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Original Article

Optimising Geotextile-Reinforced Earth Wall Design for Embodied Carbon Reduction

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Abstract *- The construction industry is facing increasing pressure to reduce its environmental footprint, particularly in terms of embodied carbon emissions. Although geotextile-reinforced earth walls are widely used owing to their structural and economic advantages, their environmental performance remains underexplored. This study aimed to investigate the optimum design of geotextile-reinforced earth walls by evaluating the interplay between structural stability and embodied carbon. A series of wall configurations with varying heights (2-10 m) and geotextile types were analyzed using the limit equilibrium method under static loading conditions to ensure compliance with global and internal stability criteria. Embodied carbon was assessed using a cradle-to-gate life cycle approach (Modules A1-A3) with emission factors derived from Environmental Product Declarations. The results show that the reinforcement length increases with the wall height but is largely unaffected by the geotextile strength. In contrast, the vertical spacing is significantly influenced by the tensile capacity. At lower wall heights (≤ 6 m), low-strength geotextiles (LF 35) yielded the lowest embodied carbon. In contrast, for taller walls (≥ 8 m), higher-strength geotextiles (LF 46 and LF 57) performed more efficiently because of reduced material use. Among all alternatives, LF 46 offers a balanced solution across a range of heights. This study highlights the importance of integrating structural design with environmental assessment to support the development of low-carbon geotechnical infrastructures.*

Keywords *- Embodied Carbon, Geotextile-Reinforced Earth Wall, Life Cycle Assessment (LCA), Sustainable Geotechnical Design.*

1. Introduction

1.1. Background

Reinforced earth walls have emerged as a key innovation in geotechnical engineering, integrating compacted soil with tensile reinforcement to enhance the structural stability and load-bearing capacity [1-3]. These systems typically consist of engineered fill reinforced with multiple horizontal layers of reinforcement materials, which are placed between the soil lifts and anchored to the wall face.

The development and widespread adoption of synthetic polymer-based materials have led to the extensive use of geosynthetics, particularly geotextiles, in Mechanically Stabilized Earth (MSE) structures.

Geotextiles offer a durable, flexible, and cost-effective solution for improving soil strength, controlling deformation, and enhancing the overall performance. Their advantageous properties make them highly suitable for a wide range of applications, including retaining walls, embankments, and slope stabilization [4-8].

1.2. Literature Review

Geotextile reinforcement has proven to be highly effective in enhancing slope and earth wall stability across a wide range of geotechnical applications. Research indicates that including multiple geotextile layers can substantially improve stability, with the safety factor increasing from 3.437 to 9.978 depending on the configuration [9]. The reinforcement's effectiveness depends on the material used and its placement. For example, arranging geotextile layers optimally can achieve similar safety performance while cutting material use by up to 14% [10].

Additional tools, like stability charts, have been created to quickly assess stacked geotextile tube systems, providing practical guidance for early design [11]. Numerical studies show that axial forces in geotextile layers change significantly with slope angle, with the highest forces usually found in near-vertical slopes [12]. Key factors that affect reinforced slope performance include soil cohesion, internal friction angle, spacing of reinforcements, embedded length, and tensile strength [10]. These results emphasize the significance of reinforcement configuration and material choice in improving both structural performance and resource efficiency in geotextile-reinforced systems.

While the structural benefits of geotextile-reinforced systems are well known in geotechnical literature, their environmental effects, especially concerning embodied carbon, have not received much attention. The construction industry significantly contributes to Global Greenhouse Gas (GHG) emissions, creating a big opportunity to improve sustainability in this sector [13-15]. However, the environmental impact of geotechnical engineering, a key part of construction, is often overlooked [16]. Jefferis [17] suggested that this oversight may come from the nature of geotechnical processes, which are usually less visible than those in structural or architectural fields. Geotechnical activities greatly affect land use, resource consumption, and long-term environmental results. Therefore, improving the sustainability of geotechnical practices is crucial for achieving overall sustainable development in the built environment [18-20].

Over the past few decades, there has been a growing amount of research on the sustainability of retaining structures, with many studies using Life Cycle Assessment (LCA) to assess the environmental performance of these structures. A parametric Life Cycle Assessment (LCA) of 30 cost-optimized earth-retaining wall configurations was carried out by Zastrow et al. [21], taking into account differences in wall height (4-13 m) and permissible soil pressure (0.2-0.4 MPa). The environmental impact of popular retaining wall types, such as cantilever, gravity, masonry, and gabion walls, over a height range of 1-6 m was also evaluated by Pons et al. [22] using life Cycle Assessment (LCA). By determining the most sustainable wall types based on structural and environmental criteria, their study sought to offer design guidance. Junior et al. [23] compared different retaining wall systems using quantitative and qualitative LCA in a different study. Their research revealed that, compared to traditional concrete Earth-Retaining Walls (ERWs), geosynthetic-reinforced Mechanically Stabilized Earth (MSE) walls require significantly less concrete but more soil, underscoring the environmental advantages of geosynthetic reinforcement in appropriate situations.

According to Heerten [24], Mechanically Stabilized Earth (MSE) structures reinforced with geosynthetic materials have substantially less of an adverse environmental impact than those reinforced with metallic elements. In support of this, Stucki et al. [25] offered a thorough analysis of Life Cycle Assessment (LCA) techniques and how they are used to assess the environmental performance of common earth-retaining structures, such as MSE walls. In the same direction, geosynthetic-reinforced MSE systems showed marginally less environmental impact than their metal-reinforced counterparts, according to Rafalko et al. [26]. All of these studies point to the possibility that MSEs with geosynthetics could be a more environmentally friendly option than traditional earth-retaining walls, especially when evaluated in terms of life-cycle performance and embodied carbon.

1.3. Research Gap and Objective

Although many studies have used Life Cycle Assessment (LCA) to look at the environmental effects of different retaining wall systems, most have concentrated on comparing general wall types or material options. They have not examined the optimization of geosynthetic reinforcement itself. It is well known that geosynthetics have lower embodied carbon than metal reinforcements. However, few studies have systematically investigated the influence of geotextile design factors on both the structural performance and embodied carbon. Furthermore, the potential of optimizing geotextile-reinforced earth walls to find a balance between stability and environmental sustainability has not been fully explored.

This study aims to fill this gap by investigating the application of geotextile reinforcement in earth-wall systems from a sustainability perspective. Unlike previous studies that have primarily compared different wall types or reinforcement materials, this research introduces a performance-based optimization approach that evaluates how specific reinforcement configurations influence both mechanical stability and cradle-to-gate embodied carbon. By examining the interactions between wall height, reinforcement layout, and geotextile type, the study provides new insights into the trade-offs between structural demands and carbon efficiency, an area that has received limited attention in the current geotechnical literature. The primary objective is to identify the optimal reinforcement configurations that ensure geotechnical stability while minimizing the embodied carbon. Through numerical analysis and life cycle assessment, this study sought to establish a practical framework for designing geotextile-reinforced earth walls that support low-carbon development in the construction industry.

2. Methodology

This study investigated a geotextile-reinforced earth-wall system's performance and environmental impact, as illustrated in Figure 1. The wall consisted of multiple horizontal geotextile layers embedded between the lifts of the compacted backfill soil. The analysis considered two distinct soil zones: foundation and backfill. Both soils were assigned a unit weight of 18 kN/m³, representing typical values for medium-dense granular material. The foundation soil is characterized by a cohesion value of 20 kN/m² and an internal friction angle of 35°, indicating a cohesive-frictional soil that provides adequate bearing capacity and anchorage for the reinforcement. In contrast, the backfill soil is modelled as a cohesionless material with zero cohesion and an internal friction angle of 35°, which is consistent with the well-compacted granular fill commonly used in reinforced earth structures. In addition to the self-weight of the wall and retained soil, an external uniform surcharge of 10 kN/m² was applied across the full horizontal extent of the backfill surface to simulate operational loads such as traffic, storage, or adjacent structural loads. These parameters were adopted to ensure realistic modelling of the mechanical behaviour of the earth wall system under static conditions.

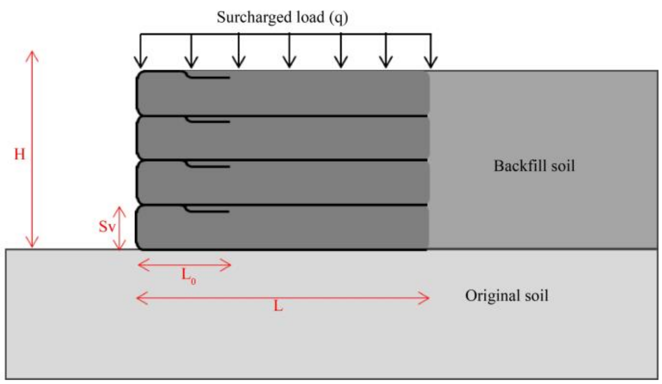

Fig. 1 Earth wall configuration

To cover a range of common retaining wall applications, the height of the geotextile-reinforced earth wall (H) in this study was varied from 2 m to 10 m. For each wall height, we adjusted the design of the reinforcement system. This included the vertical spacing between the geotextile layers (S_v) and the length of the reinforcement (L) to meet stability needs. We optimized the geotextile layout to ensure the factor of safety against failure is at least the minimum acceptable value, usually determined by limit equilibrium analysis. The analysis looked at both internal and external stability mechanisms, such as sliding, overturning, and tensile rupture or pullout of the reinforcement.

The geotextile used in this study was a commercially available woven geotextile product commonly used in reinforced soil applications. Three different types of geotextile reinforcement were considered, each with varying tensile strengths and areal weights, to assess their influence on both stability and embodied carbon performance. The specifications of these geotextiles are listed in Table 1.

Table 1. Woven geotextile types used in this study

Type	Weight (w)	Tensile strength (T_a)
Terralys LF 35	137 g/m^2	35 kN/m
Terralys LF 46	186 g/m^2	46 kN/m
Terralys LF 57	228 g/m^2	57 N/m

2.1. Reinforced Earth Wall Stability

The global stability of the reinforced earth wall was evaluated by examining three primary external failure mechanisms: sliding, overturning, and bearing-capacity failure. These checks were performed by using classical limit equilibrium formulations under static conditions. Sliding stability was assessed by comparing the resisting force due to base friction with the driving horizontal earth pressure and surcharge-induced loads. The Factor of Safety against sliding (FS_S) is calculated as:

$$FS_S = \frac{LH\gamma \tan\varphi}{0.5H^2\gamma K_a + qHK_a} \geq 1.5 \tag{1}$$

Where L is the length of the reinforcement, H is the wall height, γ is the soil unit weight, ϕ is the internal friction angle of the foundation soil, K_a is the Rankine active earth pressure coefficient [27], and q is any applied uniform surcharge.

The overturning stability was verified by comparing the resisting moment due to the self-weight of the reinforced mass against the overturning moments generated by the lateral earth and surcharge pressures. The Factor of Safety against overturning (FS_O) is given by:

$$FS_O = \frac{\sum M_r}{\sum M_d} = \frac{0.5\gamma HL^2}{0.5P_qH + \frac{1}{3}P_sH} \geq 1.5 \tag{2}$$

Where P_q and P_s are the horizontal forces exerted by the surcharge and soil pressure, respectively.

Bearing capacity stability ensures that the vertical stress imposed on the foundation soil does not exceed its allowable capacity. The Factor of Safety against bearing failure (FS_B) is expressed as:

$$FS_B = \frac{q_u}{\sigma_v} \geq 2.0 \tag{3}$$

Where q_u is the ultimate bearing capacity and σ_v is the applied vertical stress, which is determined by

$$\sigma_v = \frac{W}{L-2e} \tag{4}$$

$$e = \frac{\sum M_d}{W} \geq \frac{L}{6} \tag{5}$$

Where W is the total weight of the reinforced mass and e is the eccentricity of the resultant force. Condition $e \leq L/6$ was maintained to avoid eccentric loading beyond the middle third of the foundation base.

In addition to the global stability, the internal stability of the geotextile-reinforced earth wall must be verified to ensure that the reinforcement layers can withstand the induced tensile forces without rupture or pullout. Two failure modes were considered: geotextile rupture and geotextile pullout, which were evaluated for each reinforcement layer. Rupture occurs when the tensile force within the reinforcement exceeds the allowable tensile strength. The Factor of Safety against rupture (FS_r) is defined as follows.

$$FS_r = \frac{T_a}{K_a\sigma_v S_v} \geq 1.2 \tag{6}$$

Where T_a represents the allowable tensile strength of the geotextile, S_v is the vertical spacing between the reinforcement layers, and σv is the vertical stress at the reinforcement layer.

Pullout failure occurs when the geotextile is not sufficiently embedded in the passive zone of the foundation soil to develop an adequate frictional resistance. The Factor of Safety against pullout (FS_p) is expressed as

$$FS_p = \frac{2\mu\sigma_v L_p}{K_a \sigma_v S_v} \geq 1.2 \quad (7)$$

Where μ is the interface friction coefficient between the soil and geotextile, σ_v is the vertical stress acting on the reinforcement, S_v is the vertical spacing between reinforcement layers, and L_p is the length of reinforcement embedded in the passive zone, calculated using the following empirical expression:

$$L_p = L - tan\left(45° - \frac{\varphi}{2}\right)(H - z) \quad (8)$$

Where L represents the total length of the reinforcement and z is the vertical depth of the reinforcement layer from the top of the wall.

2.2. Embodied Carbon Assessment

The environmental impact of each geotextile-reinforced earth wall configuration was assessed through cradle-to-gate-embodied carbon analysis, following the guidelines outlined in BS EN 15978 [28] and established life cycle assessment (LCA) practices. The system boundary includes Modules A1-A3, which cover the emissions associated with raw material extraction (A1), transportation to the manufacturing plant (A2), and manufacturing processes (A3). The total Embodied Carbon (EC) was calculated as the product of the total geotextile area used in the design and the corresponding emission factor. This calculation is expressed as follows:

$$EC = A \times EF \quad (9)$$

Where A is the total area of the geotextile used (m^2), and EF is the emission factor of the geotextile ($kgCO_2e/m^2$). Emission factors were obtained from published Environmental Product Declarations (EPDs) [29] for each geotextile type considered in this study. These values reflect specific material characteristics, such as polymer type and manufacturing efficiency. Table 2 summarises the emission factors applied to the different woven geotextile products used in the analysis.

Table 2. Woven geotextile types used in this study

Type	Emission Factor
Terralys LF 35	0.274 $kgCO_2e/m^2$
Terralys LF 46	0.372 $kgCO_2e/m^2$
Terralys LF 57	0.456 $kgCO_2e/m^2$

This approach enables a direct comparison of various design configurations by evaluating their structural efficiency and environmental impact, thus supporting the identification of optimal, low-carbon solutions.

3. Results and Discussion

Figure 2 shows the relationship between the wall height and the corresponding reinforcement length required to satisfy the stability criteria. The results indicated a clear trend: as the height of the earth wall increased, the required reinforcement length also increased. This behaviour is consistent with fundamental geotechnical principles, as taller walls are subjected to greater lateral earth pressures and therefore require longer reinforcement to mobilize sufficient tensile resistance and ensure global stability, particularly against sliding and overturning. Interestingly, the analysis indicated that the required reinforcement length was largely independent of the geotextile tensile strength. Across all tested configurations, variations in the geotextile strength had a negligible influence on the total length required for stability. This suggests that the geometric configuration of the reinforcement, rather than its tensile capacity, is the dominant factor governing stability with respect to the reinforcement length.

The implication is that the reinforcement length is primarily dictated by the wall geometry and soil conditions rather than the material strength. While stronger geotextiles allow for reduced vertical spacing or fewer layers, they do not significantly reduce the anchorage length required to satisfy external stability requirements. This finding reinforces the need to optimize both the length and layout in reinforced earth wall designs, especially for taller structures.

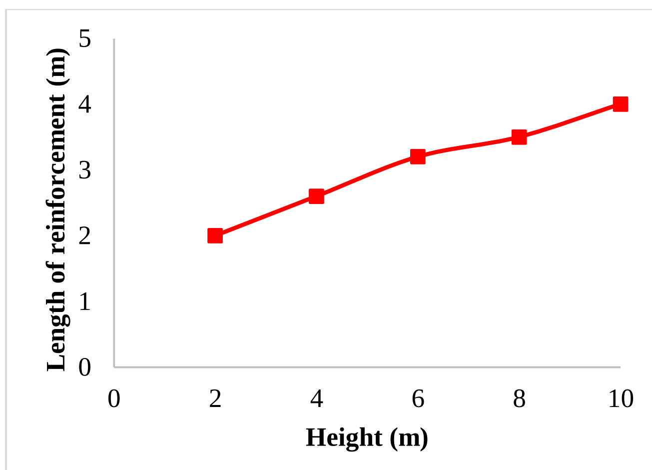

Fig. 2 Required geotextile reinforcement length

Figure 3 presents the variation in the required vertical spacing (S_v) between the geotextile layers as a function of the wall height for three geotextile types: LF 35, LF 46, and LF 57. The results showed a clear inverse relationship between the wall height and vertical spacing as the wall height increased, and the required vertical spacing decreased. This is due to the greater mobilization of tensile forces in taller walls, which necessitates closer spacing to distribute loads and maintain internal stability.

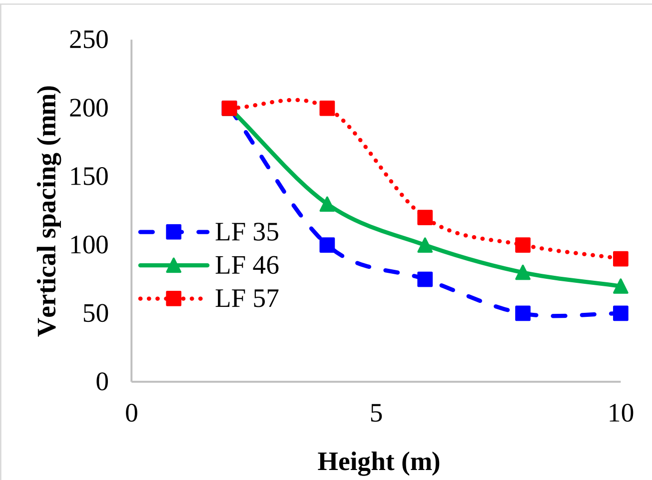

Fig. 3 Vertical spacing of geotextile layers for different geotextile types

Moreover, the geotextile type significantly influences the allowable spacing. At each height level, stronger geotextiles (e.g. LF 57) enable wider spacing than lower-strength alternatives. For instance, at a wall height of 6 m, LF 57 permitted a spacing of approximately 120 mm, whereas LF 35 required a spacing of less than 80 mm to satisfy the rupture and pullout criteria. This behaviour is consistent with theoretical expectations, where a higher tensile capacity allows each layer to resist a greater force, thereby reducing the total number of layers required. However, as the wall height exceeded 6 m, the differences between the spacing for different geotextile types began to narrow. This is likely due to the increasing influence of cumulative stresses and critical depths, where high-strength geotextiles must be placed more frequently to prevent failure. The results highlight the importance of integrating geotextile strength with geometric layout optimization to achieve structurally sound and material-efficient design.

Figure 4 presents the variation in embodied carbon per meter of wall length as a function of wall height for three geotextile types: LF 35, LF 46, and LF 57. The results reveal a distinct relationship between wall height and embodied carbon, and how this relationship is influenced by the mechanical properties of the geotextile. At lower wall heights (≤ 6 m), the use of low-strength geotextiles (LF 35) resulted in the lowest embodied carbon content. This is primarily because the required tensile resistance at these heights is relatively modest, allowing a wider vertical spacing and a smaller total quantity of reinforcement. Because LF 35 has the lowest areal weight and emission factor per unit area, it is the most carbon-efficient option for short walls.

However, as the wall height increased beyond 8 m, the embodied carbon associated with LF 35 rose sharply. This was attributed to the need for significantly closer spacing and greater overall material use to satisfy the internal stability criteria (i.e. pullout and rupture resistance). In contrast, higher-strength geotextiles (LF 46 and LF 57) can be spaced more widely at greater depths, effectively reducing the total required area. As a result, they demonstrated lower embodied carbon at taller wall heights, despite their higher per-unit emission factors. Another important observation was that the embodied carbon values for LF 46 and LF 57 were nearly identical across all wall heights. This suggests that while LF 57 offers a higher tensile strength, its marginal benefit in terms of reduced material use is offset by its slightly higher carbon intensity. Therefore, LF 46 emerged as a more balanced option, offering both performance efficiency and embodied carbon savings, particularly for medium to high wall heights.

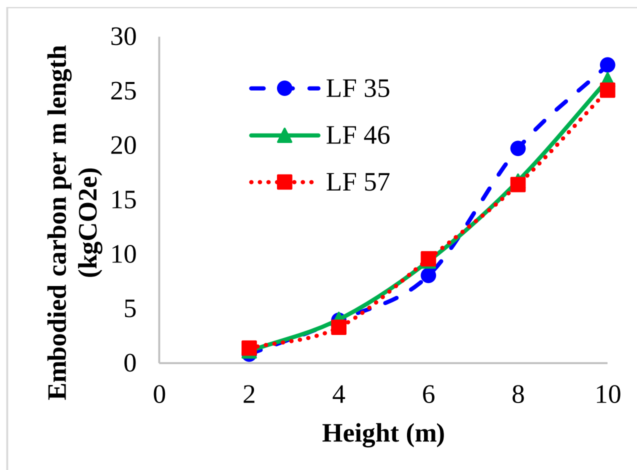

Fig. 4 Embodied carbon per m length of earth wall for different geotextile types

Compared with previous studies that primarily evaluated the environmental performance of retaining wall systems at a macro level, this study offers a more nuanced analysis by linking reinforcement configurations with both geotechnical stability and embodied carbon. The results demonstrated that selecting reinforcement types based solely on mechanical strength or emission factors may lead to suboptimal outcomes. Instead, a performance-based approach that considers wall height, reinforcement spacing, and reinforcement strength provides a more sustainable and structurally sound solution. This study contributes a practical framework for engineers aiming to achieve carbon-efficient designs without compromising stability, a dimension largely absent in the existing literature.

4. Conclusion

This study looked at the performance and carbon impact of geotextile-reinforced earth walls. It used limit equilibrium analysis and cradle-to-gate life cycle assessment. The researchers evaluated different wall heights, ranging from 2 to 10 m, along with various geotextile types with different tensile strengths and emission factors. The goal was to find the best configurations that ensure both structural stability and environmental sustainability.

The results show that as the wall height increases, the reinforcement length also increases. However, it does not depend much on the geotextile tensile strength. The vertical spacing, on the other hand, is significantly influenced by the type of geotextile. Higher-strength geotextiles allow for greater spacing and lower material use. The analysis of embodied carbon found that low-strength geotextiles, like LF 35, work better for shorter walls because they require less material and produce fewer emissions. For taller walls (8 m or more), high-strength geotextiles such as LF 46 and LF 57 resulted in lower embodied carbon because they reduced the overall reinforcement area. Among these choices, LF 46 was recognized as a balanced option for various heights, providing both efficiency and carbon savings.

These findings show the need to combine geotechnical design principles with environmental assessment. Sustainable reinforced earth wall design should not depend only on changing materials. It must also look at reinforcement shape, strength, and arrangement to improve both safety and carbon performance. The suggested approach provides useful insights for designing low-carbon geotechnical structures and aids wider efforts for sustainable infrastructure development.

Future research should build on this study by including more factors like seismic loading, the long-term creep behaviour of geotextiles, and different soil types to represent real-world conditions better. In addition, broadening the life cycle assessment beyond the cradle-to-gate scope to cover transportation, installation, maintenance, and end-of-life phases would give a clearer picture of environmental impacts. Using better optimization techniques, such as multi-objective algorithms, can improve design efficiency by reducing embodied carbon and construction costs at the same time while meeting performance standards. Testing and monitoring optimized configurations in real-world settings would also help support practical use.

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Author Contribution
RS prepared the manuscript, AS reviewed the manuscript, JJ reviewed the manuscript, and MA reviewed the manuscript.

Data availability
Data analysis https://zenodo.org/records/15875297

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