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Original Article

Comparative Assessment of Embodied Carbon and Construction Cost in Concrete and Geotextile-Reinforced Retaining Walls

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Abstract *- The construction industry is a significant contributor to global carbon emissions. Concrete retaining walls are particularly high in embodied carbon because of their cement and steel components. As a response to rising sustainability challenges, geotextile-reinforced Mechanically Stabilised Earth (MSE) walls have recently been gaining popularity. This study offers an embodied carbon and cost analysis comparison of traditional cast-in-place Concrete Retaining Walls (CRW) and geotextile-reinforced MSE walls. These wall varieties were designed and assessed at 2, 4, 6, and 8 m heights and were kept under similar design and stability constraints. The Life Cycle Assessment (LCA) emissions accounting followed BS EN 15978, which covers stages A1 to A5, and the cost assessment utilised unit cost rates from the Indonesian Ministry of Public Works. MSE walls use a fraction of the high-embodied-carbon materials necessary for concrete retaining walls and thus have 98% less embodied carbon and are more environmentally beneficial. While MSE walls are less expensive to build at the lower design heights, the costs rise at the higher design heights because of the more expensive reinforced earth construction and excavation necessary. A trade-off analysis highlighted that MSE walls perform best in sustainability for low to medium-height applications, while CRWs are still cost-effective for high structures. This indicates that considering carbon and financial costs for retaining walls would anchor the design for sustainability-focused cross-reasoning in civil infrastructure frameworks.*

Keywords *- Embodied Carbon, Retaining Wall Design, Mechanically Stabilised Earth Wall, Construction Cost Analysis, Life Cycle Assessment.*

1. Introduction

Retaining walls are an essential part of civil infrastructure for slope stabilisation and embankment support [1–3]. Cast-in-place Concrete Retaining Walls (CRWs), which include cantilever and gravity walls, are popular because of their structural reliability and well-established construction methods. Despite this, the high embodied carbon of these retaining walls, specifically cement and steel, poses a challenge to sustainability. Concrete is a highly versatile and abundant construction material.

However, concrete production, specifically Portland cement production, the primary ingredient in concrete, is responsible for 8% of global CO_2 emissions and growing [4–6]. Given CRWs oversized construction materials, they represent an opportunity to reduce embodied carbon in the construction industry, and more specifically, the construction industry to respond to the need for alternative building materials.

Geosynthetics, especially geotextiles, are used as reinforcing elements in Mechanically Stabilised Earth (MSE) constructions, stemming from development of synthetic polymer-based materials. Flexibility, durability, and low cost of geotextiles significantly enhance soil stability, and help reduce deformation, making geotextiles the preferred option for numerous geotechnical applications, including retaining walls, embankments, and slope stabilisation [7–11]. Their strong structural performance in stabilising soil-structure systems, together with the systems' effectiveness in soil-structure systems, are recorded in the geotechnical engineering literature[12–15].

The practical use of geotextile-reinforced MSE walls has proven effectiveness. Adoption of geotextile-reinforced systems has been implemented in Indonesia for large-scale infrastructure like Lake Tempe revitalisation. These case studies emphasise the adaptability of infrastructure development for MSE systems. The feasibility, speed of construction, and versatility in applications of MSE systems are critical to building infrastructure.

The positive attributes of geotextile-reinforced systems from a geotechnical viewpoint are unquestionable. Still, the environmental impacts of such systems, particularly the embodied carbon, remain unstudied. This is surprising considering how much GHGs the construction sector continues to emit. Geotechnical engineering is an area of construction that impacts the environment more than most people assume[16]. Geotechnical processes, being less visible than other construction activities, tend to make people less aware of their existence. Jefferis [17] mentioned that other disciplines, such as structural or architectural systems, overshadow geotechnical systems. Geotechnical methods, such as using geotextiles (which are low-carbon building materials), must be adopted to maximise geotechnical sustainability, as the geotechnical construction methods, such as landfilling and soil stabilisation, create long-lasting and substantial impacts on land use, material consumption, and the environment. This is essential for achieving holistic sustainability in the built environment [18–20].

Over the last few decades, the sustainability of retaining structures has become a focus of research, particularly the application of Life Cycle Assessments (LCA) to measure the environmental performance of these structures. Zastrow et al. [21] conducted a parametric LCA on 30 cost-optimized configurations for earth-retaining walls where they varied the height of the walls and the pressure of the soil to study the environmental impacts of retaining walls. His results highlighted the impact of design on the overall sustainability of retaining structures. In the same line, Pons et al. [22] also worked on the 1-6 meter height range walls, where they compared the cantilever, gravity, masonry, and gabion walls, determining which options had the best structural and environmental performance. This was also in line with the work of Junior et al. [23], where they performed a qualitative and quantitative analysis of multiple retaining walls for an LCA. He made an important contribution by demonstrating that geosynthetic-reinforced Mechanically Stabilised Earth (MSE) walls, in the right geotechnical conditions, use much less concrete than traditional reinforced concrete walls, which greatly reduces the embodied carbon.

Expanding on this, Heerten [24] pointed out that using polymeric geosynthetics in MSE systems in place of metallic reinforcements has a much lower environmental impact. These points coincide with Stucki et al.'s review[25], which synthesised LCA that applied to earth-retaining structures. MSE systems were identified as environmentally favourable, especially when geosynthetics were used as reinforcement. This was further validated by Rafalko et al. [26], who indicated that geosynthetic-reinforced MSE walls emit slightly lower life-cycle emissions than the metal-reinforced alternatives.

While many researchers have already studied the environmental performance of various retaining wall systems, only a handful of studies have compared geotextile-reinforced Mechanically Stabilised Earth (MSE) walls to conventional concrete retaining walls under the same design conditions. Much of the research to date has focused on these systems in isolation, which results in a limited ability to draw meaningful, actionable conclusions. Moreover, the overwhelming focus has been on the environmental aspect, with little research also considering the much-needed economic perspective, such as construction cost, which must be looked at in value decision-making for an infrastructure project. This raises the necessity for more literature in this area that provides a more balanced approach to compare these wall types, incorporating environmental and economic dimensions alongside other associated design principles with the same applied loads.

As a part of the gap, this study carried out a comparative approach to analyze concrete Cantilever Retaining Walls (CRWs) versus geotextile-reinforced MSE walls in terms of embodied carbon and construction cost. For a balanced comparison, both systems were designed to sustain the same loading and height conditions. For the economic evaluation of the project, the analysis employed a unit cost-based approach, wherein the cradle-to-gate life cycle assessment served for the environmental impact analysis.

This study aims to assist engineers, planners, and decision-makers address the most environmentally and economically viable options for retaining walls. The study findings are primarily based on quantitative analysis under uniform design conditions to ensure practical selection of retaining structures that comply with desired sustainability and cost targets, informing design processes, supply chain management, and public policy on low-carbon economic development.

2. Methodology

This research adopted a comparison approach to evaluate the environmental and economic impacts of two different systems of retaining walls - a cast-in-place concrete Cantilever Retaining Wall (CRW) and a geotextile-reinforced Mechanically Stabilized Earth (MSE) wall. To ensure a fair comparison, both walls were configured to retain the same soil height and were designed to be under the same loading and geotechnical conditions.

2.1. Reinforced Earth Wall Stability

This research compares the economic and environmental performances of two wall systems: a cast-in-place Concrete Retaining Wall (CRW) and a geotextile-reinforced Mechanically Stabilised Earth (MSE) wall. Figure 1 outlines the geometrical configurations and design layouts used in the analysis for both systems.

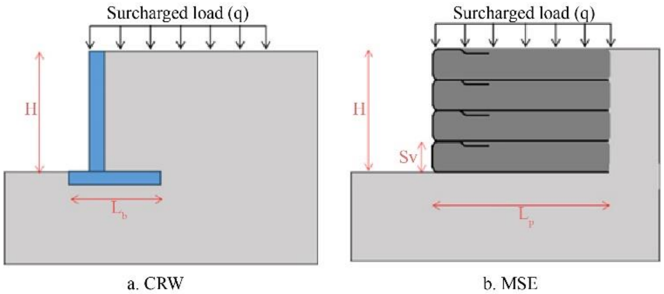


Fig. 1 Typical configurations of CRW and MSE wall

Assuming the soil had zero cohesion, was cohesionless, had an internal friction angle (ϕ) of 35°, and a unit weight of 18 kN/m^3, they used well-compacted and granular fill. To address different practical situations, the height of the retaining wall (H) was set to 2, 4, 6, and 8 m across four cases. To simulate operational conditions like vehicular traffic, stored materials, and bordering structures, an external uniform surcharge load of 10 kN/m^2 was applied over the entire backfill surface.

For the CRW system, the wall was built using standard-weight concrete having a unit weight of 24 kN/m^3 and a characteristic compressive strength (f'_c) of 20 MPa. The reinforcing steel is considered Grade BjTS 420A, having 420 MPa yield strength (f_y) [27], which aligns with the usual construction practices. The base width (Lb) was taken in line with standard practices to provide sufficient stability against sliding, overturning, and bearing pressure.

Table 1. Summary of stability equations and parameters for CRW and MSE wall systems

Stability check	CRW	MSE
Sliding	$\dfrac{\mu \sum W}{\frac{1}{2}K_a\gamma H^2 + K_a qH}$	$\dfrac{LH\gamma \tan\varphi}{0.5H^2\gamma K_a + qHK_a}$
Overturning	$\dfrac{W_c x_c + W_b x_b + (qB)x_q}{P_a \frac{H}{3}}$	$\dfrac{0.5\gamma HL^2}{0.5P_qH + \frac{1}{3}P_sH}$
Bearing capacity	$\dfrac{\sigma_u}{\sigma}$	$\dfrac{\sigma_u}{\sigma}$
Internal Stability – Rupture	NA	$\dfrac{T_a}{K_a\sigma_v S_v}$
Internal Stability – Pullout	NA	$\dfrac{2\mu\sigma_v L_p}{K_a\sigma_v S_v}$
W is the combined weight of the facing and reinforced soil block μ is the base-soil friction coefficient Pa is the horizontal earth thrust L is the reinforcement length of the MSE wall H is the wall height γ is the unit weight of soil ϕ is the foundation soil's internal friction angle Ka is the Rankine active earth pressure coefficient q is the uniform surcharge load Wc and Wb are the weights of the concrete and backfill of the CRW system, respectively B is the CRW system's basic width xc, xb, and xq are the respective moment arms from the toe of the CRW system Pq and Ps are the lateral forces from the surcharge and soil pressure, respectively σu is the ultimate bearing capacity σ is the applied vertical stress Ta is the geotextile's permissible tensile strength. Sv is the vertical distance between reinforcing layers Lp is the length of reinforcement implanted past the possible failure surface		

A commercially available woven geotextile commonly used in reinforced soil structures was used as soil reinforcement for the MSE wall. The geotextile has a tensile strength of 45 kN/m, and the reinforcement is constructed in horizontal layers with a vertical spacing (S_v) of 0.5 -1 m relative to the wall height. The reinforcement length (L_p) was taken in line with standard practices to provide external and internal stability. The geotextile was chosen with expected typical infrastructure values, assuming geotextile strength for reinforced soil structures is used with high enough sustained loads and adverse environmental conditions. Although this study did not consider a detailed time-dependent analysis (e.g., creep or chemical degradation), the chosen material is typical of geotextiles used in constructed permanent retaining wall structures. The basic reasoning used in the assumptions is in accordance with design practice. However, the consideration of more complex geotextile behaviour, such as long-term durability, creep reduction, along with installation damage, and the rest of the geotextile interactions, may be relevant for future studies, particularly for taller or crucial structures.

In order to make a technically correct as well as structurally equivalent comparison, the CRW and the MSE walls were both examined for the stability of the retained earth walls under the specified loading conditions. For the CRW, stability against sliding, overturning, and bearing capacity was evaluated per the standard design regulation described in the Indonesian Standard SNI 8460-2017 [28]. The wall dimensions were modified until a sliding safety factor of at least 1.5 was achieved, and 2.0 for overturning, and to ensure the bearing pressure of the foundation soil was not exceeded, along with the determined bearing values. For the MSE wall, more complex evaluations on external and internal stability provided the basis for the comprehensive stability assessment. The geotextile layers were designed to resist the calculated tensile forces with an adequate safety factor, and the reinforcement length was set to ensure sufficient anchorage beyond the failure surface. All designs were verified to meet or exceed the minimum required safety factors, ensuring that both systems provided reliable performance under identical loading and geometric conditions. A summary of the key equations used for the stability evaluation of both wall systems is presented in Table 1.

2.2. Embodied Carbon Assessment

The assessment of the environmental performance of construction systems according to BS EN 15978 [29] takes into consideration all life cycle stages, which consist of the product (A1–A3), construction process (A4–A5), use (B), and end-of-life (C) phases. This study considers the embodied carbon during the product stage (A1–A3) and the construction process stage (A4–A5), which is shown in Figure 2.

To derive the embodied carbon for the product stage ($EC_{A1\text{-}A3}$), the following approach was applied:

$$EC_{A1-A3} = \sum Q_i \times CF_{A1-A3} \qquad (1)$$

Where Q_i represents the cradle-to-gate emissions per unit of material. The carbon factors for this study were sourced from renowned resources such as Environmental Product Declarations (EPDs) and the Inventory of Carbon and Energy (ICE v3.0) developed by Hammond and Jones [30]. Table 2 provides a summary of the carbon factors for different construction materials that were used for the analysis.

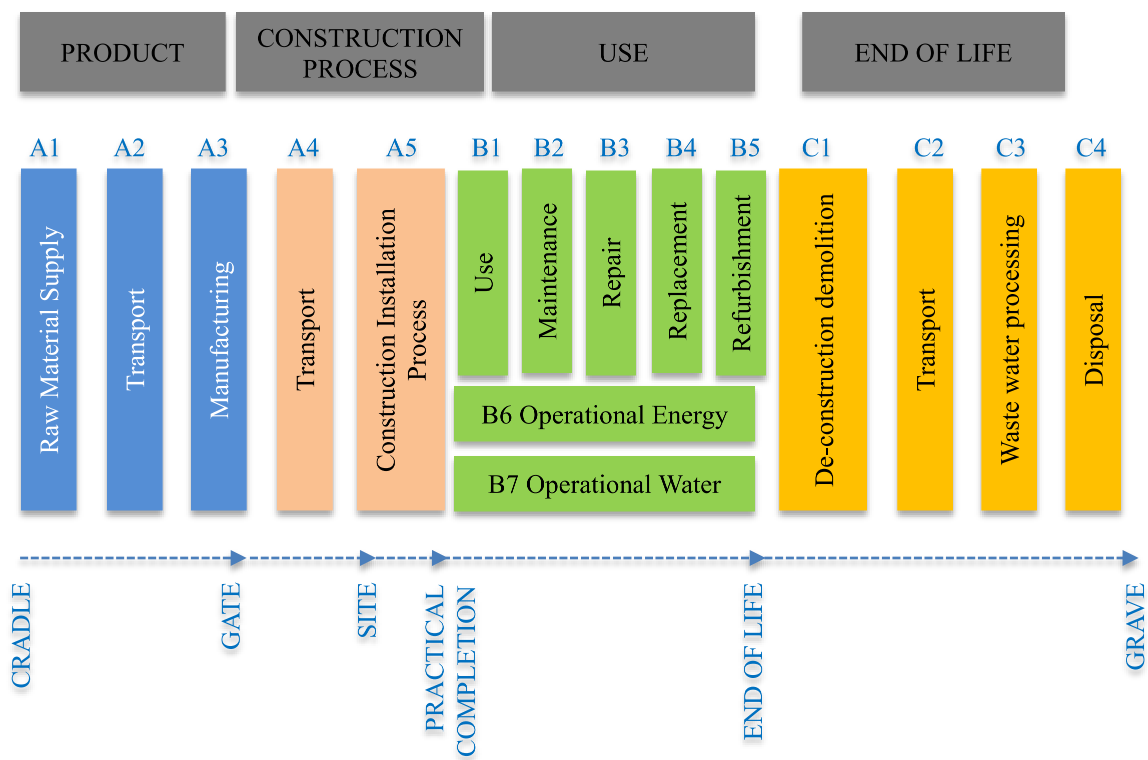


Fig. 2 Life cycle stages

Table 2. Various materials' Carbon Factors (CF)

Material	Carbon factor
Concrete grade fc' 20 MPa	267 $kgCO_2e/m^3$
Rebar	1.9 $kgCO_2e/kg$
Geotextile	0.274 $kgCO_2e/m^2$

In assessing embodied carbon for the transportation stage (EC_{A4}), the following equations were used:

$$EC_{A4} = \sum Q_i \times CF_{A4} \quad (2)$$

Where CF_{A4} represents the carbon factor for transport to the site. For this research, different supply chain assumptions were used for each wall type to reflect realistic supply chain scenarios. For the CRW system, construction materials were assumed to be sourced locally, resulting in the lower transport emission factor of 0.005 $kgCO_2e/kg$ [31].

However, for the MSE wall, the geotextile reinforcement was assumed to be imported globally, which led to a much higher transport carbon factor of 0.183 $kgCO_2e/kg$ [31]. These values were applied and kept consistent with material quantities in order to determine the transportation-related embodied carbon for each system.

For embodied carbon attributed to construction (EC_{A5}), two aspects were studied: emissions related to waste (EC_{A5w}) and emissions related to construction activities (EC_{A5a}). These are the emissions from the waste:

$$EC_{A5w} = \sum Q_i \times CF_{A5w} \quad (3)$$

$$CF_{A5w} = WF_i \times (CF_{A1-A3} + CF_{A4}) \quad (4)$$

$$WF_i = \frac{1}{1-WR_i} - 1 \quad (5)$$

Where WF_i corresponds to a waste factor, and WR_i is the waste rate of material. For construction activity emissions:

$$EC_{A5a} = CAEF \times \frac{PC}{100{,}000} \quad (6)$$

CAEF is the construction activity emissions factor, which is set to 700 $kgCO_2e$ for every £100,000 of the project cost[32], and PC is the project cost.

This methodology accounted for the impact of material construction and on-site construction for a complete evaluation of the embodied carbon emissions for the early life cycle phases (A1–A5).

2.3. Cost Estimation

For each retaining wall configuration, a cost analysis of construction economic performance was done, determining the total initial cost resulting from material and on-site construction. In line with standard engineering practices in Indonesia, a unit-cost-based method was used, which is also what the industry in Indonesia uses.

The total construction cost was calculated as follows:

$$Cost = \sum Q_i UP_i \quad (7)$$

UP_i is the unit price of material *i* obtained from the regional construction cost database released by the Indonesian Ministry of Public Works, ensuring compliance with government-regulated prices and market conditions. The cost estimation includes major construction components such as,

- Concrete and reinforcement for CRW,
- Geotextile, cut and compacted fill works for MSE walls

For easier comparison, all values were standardised per meter of wall length. The unit prices used in this work are summarised in Table 3.

Table 3. Unit prices of materials used in cost analysis

Material	Unit price (US$)
Concrete grade fc' 20 MPa	US$ 51.5/m^3
Rebar	US$ 1.51/kg
Geotextile	US$ 3.03/m^2
Cut and fill works	US$ 9.1/m^3

3. Results and Discussion

This research outlines a comparative analysis of two different types of wall systems: cast-in-place Concrete Retaining Walls (CRW) and geotextile-reinforced Mechanically Stabilised Earth (MSE) walls for different heights (2, 4, 6, and 8 m).

The aim of the study was to measure the performance of each wall system for different heights and evaluate the impact of the systems on the environment (embodied carbon, $kgCO_2e$) and the economic viability (in US$). The results were normalised and are reported per meter length of the wall for direct and consistent comparison of the two systems, independent of height or configuration.

Embodied carbon of the CRW and MSE walls illustrates the difference between the two walls using different wall heights. Figure 3 illustrates this difference. MSE walls have consistently lower values than CRW walls. CRW walls that were 2 m tall emitted 308 $kgCO_2e$ while 2 m tall MSE walls emitted 5 kgCO2e, which is a 98% reduction.

This reduction trend continued at other heights 4 me tall CRW walls emitted 598 $kgCO_2e$, while MSE walls just emitted 13 $kgCO_2e$. At 6 m tall walls, CRW walls emitted 881 $kgCO_2e$ while MSE emitted 32 $kgCO_2e$. At 8 m tall walls, CRW walls emitted 1180 $kgCO_2e$ while MSE walls emitted 62 $kgCO_2e$.

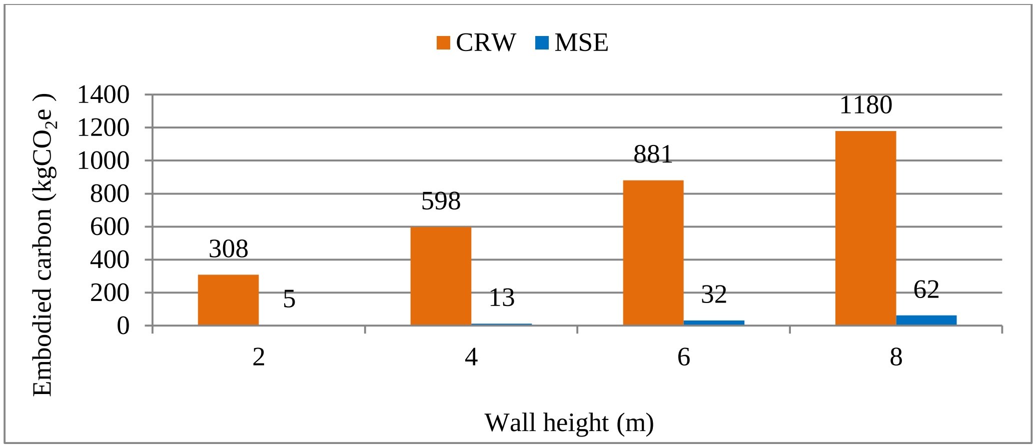
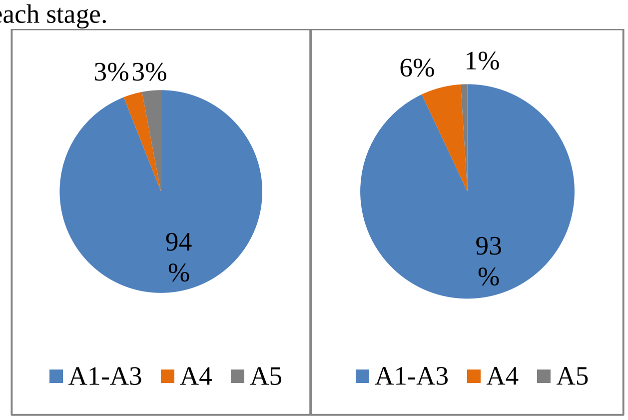


Fig. 3 Embodied carbon for CRW and MSE wall

This increase of CRW emissions with height is due to the concrete and steel used during construction growing in a quadratic manner with height. The higher the walls, the more structural concrete and reinforcing steel must be added to the walls for stability, especially for overturning and sliding stability. For contrast, the MSE wall is built mainly using compacted backfill soil and thin layers of geotextiles, so they add very little to the embodied carbon. These are especially true for taller applications because MSE walls are primarily made of materials with very low embodied carbon. These results show that replacing materials and using local soil with low-carbon materials and MSE walls, geotextiles can effectively lower the carbon footprint of construction.

To better assess the environmental profile of each retaining wall system, the embodied carbon was broken down into three components in the system's three stages of the life cycle: materials production (A1–A3), transportation to the site (A4), and construction process (A5). These results are depicted in Figure 4, which illustrates the contribution of each stage.



(a) RCW **(b) MSE**

Fig. 4 Percentage contribution of life cycle stages to total embodied carbon

For CRW, most of the embodied carbon (94 %) came from the production stage (A1–A3). This large proportion was likely due to the reliance on heavily carbon-emitting materials such as Portland cement and steel reinforcing, both of which have high embodied emissions per unit mass. In contrast, transportation (A4) and construction activities (A5) contributed equally and modestly, at 3% of total embodied carbon each. This aligns with the localised sourcing assumptions and typical construction practices for concrete wall construction. For the MSE wall, the production stage (A1–A3) also dominated the embodied carbon profile, with a 93% contribution. However, a comparatively larger portion (6%) was attributed to the transportation stage (A4), while construction activities (A5) only contributed 1%. The higher transportation emissions for the MSE system came from the distant shipping of geotextile reinforcement, which was assumed to be globally sourced in this study.

Nevertheless, the overall embodied carbon values for MSE were still significantly lower than those for CRW, as previously discussed. These findings indicate that while the A1–A3 stage is the most significant contributor to embodied carbon for both systems, transportation emissions may take on greater importance when there is the use of imported lightweight materials, especially for lightweight systems, like MSE walls. Hence, for geosynthetically reinforced retaining walls, reducing transport distance or sourcing geotextiles locally may further improve the sustainability benefits.

Figure 5 illustrates the cost differences in constructing CRW and MSE walls of varying heights. The results depict a clear pattern: while MSE walls are cheaper in cost for shorter wall heights, this cost advantage increases and then reverses when the wall heights are greater. The 2 m MSE wall, for example, costs 66 US$ compared to 113 US$ for the CRW, a 42% reduction. MSE walls continued to be more cost-efficient at 4 m (169 US$ versus 220 US$); however, the cost advantage continued to narrow. Beyond 6 m, the cost of the MSE wall surpasses the CRW wall, and the difference increases at 8 m, where the MSE wall is 651 US$ per meter, compared to 434 US$ for the CRW.

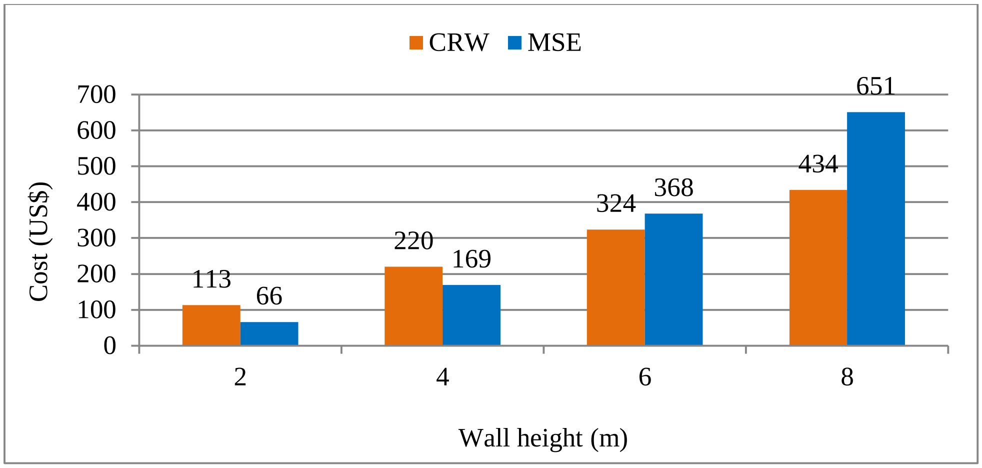


Fig. 5 Cost for CRW and MSE wall

The rising costs can be explained by how much of cut-and-fill work there is for MSE walls. Higher walls need more cut-and-fill work for the walls to be stable. This means more work has to be done to control the costs. Higher MSE walls also need more compaction, more layers of reinforcement, more geotextiles, and more tightening of the impaction, which raises the costs even more. Embankment CRWs, on the other hand, do use more construction material, but all told, the increase in the volume of concrete and the material for reinforcements, and the material used in the walls is much less than for the CRWs. Because of the vertical shape of CRWs, it is easy to place them in urban environments.

The results revealed differences with regard to costs, carbon, and height, considerable differences. For all heights, even by 90%, the geotextile reinforced MSE walls sustained less embodied carbon than the cast-in-place concrete CRW walls. However, the economic performance of the CRW has deteriorated in the taller walls (6 and 8 m to the MSE walls), and the CRW becomes economically favourable for high walls due to limited land. For the MSE walls, MSE saved considerable carbon; however, it economically has a trade-off due to the high costs of excavation, backfilling, reinforced length, and compaction in the taller wall applications. The CRW has reinforced carbon due to cement and steel, and for CRW, high walls economically will be favourable with limited land and low cut and fill volumes.

This research has two implications for design practice. One, MSE walls would probably provide the greatest cost and carbon savings for low to medium height applications. Two, for taller walls, because of site and regional conditions, the most cost effective choice may not be the most carbon-friendly. This is because the most environmentally friendly option is likely to be MSE walls, which may not be economically viable given some site conditions. These findings highlight the importance of conducting carbon and cost life cycle analysis in the early design stages to inform the choice of materials and wall systems. This is particularly important in civil infrastructure projects where net-zero and carbon reduction targets are in place.

There are also geotextile-reinforced MSE walls, which offer long-term savings that may not be accounted for in the initial cost. Because of the geotextile materials, walls may offer savings over service life because they require maintenance and are corrosion-resistant. Their flexible structure helps cope with differentials and may help with soft soils. Geotextiles pose risks and may require aggressive design and drainage under geotechnical soils. CRWs are space-efficient for long-term performance in urban settings and offer efficient carbon performance. Future research would be more helpful if it integrated life cycle cost analysis that looked at trade-offs beyond construction costs.

The findings on embodied carbon are strong because there is a significant difference between the systems. At the same time, the cost comparisons are more sensitive, particularly at lower heights where these differences are minimal. Local material costs, construction methods, and differences in priced labour may explain the variability in these conclusions. For this reason, while the embodied carbon findings are robust and do not require sensitivity analysis, future work should focus on construction costs using sensitivity or probabilistic approaches to provide more realistic economic analyses within the expected ranges of various conditions.

4. Conclusion

The analysis for this study was based on the embodied carbon and construction costs of two types of retaining walls: geotextile-reinforced Mechanically Stabilized Earth (MSE) walls and cast-in-place Concrete Retaining Walls (CRW). A uniform design, stability criteria, Life Cycle Assessment (LCA) based on BS EN 15978 (A1–A5 stages), and standard design principles were used for walls of 2, 4, 6, and 8 m heights.

The MSE wall systems had distinct environmental benefits. For every wall height, MSE wall systems had 90–98% less embodied carbon than CRW. This is because MSE walls use compacted infill and polymeric geotextiles instead of concrete and steel, which are high-carbon materials. While the MSE wall systems had higher transportation emissions because of imported materials, these emissions were still low overall.

The findings associated with costs were more mixed. For the lower wall heights (2 and 4 m), the MSE wall systems were more cost-effective than CRWs. However, the cost of MSE walls continued to increase as wall height increased because of the additional excavation, backfill, and reinforcement needed, eventually exceeding the cost of CRWs. With an 8 m height, the MSE wall cost was roughly 50% more than the CRW wall, which is substantially lower in carbon.

Due to the environmental and economic advantages MSE walls provide, the carbon–cost trade-off analysis suggested them for low to medium height applications. As the walls get taller, the designer will have to make trade-offs regarding the bottom line, since MSE walls have the best carbon balances but are the most expensive option. On the other hand, CRWs are carbon-intensive, but they are the most cost-efficient option. They are also space-efficient, which benefits constrained and urban areas.

Sustainability in the context of the CRW and MSE wall systems also focuses on life-cycle environmental aspects, not only the structure and economic aspects. This emphasises the need for infrastructure design to have an integrated approach of combined carbon reduction and sustainability. This approach should provide a basis for future research on life-cycle performance, which could incorporate behavioural use phases, durability, and end-of-life aspects.

In the case of developing countries, the use of geotextile-reinforced systems can play an important socioeconomic role. MSE walls can allow the use of local fill material, limit the use of concrete, save energy and capital, and allow more labour-intensive construction, which can foster local job creation and skill development. Nevertheless, the lack of use may be due to limited awareness, inadequate legislation in place, and expending effort on construction without the necessary quality control. Education and training, and ensuring policy coherence, will be essential to capture the full sustainable potential of geosynthetics in many situations.

There are several contributions this study makes, but it also has limitations. The analysis only considered the cradle-to-gate stages (A1–A5). It did not include the use phase, performance, durability, and end-of-life, which may be important for assessing long-term sustainability and may be important for the study. Also, the significant differential between systems accounts for the robust results on embodied carbon, but the cost analysis is influenced more by local market conditions, labour rates, and construction practices. Future work should include complete life cycle assessments, probabilistic cost modelling, and field performance data for the study to validate and improve it.

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Author Contribution

RS-manuscript preparation, AS-manuscript review, MK-data collection, MA-manuscript review.

Data availability

Data analysis https://zenodo.org/records/16735068

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