs. 200 kgCO₂e/m. This difference widened with increasing wall height; at a height of 4 m, the CSP emissions reached 1350 kgCO₂e/m, almost double that of the CCRW (750 kgCO₂e/m). Quantitatively, CSP showed 10-15% higher emissions at a height of 1-2 m and jumped to 40-50% higher at a height of 3-4 m. This steeper increase was due to the demand for precast elements with greater section modulus and flexural capacity, which required additional volumes of high-strength concrete.

These findings reveal a trade-off with CSP systems: while they are superior in terms of ease of construction and on-site productivity, they are burdened by a higher carbon intensity at the product stage. This is due to the use of high-emission precast concrete and the need for increasingly robust profiles as the wall heights increase. Therefore, decarbonisation strategies for retaining walls, particularly in projects with high walls, should focus on three key aspects: the selection of alternative materials, optimisation of sectional design, and careful evaluation of embodied emissions from the product's life cycle.

3.2. Transportation Stage (A4)

Figure 4 illustrates the embodied carbon emissions from the transportation phase (Module A4), demonstrating the superior performance of the CCRW system. With emissions increasing from only 5 kgCO₂e/m at a height of 1 m to 20 kgCO₂e/m at a height of 4 m, CCRW demonstrates that the use of locally sourced cast-in-place materials can minimise logistics burdens.

The short transportation distance (50 km) from the concrete batching plant is a key factor in limiting carbon intensity, demonstrating the critical role of local sourcing strategies in decarbonising infrastructure.

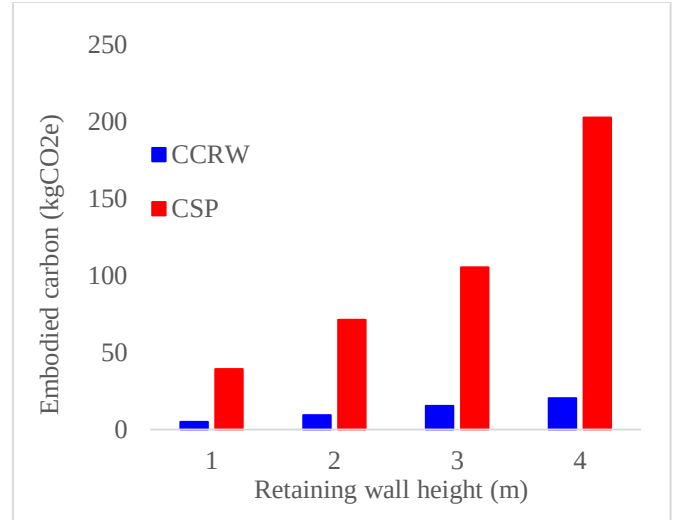


Fig. 4 Embodied carbon from transportation stage (A4)

In contrast to the CCRW, where transportation emissions increased gradually, the CSP systems experienced a drastic increase in A4 emissions. At a height of 1 m, CSP emissions were recorded at 40 kgCO₂e/m, which is eight times that of CCRW (5 kgCO₂e/m). This gap widened with height; at a 4 m wall, CSP emissions increased to 200 kgCO₂e/m, or ten times that of CCRW (20 kgCO₂e/m) emissions. The root cause of this difference was the assumption of a much longer transportation distance (300 km) for the precast elements, coupled with a significant increase in the unit weight of the high walls to meet greater embedment and flexural requirements.

This study reveals a key dilemma with precast systems, such as CSPs: while they offer advantages in speed and on-site productivity, their environmental benefits are highly dependent on the transportation distance. The farther the manufacturing site is from the project, the greater the A4 emissions generated, potentially negating any carbon efficiency gains from the construction process. Therefore, strategic decisions regarding the selection of regional suppliers or the adoption of local casting methods are key to maintaining the low-carbon profile of CSPs.

3.3. Construction Process Stage (A5)

Figure 5 presents the contribution of embodied carbon emissions from the construction stage (Module A5) for both systems, revealing a significant difference between CCRW and CSP in terms of both magnitude and the trend of increase. For CCRW, A5 emissions increased sharply as the wall height increased—from 10 kgCO₂e/m at a height of 1 m to over 40 kgCO₂e/m at 4 m. This increase was driven by the complexity of on-site construction activities, including excavation, formwork installation, and the casting and curing of reinforced concrete. As the height increased, these activities required more labour, equipment, and resources, thereby raising construction-stage emissions.

In contrast, the CSP system consistently recorded lower construction emissions (Module A5) across all heights, with values ranging from 3 kgCO₂e/m (1 m) to 15 kgCO₂e/m (4 m)—remaining below half the emissions of the CCRW system in any scenario. This performance is attributed to the relatively simple and rapid installation process for the precast piles. This process minimises on-site material handling, reduces equipment operating time, and shortens the overall construction duration compared to cast-in-place methods.

A comparison between CSP and CCRW highlights the importance of a comprehensive life-cycle assessment (A1–A5), as each system excels at different stages of the lifecycle. While CSP performs better during the construction stage (A5), it is disadvantaged in the transportation stage (A4); conversely, CCRW exhibits the opposite pattern. The high A5-stage emissions associated with CCRW also present opportunities for improvement through the use of modular formwork, efficient casting techniques and low-carbon equipment.

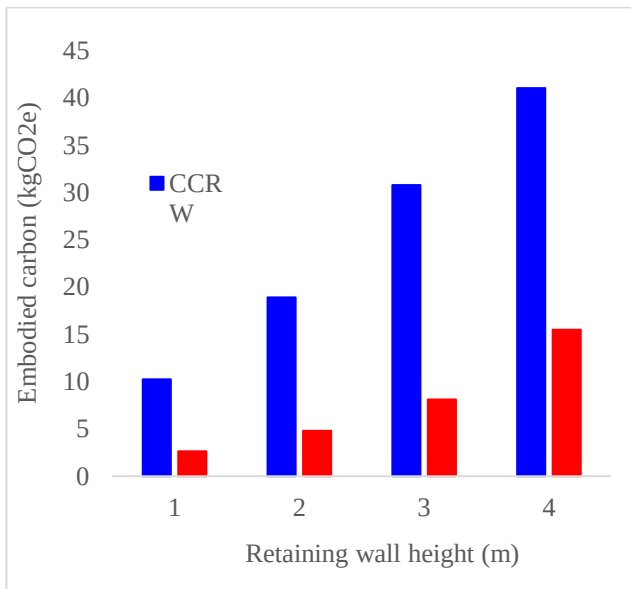


Fig. 5 Embodied carbon from construction process stage (A5)

3.4. All stages (A1–A5)

Figure 6 illustrates the total embodied carbon (A1–A5) for CCRW and CSP, confirming that CSP consistently has a higher carbon footprint at all heights. At low walls (1 m), CSP's total emissions (280 kgCO₂e/m) are already 20% higher than CCRW's (220 kgCO₂e/m). This gap widens with increasing height; at 4 m walls, CSP emissions jump to 1,550 kgCO₂e/m—nearly double that of CCRW (820 kgCO₂e/m) or equivalent to 90% higher than that of CCRW. This pattern confirms that CSP's weaknesses in the product and transportation stages become increasingly dominant in high-wall applications, outweighing its efficiency during the construction stage.

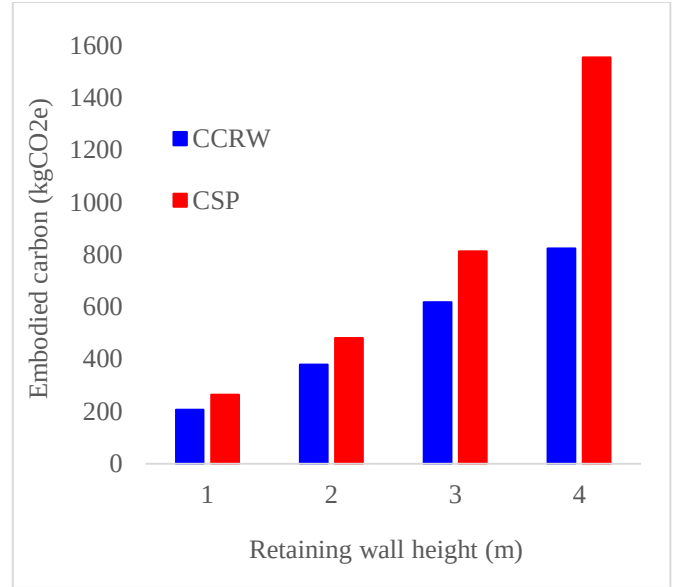


Fig. 6 Embodied carbon all stages (A1–A5)

The difference in total emissions between the two systems can be attributed to two main factors: (1) Higher product stage emissions (A1–A3) in CSP: The need for deeper embedment and higher section modulus in tall walls requires a greater volume of high-strength concrete, which significantly increases emissions, and (2) Significantly higher transportation emissions (A4) in CSP: CSP precast elements are transported from a centralised facility over a longer distance (300 km) than locally sourced cast-in-place concrete (CCRW). Although CSP has a superior construction emissions (A5) advantage owing to the efficiency of precast installation, this advantage does not offset the significant contribution of emissions from the product and transportation stages, particularly for taller walls.

Figure 7 illustrates the proportional breakdown of embodied carbon emissions at a height of 3 m, reinforcing the distinct dominance patterns observed in both systems' results. In CCRW, the product stage (A1–A3) dominated, contributing 93%, whereas transportation and construction contributed only 2% and 5%, respectively. This overwhelming dominance underscores the need for CCRW decarbonisation efforts to focus on material efficiency and the selection of low-carbon materials, as improvements in other stages will have only marginal impact.

In contrast, in CSP, although the product stage remains dominant (86%), the contribution of transportation increases significantly to 13%, which directly reflects the long-distance logistics burden of the precast elements. Interestingly, CSP construction emissions decreased to only 1%, demonstrating the efficiency of the on-site installation. However, this advantage does not offset the increase in transportation emissions. In other words, CSP incurs a high price for construction efficiency through high logistics burden.

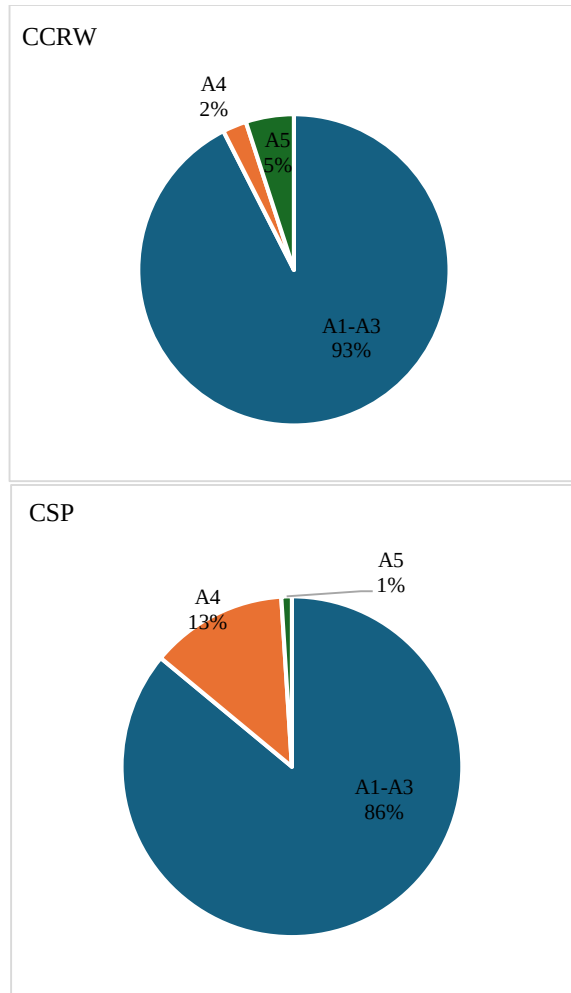


Fig. 7 Proportional contribution of embodied carbon by life cycle stage at H = 3 m

These findings convey an important message: no single decarbonisation strategy fits all systems in all contexts or regions. Although material emissions (A1–A3) dominate the total embodied carbon in both systems, the contribution of secondary stages, particularly transportation in CSP, is significant enough to shift the intervention priorities. For CCRW, where 93% of emissions originate from materials, improvement efforts should focus on design efficiency and the substitution of low-carbon materials. Conversely, CSP demands a more complex approach: in addition to optimising material selection, serious attention must be paid to supply chain logistics, including the proximity of production facilities to project sites. In other words, CCRW requires a deep decarbonisation strategy upstream, whereas CSP requires a supply chain optimisation strategy in the middle stream.

3.5. Sensitivity Analysis

To evaluate the robustness of the embodied carbon assessment, a sensitivity analysis was conducted by varying the key input parameters commonly associated with uncertainty in life cycle assessment studies. The concrete and

steel embodied carbon factors were varied by $\pm 20\%$, whereas the transportation distances were varied by $\pm 50\%$ to represent potential variations in material sourcing and supply chain logistics. The resulting changes in the total embodied carbon are summarised in Table 5.

The results indicate that the embodied carbon of both retaining wall systems is highly sensitive to variations in the concrete carbon factors. A $\pm 20\%$ change in the concrete emission factor resulted in changes of approximately $\pm 11\%$ and $\pm 14\%$ in the total embodied carbon of CCRW and CSP, respectively. The greater sensitivity observed in CSP can be attributed to its larger concrete volume and the use of higher-strength precast concrete, which contributed to more than 70% of product stage emissions. These findings suggest that adopting low-carbon concrete mixtures or supplementary cementitious materials could substantially reduce the embodied carbon of both systems, particularly CSP.

Table 5. Sensitivity analysis of key input parameters

Variable	Variation	Change in Total EC	
		CCRW	CSP
Concrete carbon factor	$\pm 20\%$	$\pm 11\%$	$\pm 14\%$
Steel carbon factor	$\pm 20\%$	$\pm 7\%$	$\pm 4\%$
Transport distance	$\pm 50\%$	$\pm 1\%$	$\pm 7\%$

In contrast, variations in the steel carbon factor produced relatively smaller changes in the total embodied carbon, amounting to approximately $\pm 7\%$ for CCRW and only $\pm 4\%$ for CSP, respectively. This indicates that, although reinforcement contributes significantly to overall emissions, the embodied carbon performance of the systems is primarily governed by concrete-related emissions.

Transportation distance exhibited the lowest influence on CCRW, causing only a $\pm 1\%$ variation in the total embodied carbon due to the relatively short transport distance assumed for cast-in-place concrete.

However, CSP demonstrated greater sensitivity, with the total embodied carbon varying by approximately $\pm 7\%$ under a $\pm 50\%$ change in the transport distance. This finding highlights the importance of supply chain optimisation and the selection of regional precast manufacturing facilities to minimise transportation-related emissions in CSP applications.

Overall, the sensitivity analysis confirmed that the principal conclusions of this study remained unchanged under all the considered scenarios, with CSP consistently exhibiting higher embodied carbon than CCRW. Therefore, the comparative findings presented in this study can be considered robust within the range of uncertainties investigated.

3.6. Study Limitations and Future Research Directions

Although this study presents a comprehensive comparison of the embodied carbon in CCRW and CSP systems, several limitations must be acknowledged. First, the analysis employed simplified geotechnical assumptions: homogeneous cohesionless soil, dry conditions, and no friction at the wall-soil interface. Under actual field conditions, variations in soil layers, groundwater conditions, and interface behaviour can significantly influence design requirements and material needs.

Second, this study employed fixed transportation distances—50 km for CCRW and 300 km for CSP—to represent typical conditions, although these values may vary depending on the project location and supply chain configuration. Sensitivity analysis indicated that transportation plays a crucial role, particularly for CSP, meaning that site-specific logistics factors could alter the comparative results.

Third, the embodied carbon assessment covers only Modules A1-A5 (cradle-to-site); consequently, end-of-life stages (Modules C and D: dismantling, recycling, and reuse) are excluded, even though these stages are significant for the precast systems. Furthermore, construction emissions (A5) were calculated using a cost-based approach, resulting in a lower level of certainty than detailed activity-based calculations.

Finally, this study examines only embodied carbon without addressing economic performance, construction duration, or constructability. However, the selection of a retaining wall involves various factors, including cost, site conditions, schedule, and environmental impact. For instance, although CSP generates higher emissions, its rapid installation and minimal site impact may make it a more advantageous choice for projects with limited access or tight schedules. Future research should broaden the scope of the analysis to include varying soil conditions, groundwater effects, and alternative systems such as Mechanically Stabilised Earth (MSE) walls or hybrid solutions. A comprehensive life-cycle assessment (Modules A1–D)-covering durability, maintenance, and potential for reuse-is necessary for a more complete evaluation. Furthermore, integrating life-cycle cost assessment with multi-objective optimisation could enable simultaneous reductions in carbon and costs, providing more practical guidance for designing low-carbon retaining structures.

4. Conclusion

This study compares the embodied carbon of CCRW and CSP systems with heights ranging from 1 to 4 m, covering all life-cycle stages (Modules A1–A5). The analysis results indicate that the total embodied carbon for both systems increases with wall height, primarily due to the greater material requirements needed to withstand higher lateral pressures. In terms of emission distribution, the CCRW system

exhibited a highly concentrated pattern, with the material production stage (Modules A1-A3) dominating the total contribution-exceeding 90%-while the transportation (A4) and construction (A5) stages contributed only marginally. In contrast, the CSP system recorded consistently higher total emissions across the entire range of heights analysed—with a disparity reaching nearly 90% for a 4-meter-high wall—and displayed an emission distribution that was far more dispersed across the life-cycle stages. Two factors explain this weakness of the CSP. First, product emissions increase sharply because tall walls require significantly larger volumes of high-strength precast concrete. Second, the heavy transportation burden (13% of total emissions) resulting from the 300 km distance from the centralised factory, in contrast to CCRW, which benefits from a local supply of only 50 km. As a result, while CSP excels in construction efficiency with A5 emissions of only 1%, this advantage is offset by the accumulation of emissions from upstream and midstream in the supply chain. These findings underscore the importance of holistic life-cycle assessment in evaluating the embodied carbon performance of retaining-wall systems.

For CCRWs, where emissions are concentrated in the product stage, decarbonisation strategies should focus on selecting low-carbon materials and optimising cross-sectional design as the two greatest opportunities for emission reduction. For CSPs, strategies to minimise transport distances or develop regional precast production facilities are essential to mitigate their elevated transportation impacts. Ultimately, early design decisions that integrate embodied carbon considerations can play a pivotal role in delivering more sustainable retaining structures without compromising sustainability.

Acknowledgements

The authors would like to thank the Karbonara Research Institute for all the assistance and resources provided during this study. Special appreciation is given to the Civil Engineering Department of BINUS University for their consistent mentoring and for providing the means and tools required to complete this study.

Conflict of Interest

The authors have no conflict of interest to declare

Ethical Approval

This study did not involve human participants, animal subjects, or confidential data, requiring ethical approval. All analyses were conducted with respect to academic integrity and ethical considerations. The authors affirm that the data presented are original and have not been manipulated or fabricated.

Funding Statement

This work was supported by Bina Nusantara University.

Author Contribution

RS prepared the manuscript, and AS, TA, and YS reviewed and revised the manuscript.

Data availability

The dataset and analysis are available at: <https://zenodo.org/records/15765850>

References

- [1] Ian Hamilton et al., “2022 Global Status Report for Buildings and Construction: Towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector,” United Nations Environment Programme, Global Alliance for Buildings and Construction, pp. 1-101, 2022. [[Google Scholar](#)] [[Publisher Link](#)]
- [2] “Global Status Report for Buildings and Construction,” United Nations Environment Programme, Global Alliance for Buildings and Construction, pp. 1-100, 2023. [[Publisher Link](#)]
- [3] Xiaocun Zhang, and Xueqi Zhang, “Design of Low-Carbon and Cost-Efficient Concrete Frame Buildings: A Hybrid Optimization Approach Based on Harmony Search,” *Journal of Asian Architecture and Building Engineering*, vol. 22, no. 4, pp. 2161-2174, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [4] Breakthrough Strategies for Climate-Neutral Industry in Europe: Policy and Technology Pathways for Raising EU Climate Ambition, Agora Energiewende and Wuppertal Institute, pp. 1-216, 2021. [Online]. Available: https://epub.wuppertalinst.org/frontdoor/deliver/index/docId/7751/file/7751_Climate-Neutral_Industry.pdf
- [5] Borja Izaola, Ortiz Akizu-Gardoki, and Xabat Oregi, “Setting Baselines of the Embodied, Operational and Whole Life Carbon Emissions of the Average Spanish Residential Building,” *Sustainable Production and Consumption*, vol. 40, pp. 252-264, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [6] M. Nabiyeu and A. Abobakirov, “Energy-Efficient Materials in Buildings and Structures: Technologies and Trends,” *Innovative Development in Educational Activities*, vol. 2, no. 23, pp. 43-48, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [7] Xiaonan Wang et al., “A Critical Review on Phase Change Materials (PCM) for Sustainable and Energy Efficient Building: Design, Characteristic, Performance and Application,” *Energy and Buildings*, vol. 260, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [8] O.P. Gibbon et al., *How to Calculate Embodied Carbon*, 2nd ed., The Institution of Structural Engineers, 2022. [[Google Scholar](#)] [[Publisher Link](#)]
- [9] Demi Fang et al., “Reducing Embodied Carbon in Structural Systems: A Review of Early-Stage Design Strategies,” *Journal of Building Engineering*, vol. 76, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [10] James Hunt, and Carlos A. Osorio-Sandoval, “Assessing Embodied Carbon in Structural Models: A Building Information Modelling-Based Approach,” *Buildings*, vol. 13, no. 7, pp. 1-15, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [11] Johanna Lehne, and Felix Preston, “Making Concrete Change: Innovation in Low-Carbon Cement and Concrete,” *Chatham House*, 2018. [[Google Scholar](#)] [[Publisher Link](#)]
- [12] Robbie M. Andrew, “Global CO₂ Emissions from Cement Production,” *Earth System Science Data*, vol. 10, no. 1, pp. 195-217, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [13] Chen Li et al., “CO₂ Emissions Due to Cement Manufacture,” *Materials Science Forum*, vol. 685, pp. 181-187, 2011. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [14] Anurag Sahare, GyuChan Choi, and Kyohei Ueda, “Role of Initial Static Shear on the Cyclic Response of Saturated Backfill Retained by a Sheet-Pile Wall: Insights from the Strain Space Multiple Mechanism Model,” *Soil Dynamics and Earthquake Engineering*, vol. 179, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [15] Yuan Cao et al., “Liquefaction and Fluidization Responses of Level Ground Retained by Sheet-Pile Wall through Centrifuge Model Tests,” *Soil Dynamics and Earthquake Engineering*, vol. 178, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [16] Ning Bao et al., “Experimental and Numerical Investigations of Seismic Behavior of Slopes Reinforced with Sheet Pile Walls: Role of Retaining Sheet,” *Engineering Geology*, vol. 354, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [17] Mohammad Khajehzadeh et al., “A Fuzzy Multi-Objective Enhanced Arithmetic Optimization Algorithm for Stochastic Design of Reinforced Concrete Cantilever Retaining Wall Using Unscented Transformation,” *Results in Engineering*, vol. 28, 2025. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [18] Kewei Fan et al., “Impact of Incorporating Waste Tire Rubber Particles into Granular Inclusion on Reducing Lateral Swelling Pressures of Expansive Soil Against Concrete Retaining Walls,” *Construction and Building Materials*, vol. 457, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [19] M.C. Caruso et al., “Methodology for Life-Cycle Sustainability Assessment of Building Structures,” *ACI Structural Journal*, vol. 114, no. 2, pp. 323-336, 2017. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [20] Alla Toktarova et al., “Pathways for Low-Carbon Transition of the Steel Industry—A Swedish Case Study,” *Energies*, vol. 13, no. 15, pp. 1-18, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [21] Zhiyuan Fan, and S. Julio Friedmann, “Low-Carbon Production of Iron and Steel: Technology Options, Economic Assessment, and Policy,” *Joule*, vol. 5, no. 4, pp. 829-862, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]

- [22] T. Demus et al., “Increasing the Sustainability of Steel Production in the Electric Arc Furnace by Substituting Fossil Coal with Biochar Agglomerates,” *Ironmaking & Steelmaking: Processes, Products and Applications*, vol. 43, no. 8, pp. 564-570, 2016. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [23] Qianqian Chen et al., “Assessment of Low-Carbon Iron and Steel Production with CO₂ Recycling and Utilization Technologies: A Case Study in China,” *Applied Energy*, vol. 220, pp. 192-207, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [24] Ali Abdulhussein Shubbar et al., “Future of Clay-Based Construction Materials – A Review,” *Construction and Building Materials*, vol. 210, pp. 172-187, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [25] Will Hawkins et al., “A Design Methodology to Reduce the Embodied Carbon of Concrete Buildings Using Thin-Shell Floors,” *Engineering Structures*, vol. 207, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [26] H.L. Gauch et al., “Carbon vs. Cost Option Mapping: A Tool for Improving Early-Stage Design Decisions,” *Automation in Construction*, vol. 136, pp. 1-18, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [27] Alper Kanyilmaz, Patricia Raquel Navarro Tichell, and Daniele Loiacono, “A Genetic Algorithm Tool for Conceptual Structural Design with Cost and Embodied Carbon Optimization,” *Engineering Applications of Artificial Intelligence*, vol. 112, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [28] Kareem Abushama et al., “Embodied Carbon Optimisation of Concrete Pile Foundations and Comparison of the Performance of Different Pile Geometries,” *Engineering Structures*, vol. 310, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [29] Eleni Georgiou et al., “The Significance of Measuring Embodied Carbon Dioxide Equivalent in Water Sector Infrastructure,” *Journal of Cleaner Production*, vol. 216, pp. 268-276, 2019. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [30] Harry G. Poulos, and Grahame Bunce, “Foundation Design for the Burj Dubai – the World’s Tallest Building,” *International Conference on Case Histories in Geotechnical Engineering*, vol. 14, pp. 1-17, 2008. [[Google Scholar](#)] [[Publisher Link](#)]
- [31] M.L. Berndt, “Influence of Concrete Mix Design on CO₂ Emissions for Large Wind Turbine Foundations,” *Renewable Energy*, vol. 83, pp. 608-614, 2015. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [32] BS 15978: 2011, *Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method*, British Standard Institution 2011. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [33] W.J. Macquorn Rankine, “On the Stability of Loose Earth,” *Philosophical Transactions Royal Society*, vol. 141, pp. 9-27, 1857. [[Google Scholar](#)] [[Publisher Link](#)]
- [34] “The Inventory of Carbon and Energy (The ICE Database),” *Global Alliance for Building and Construction*, 2020. [[Google Scholar](#)] [[Publisher Link](#)]