Whole Life Civil Systems Analysis Term Project

Life Cycle–Based Environmental and Sustainability Assessment of Retaining Wall Design Alternatives

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1. Scope and Objective

The objective of this study is to comparatively evaluate the life cycle-based environmental and sustainability performance of different retaining wall design alternatives. Three different reinforced concrete wall systems containing reinforced concrete were examined in the study.

The evaluations were conducted on a functional unit measuring 2.5 m in height and 1 m in length, which included the body and base plate of each system.

The three alternatives addressed in the study are as follows:

1) Conventional Reinforced Concrete (RC) Retaining Wall: Consists of a cast-in-place RC footing and stem; Grade C30 concrete containing 15% fly ash replacement was used.
2) Ultra-High-Performance Concrete (UHPC) Retaining Wall: Composed of a prefabricated base slab and vertical panel; uses partially prestressed UHPC with steel fibers and a compressive strength of approximately 150 MPa.
3) Precast Sandwich Composite Retaining Wall: Consists of a cast-in-place RC footing and a prefabricated sandwich panel; two thin concrete layers are separated by a rigid foam insulation core.

Analyses include the following stages within the life cycle system boundaries:

- A1 – Raw Material Extraction
- A2 – Material Processing
- A3 – Product Fabrication.
- B – Maintenance and Repairs: Activities performed during the 100-year service life, including inspection (INSP), surface repair (SR), medium-scale repair (MR), and rehabilitation (REH).

Within this scope, four key environmental indicators were calculated: embodied energy (MJ), CO_2 emissions (kg), NO_x emissions (kg), and SO_2 emissions (kg).
Life cycle inventory (LCI) data and emission factors were obtained from the Ökobaudat database. Maintenance scenarios for alternatives were modeled using the equivalent material replacement rate approach over a 100-year service life.

2. Design Alternatives

The selected main system is a reinforced concrete retaining wall. Since this structure generally exhibits monolithic behavior, dividing it into separate independent elements is structurally meaningless. Therefore, within the scope of this project, the stem and base slab have been considered together and evaluated as a subsystem of the wall system.This subsystem has been used as the basic unit in all subsequent analyses, including geometry definition, life cycle analysis, and multi-criteria decision analysis.

This study evaluates three reinforced concrete retaining wall alternatives that is also shown in Table 1. Due to their monolithic structure, retaining walls are not very suitable for material-based design alternatives. For this reason, based on some studies in the literature, three different types of walls containing reinforced concrete were used in the study.

Table 1. Design Options

Design Option	Foundation	Stem	Material Concept	Main Reference
Option 1 – Conventional RC Wall	Cast-in-place reinforced-concrete footing	Cast-in-place reinforced-concrete stem	Grade-30 concrete (15 % fly ash) + B500B steel reinforcement	Balasbaneh et al (2020) Nematollahi et al. (2015)
Option 2 –UHPC Wall	Prefabricated UHPC base slab	Prefabricated UHPC vertical panel	UHPC 150 MPa with 1.5 % steel fibers and limited prestressing)	Nematollahi et al. (2015)
Option 3 – Precast Sandwich Composite Wall	Cast-in-place RC footing	Precast sandwich wall panel	Concrete 35 MPa, Rebar and wythe connectors	PCI Sandwich Wall Panels Guide (2021)

Since the study represents a retaining wall 1 meter in length, the cross-sectional area directly represents the volume in calculating the quantities of materials to be used in subsequent analyses.

3. Section Geometry and Material Details

3.1 Conventional RC Cantilever Wall

The conventional reinforced concrete retaining wall section used in this study was taken from Nematollahi et al. (2015). For some adjustments, Balasbaneh et al. (2020) was also consulted. This reference presents a wall configuration based on realistic geometry and engineering design, as shown in Figure 1. At the same time, these section parameters are shown in Table 2.

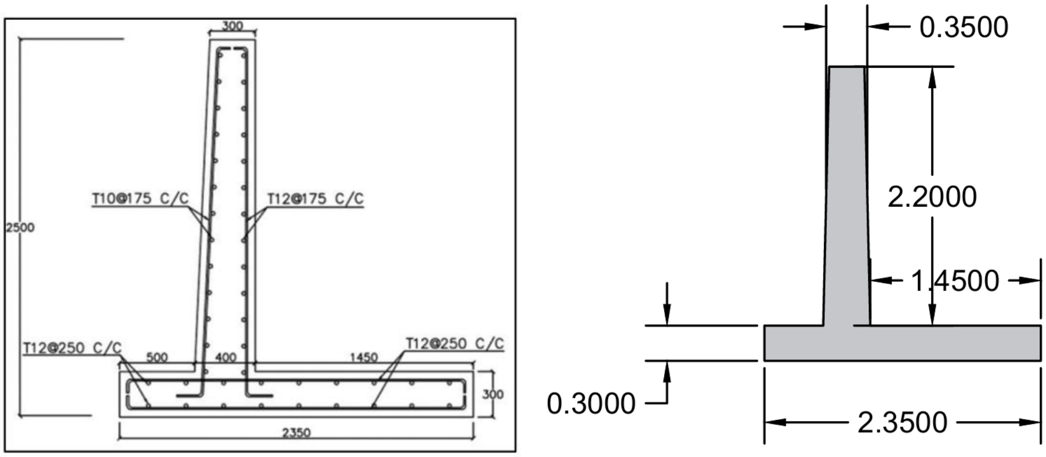

Figure 1. Cross-section of a conventional RC cantilever wall design

Table 2. Geometric and material properties of conventional RC retaining wall

Structural Element	**Dimension / Geometry**	**Material**
Stem Heihgt	2.2 m	Reinforced concrete (C30/37)
Stem Thickness	350 mm	Reinforced concrete (C30/37)
Base Slab Width	2.35 m	Reinforced concrete (C30/37)
Base Slab Thickness	300 mm	Reinforced concrete (C30/37)
RC stem Section	0.77 (2.2 m × 0.35 m)	RC (30 MPa) + 15 % fly ash
RC Base Slab Section	0.705 (2.35 m × 0.3 m.)	RC (30 MPa) + 15 % fly ash

However, since the material quantities given in the same source are low from an engineering perspective, the material ratios in this study have been rearranged according to the ACI 211.1-91 standard and are shown in Table 3.

The concrete quantity in the table is provided for informational purposes only. Since it is already separated into its ingredients, it has not been included in the analysis.

Table 3. Material quantities (kg/m³) for conventional RC retaining wall

Material	**Quantity**	**Unit**
Concrete	2.07	m³
Reinforcement	95.3	kg
Cement content	300	kg/m³
Fly Ash (15%)	45	kg/m³
Water content	165	l/m³
Coarse Aggregates	1050	kg/m³
Fine Aggregates	700	kg/m³

3.2 UHPC Cantilever Wall

The UHPC retaining wall section used in this study is based on the precast ultra-high performance concrete (UHPC) cantilever wall design presented in Nematollahi, Voo, and Sanjayan (2015).

The section consists of a 30 mm thick stem and a 40 mm thick base slab (Figure 2). and its detailed geometric and material properties are summarized in Table 4.

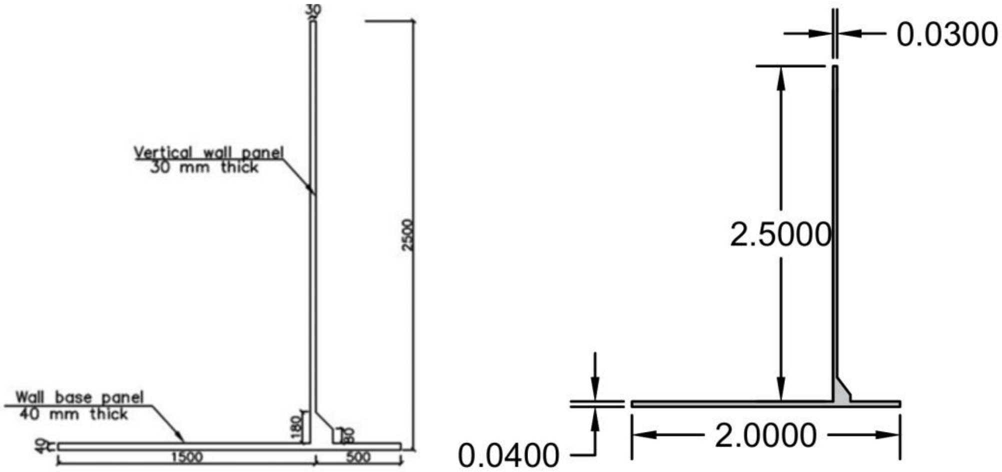

Figure 2. Cross-section of the precast UHPC cantilever retaining wall

Tablo 4. Geometric and material properties of the UHPC cantilever retaining wall

Structural Element	Dimension / Geometry	Material
Stem height	2.46 m	UHPC (150 MPa, 1.5 % steel fibers)
Stem panel thickness	30 mm	UHPC plate + vertical
Base slab total width	2.0 m (heel 1.5 m + toe 0.5 m)	UHPC (2 stiffeners)
Base slab thickness	40 mm	UHPC plate
UHPC stem panel	0.0861 (2.46 m × 0.035 m)	UHPC (150 MPa, 1.5 % steel fibres)
UHPC base slab	0.080 (2.0 m × 0.04 m)	UHPC (150 MPa, 1.5 % steel fibres)
Base stiffeners	0.016 (2 × 0.008)	Structural steel T16 bars
Vertical stiffener	0.008 (1 × 0.08 × 0.10)	Structural steel T20 bar

Thanks to UHPC's high compressive strength and fiber-reinforced structure, the wall section can be kept quite thin, resulting in a significant reduction in material usage compared to traditional RC walls. Vertical and horizontal stiffening is provided by steel profiles placed in the stem and two stiffener elements used in the base section. According to the literature, UHPC premix material contains all the components used in concrete production, which is evident from its density.
In addition, an average of 7.35 kg/m of reinforcement was used along the wall, which corresponds to a density of approximately 48 kg/m³ relative to the UHPC volume. The quantities of UHPC components and structural steel elements used in this system are given in Table 5.

Table 5. Material quantities (kg/m³) for UHPC retaining wall

Material	**Quantity**	**Unit**
UHPC Premix	2100	kg/m³
Superplasticizer	4	kg/m³
Steel Fibre (Type I)	60	kg/m³
Steel Fibre (Type II)	60	kg/m³
Base and Vertical stiffeners	2 × T16, 1 × T20 = 800	kg/m³
Reinforcement / Prestress	7.35 kg for the 1m Wall= 48	kg/m³

3.3 Precast Sandwich Composite Retaining Wall

The precast concrete sandwich retaining wall used in this design is based on the system specifications outlined in the State of the Art of Precast Concrete Sandwich Wall Panels report published by the Precast Concrete Institute (PCI, 2011).

The cross-section consists of a rigid foam layer between two reinforced concrete layers (Figure 3). The dimensions and material distribution in this cross-section are summarized in Table 6.

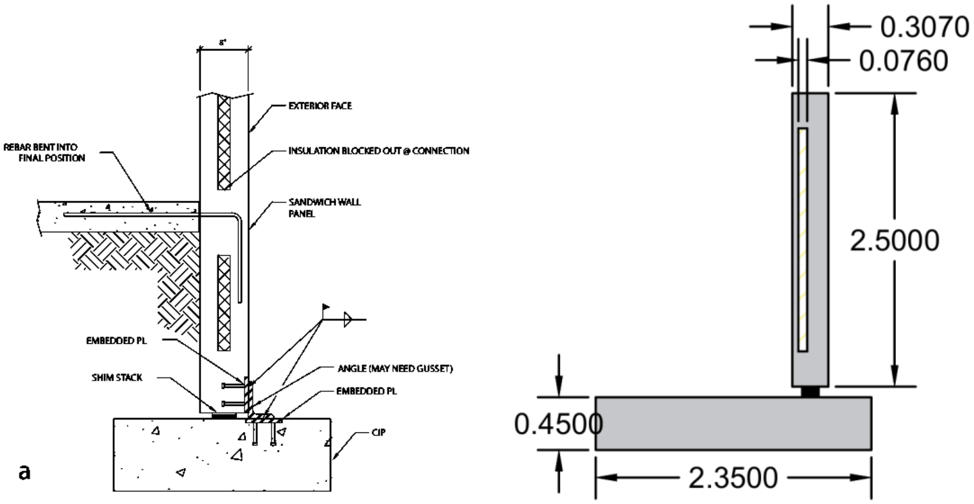

Figure 3. Cross-section of the precast sandwich composite retaining wall

Table 6. Geometric and material properties of the precast sandwich composite retaining wall

Structural Element	**Dimension / Geometry**	**Material**
Wall height (stem)	2.50 m	Precast concrete (35 MPa)
Sandwich build-up	51 mm concrete / 76 mm rigid foam / 180 mm concrete	Concrete + rigid foam
Footing (base)	Width 2.35 m, thickness 0.45 m	Precast concrete (35 MPa)
Concrete wythe (front, fascia)	0.128 *(2.50 m × 0.051 m)*	Precast concrete (35 MPa)
Concrete wythe (back, structural)	0.450 *(2.50 m × 0.180 m)*	Precast concrete (35 MPa)
Rigid insulation core	0.190 *(2.50 m × 0.076 m)*	Rigid Foam
RC footing	1.06 *(≈2.35 m × 0.45 m)*	Concrete (35 MPa)

The concrete used in the sandwich wall system has been selected according to the same mix design principles as that used in conventional RC walls since no clear values could be found in the literature. The concrete mix ratios are defined as 300 kg/m³ cement, 165 kg/m³ water, 1050 kg/m³ coarse aggregate, and 700 kg/m³ fine aggregate, according to the approximate 35 MPa class mix ranges given in the ACI 211.1-91 standard.

However, only part of the total wall volume in the sandwich section is concrete; the rest consists of rigid foam insulation. Therefore, in life cycle calculations, material quantities have been rescaled based on 1 m³ of wall volume.

The rigid foam core and steel connectors used in the sandwich wall system have been included in the model based on the typical values defined in the Precast Concrete Institute (PCI, 2011) guide. The density and volume ratio of this component were determined based on the typical XPS ranges (25–35 kg/m³) given in the Ökobaudat technical database. For steel connectors, an average mass estimate per unit wall was made based on approximately 0.5 kg/piece, using the specified connector density range of 4–6 pieces/m² as a reference. In addition, the prefabrication process contributes to reduced cement-related emissions.

Table 7. Material quantities (kg/m³) for Precast Sandwich Composite Retaining Wall

Material	**Quantity**	**Unit**
Cement	269	kg/m³
Steel Connectors	3.0	kg/m³
Water	148	kg/m³
Coarse Aggregates	941	kg/m³
Fine Aggregates	627	kg/m³
Reinforcement Steel	63	kg/m³
Rigid Foam (EPS/XPS)	3.1	kg/m³

4. Life Cycle Inventory (LCI) of Materials and Emission Data

The life cycle inventory data used in this study are summarized in Table 8. below, based on the material quantities corresponding to a 1 m long retaining wall for each design option. Material quantities were determined considering the geometric properties of each system and mixture ratios obtained from literature.
Energy consumption and emission factors (CO_2, NO_x, and SO_2) were taken from material profiles in the Ökobaudat database. Although the scope of the project's initial phase was defined as the interior regions

of the USA, the use of the same data set for all design alternatives means that basing it on Germany will not create any inconsistencies.

For materials of the same type (e.g., reinforcing steel and stiffening steel profiles), the integrity of the model has been maintained by using consistent data sets. NO_x and SO_2 values have been represented by referring to the average values of similar material categories when direct data was not available for some materials.

The emission values of premix, superplasticizers, and steel fibers used in the UHPC system have been matched with the high-performance concrete C75 and steel product data sets in Ökobaudat. The energy and emission coefficients of the insulation material (EPS/XPS) and steel connection elements in the sandwich panel system were obtained from the EPS-Hartschaum and Metal Connector datasets.

The resulting table contains the energy consumption (MJ/unit) and emission values (kg/unit) per unit for each material, providing a comparable basis for all design options.

Table 8. Life cycle inventory (LCI) data: energy consumption and emission values

Material	**Design Option**	**Quantity**	**Energy (MJ/unit)**	**CO_2 (kg/unit)**	**NO_x (kg/unit)**	**SO_2 (kg/unit)**
Cement	RC	300	2.401	0.553	0.000643	0.000801
Cement	Sandwich	269	2.401	0.553	0.000643	0.000801
UHPC Premix	UHPC	2100	1.795	0.368	0.000389	2.28E-05
Fly Ash	RC	45	0.7856	0.1581	0.00023	0.00026
Coarse Aggregate	RC	1050	0.4882	0.02739	1.01E-05	1.08E-05
Coarse Aggregate	Sandwich	941	0.4882	0.02739	1.01E-05	1.08E-05
Fine Aggregate	RC	700	0.5635	0.03498	3.46E-05	2.92E-05
Fine Aggregate	Sandwich	627	0.5635	0.03498	3.46E-05	2.92E-05
Reinforcement Steel	RC	80	8.483	0.474	0.000884	0.001286
Reinforcement Steel	UHPC	48	8.483	0.474	0.000884	0.001286
Reinforcement Steel	Sandwich	63	8.483	0.474	0.000884	0.001286
Steel Stiffeners	UHPC	1220	8.483	0.474	0.000884	0.001286
Steel Fibers	UHPC	120	13.416	0.6422	0.001351	0.001391
Steel Connectors	Sandwich	3	13.416	0.6422	0.001351	0.001391
Insulation	Sandwich	3.1	16.897	0.6041	0.005571	0.000857
Water	RC	165	0.001674	0.00011	0.00001	0.000005
Water	UHPC	125	0.001674	0.00011	0.00001	0.000005
Water	Sandwich	148	0.001674	0.00011	0.00001	0.000005
Superplasticizers	UHPC	4	17.006	0.5142	0.001392	0.001214

5. Maintenance Interventions and Service Life Assumptions

Conventional RC Cantilever Retaining Wall

Balasbaneh et al. (2020) stated that reinforced concrete cantilever retaining walls have a service life exceeding 50 years and require less maintenance due to the advantages of reinforced concrete structures. However, a design life of 100 years is generally accepted for this type of wall in various sources.

In these systems, routine surface maintenance and inspection every 5 years (CTOD,2016) along with comprehensive rehabilitation every 30–40 years, is considered sufficient to maintain the wall's durability throughout its service life.

UHPC Retaining Wall

In a study conducted by Nematollahi et al. (2015), it was stated that UHPC retaining walls can achieve a service life exceeding 100 years due to their very low permeability and high strength properties. These types of walls are defined as systems that require almost no maintenance throughout their service life. Only a visual inspection every 10–20 years and, if necessary, minor surface repairs every 40–50 years are sufficient.

Precast Sandwich Composite Retaining Wall

According to the Precast Concrete Institute (PCI, 2011) report, sandwich panel walls offer high strength and low maintenance requirements because they are manufactured in factory conditions, and their service life can exceed 100 years.

Industrial data from Tenax (2024) further supports this characterization: A sandwich panel retaining wall requires 2–4 inspections and cleanings throughout its service life to maintain surface integrity. standard maintenance is required every 25 years and approximately every 35 years for major rehabilitation while the overall service life of the panels can exceed 70 years with proper maintenance

In this study, interventions were modeled using engineering accumulation as an equivalent material renewal rate rather than direct element replacement due to the monolithic structure of retaining walls. Each maintenance type was divided into four categories: visual inspection (INSP), surface repair (SR), medium repair (MR), and rehabilitation (REH). These interventions represent material renewal rates of 0%, 5%, 10%, and 20%, respectively. Thus, instead of direct element replacement, the amount of repair mortar, concrete, or steel used during maintenance has been included in the model as equivalent material consumption. Maintenance frequencies (Table 9) and renewal rates were defined based on typical service lives reported in the literature (Balasbaneh et al., 2020; Nematollahi et al., 2015; PCI, 2011) and engineering assessments. Based on these assumptions, the intervention factors representing the total equivalent material usage over a 100-year design life were taken as 2.1 for RC walls, 1.3 for UHPC walls, and 1.7 for sandwich panel walls.

Table 9. Maintenance types, frequencies for different retaining wall designs

Design Option	**Event**	**Frequency (years)**	**Total Lifespan (years)**
1. RC Wall	INSP	5	100
1. RC Wall	SR	15	100
1. RC Wall	MR	25	100
1. RC Wall	REH	50	100
2. UHPC Wall	INSP	10	100
2. UHPC Wall	SR	35	100
2. UHPC Wall	MR	60	100
3. Sandwich Wall	INSP	5	100
3. Sandwich Wall	SR	25	100
3. Sandwich Wall	MR	35	100
3. Sandwich Wall	REH	70	100

Figures 3–5 below show the types of maintenance required for three different retaining wall types (RC, UHPC, and sandwich panel) and the intervals at which they occur over a 100-year service life. Upon examination of the figures, it is observed that the RC wall requires more frequent and varied maintenance interventions compared to the other systems, while the UHPC wall requires limited maintenance at long intervals. The sandwich panel wall falls between these two systems in terms of maintenance frequency and maintains its structural integrity through periodic inspections.

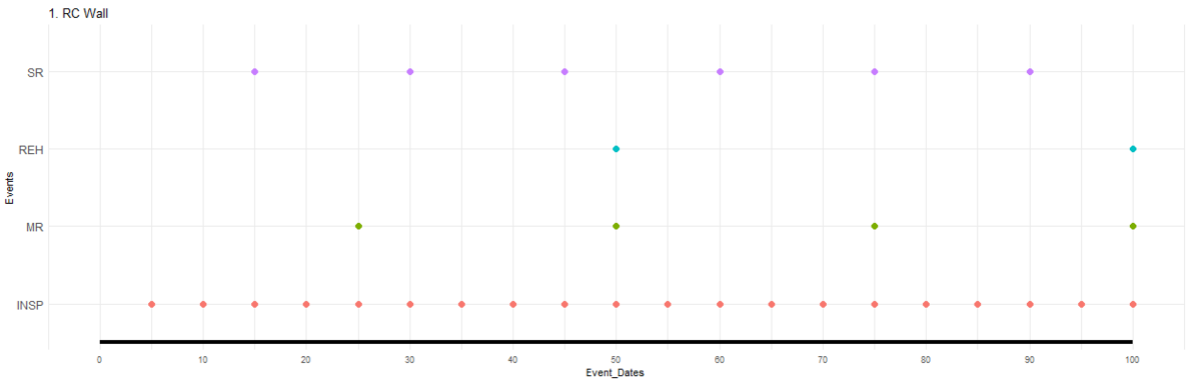

Figure 3. Scheduled maintenance events for the RC retaining wall over a 100-year service life

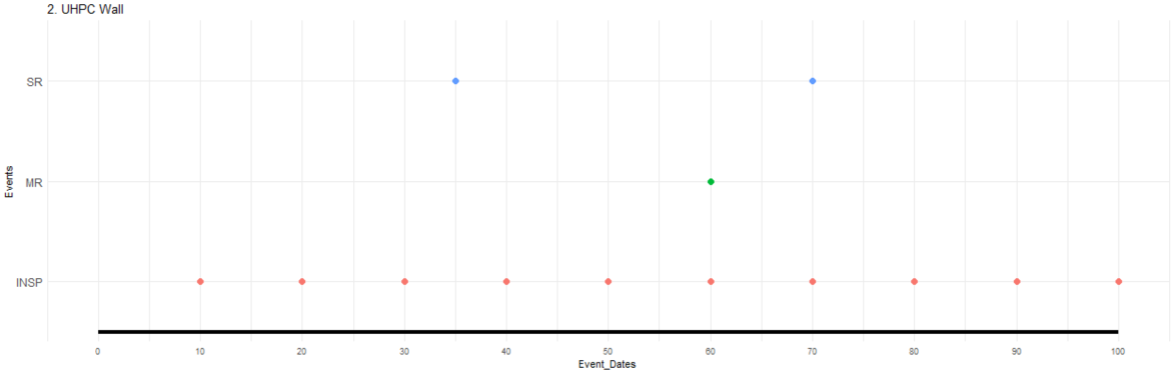

Figure 4. Scheduled maintenance events for the UHPC retaining wall over a 100-year service life

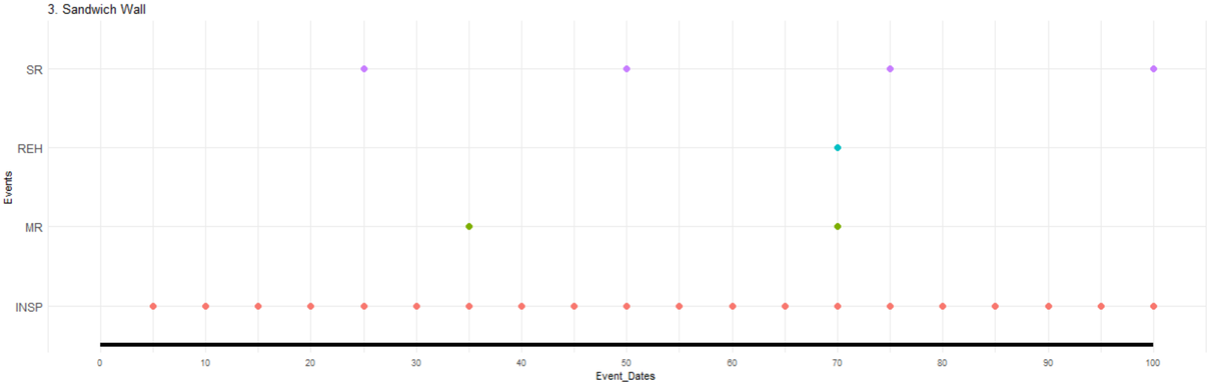

Figure 5. Scheduled maintenance events for the precast sandwich retaining wall over a 100-year service life

6. Life Cycle Inventory Analysis

This section compares the results shown in Figures 6–9, which present the lifetime energy consumption (MJ) and CO_2, NO_x, and SO_2 emissions for a 1 m long wall unit over a 100-year service life for three different retaining wall alternatives (RC, UHPC, and sandwich panel). These emission values cover production, processing, fabrication, and maintenance processes.

Energy consumption

The total embodied energy values of the three retaining wall alternatives are illustrated in Figure 6. RC walls show the highest energy consumption. The main reasons for this are that the system contains large volumes of concrete and steel reinforcement and also requires more frequent repairs throughout its lifetime. Although the high-strength material used in the UHPC system consumes a lot of energy during production, the total energy value has decreased by approximately 50% compared to RC due to the significant reduction in total building volume and maintenance frequency.

Although prefabricated production processes and thinner concrete layers in the sandwich panel system save energy, the production energy of XPS foam and metal connection elements partially offsets this advantage. It lies between the two alternatives.

CO$_2$ emissions

RC walls show the highest carbon emissions, with a value of approximately 800 kg/m. Due to low structural efficiency, more material is used, increasing the total cement and steel input, which in turn increases the emission load.

In the UHPC system, despite an energy-intensive process during production, the total CO$_2$ emissions are significantly reduced thanks to the thin section geometry, dense and low-permeability microstructure, and long maintenance intervals. In this system, the concrete volume is reduced, and the maintenance requirement is almost eliminated; therefore, the “high initial production energy – low life cycle impact” balance is clearly evident.

Although the composition of the concrete used in sandwich panel walls is similar to that of RC walls, CO$_2$ emissions are lower due to the smaller total concrete volume required by the structure's geometry and the high curing efficiency of prefabricated production.

NO$_x$ ve SO$_2$ emissions

NO$_x$ and SO$_2$ emission trends are generally parallel to CO$_2$. The RC system shows the highest values due to cement clinker production and steel processing. In the UHPC system, these values decrease due to material optimization and low maintenance requirements, while in the sandwich panel system, an intermediate level is observed due to composite production and the effect of additional connection elements.

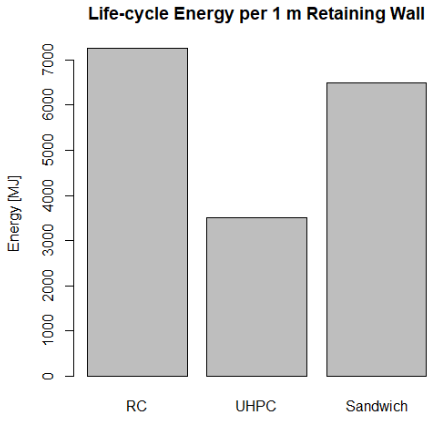

Figure 6. Energy consumptions

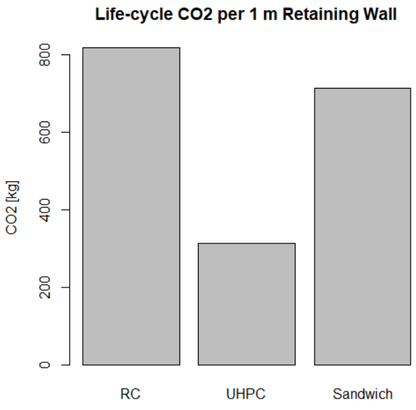

Figure 7. CO$_2$ emissions

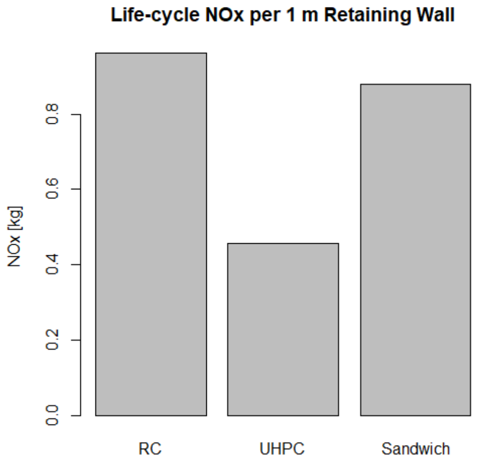

Figure 8. NO_x emissions

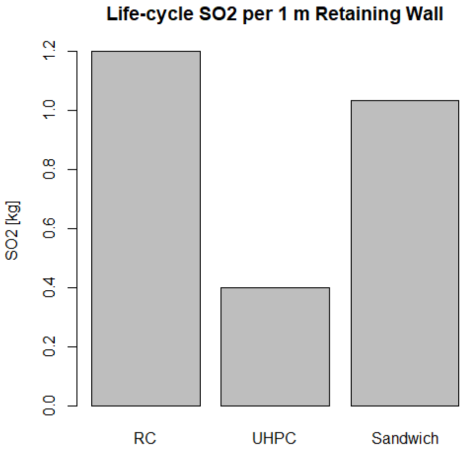

Figure 9. SO_2 emissions

7. Analytic Hierarchy Process (AHP) Evaluation

In this study, the Analytic Hierarchy Process (AHP) method was applied to evaluate the environmental performance of design alternatives using a multi-criteria approach. The method is a decision support tool developed by Saaty (1980) in which the relative importance of decision criteria is determined through pairwise comparisons.The quantitative difference between two alternatives was evaluated based on the poor/good ratio.

If the ratio was approximately in the range of 1.1–1.3, the difference was considered weak and assigned a value of 2. When the ratio was in the range of 1.3–2.0, the difference was considered moderate and values in the range of 3–4 were used. When the ratio reached approximately 2–3 times the level, this difference was interpreted as a strong preference and assigned a value of 5. To avoid extreme evaluations in this study, the highest values on the scale, such as 7 and 9, were not used.

7.1 Decision Matrix Based on Environmental Indicators

The pairwise comparison matrices used within the AHP method were created based on each alternative's energy consumption (MJ) and CO_2, NO_x, and SO_2 emissions (kg).For each criterion, alternatives with lower environmental impact will have a higher preference value. For example, in terms of energy consumption, the UHPC wall (≈ 3000 MJ) showed approximately 2.4 times lower energy requirements than the RC wall (≈ 7200 MJ); this difference was evaluated as a strong preference (5).

An example of the pairwise comparison matrix constructed for the *energy consumption* criterion is presented in Table 10.

Table 10. Example pairwise comparison matrix of design alternatives with respect to energy consumption

Alternatives	**RC**	**UHPC**	**Sandwich**
RC	1	1/5	1/2
UHPC	5	1	4
Sandwich	2	1/4	1

Criterion weights have been determined by taking into account life cycle assessment (LCA) principles and climate impact priorities.

CO_2 emissions: A direct indicator of global warming potential (GWP), it is of the highest importance due to its cumulative effect on determining climate stability (IPCC AR6, 2023).

Energy consumption: It ranks second as it is the primary source of both CO_2 and other pollutants. However, its environmental impact varies depending on the type of energy source, so it is not as direct an indicator as CO_2.

NO_x and SO_2 emissions: Although important due to their short-term effects on air quality and human health, they are given lower weight in this study because their contribution to the global climate system is limited.

As a result, the order of importance among the criteria is determined as follows:

CO_2 > Energy > $NO_x \approx SO_2$.

Accordingly, the pairwise comparison matrix reflecting these relative importance values among the criteria is presented in Table 11.

Table 11. Pairwise comparison matrix of environmental criteria based on their relative importance

Criteria	**Energy**	**CO_2**	**NO_x**	**SO_2**
Energy	1	1/2	3	3
CO_2	2	1	4	4
NO_x	1/3	1/4	1	1
SO_2	1/3	1/4	1	1

The reciprocal condition of the created pairwise comparison matrices has been verified. In the control test performed in the R environment, this condition was found to be TRUE for all elements; therefore, the logical consistency and symmetry of the matrices have been ensured.

7.2 Results of the AHP Analysis

The weights obtained from the AHP analysis quantitatively indicate the environmental sustainability performance of the alternatives.

According to the results given in Figure 10, the wall has the highest total importance at approximately 69.5%, indicating that it is the most sustainable alternative in terms of the four environmental indicators (Energy, CO_2, NO_x, SO_2) evaluated in the study.

The high performance of the UHPC wall is explained by its low CO_2 emissions (≈ 280 kg) and reduced energy consumption (≈ 3000 MJ). Its high strength and long service life, resulting in low maintenance frequency, is an indirect factor supporting this result.

The sandwich wall design ranked second with approximately 19.9% of the weight. This alternative offers advantages in energy efficiency and partial emission reduction compared to traditional RC walls due to prefabricated production. However, material-related environmental impacts could not be completely minimized due to its multi-layered component structure.

The traditional RC wall received the lowest score, at approximately 10.7%. The main reason for this is the high amount of cement and reinforcing steel used in the production process, resulting in high embodied energy and CO_2 emission values. And these emission criteria have been selected as the most important factors for the AHP analysis.

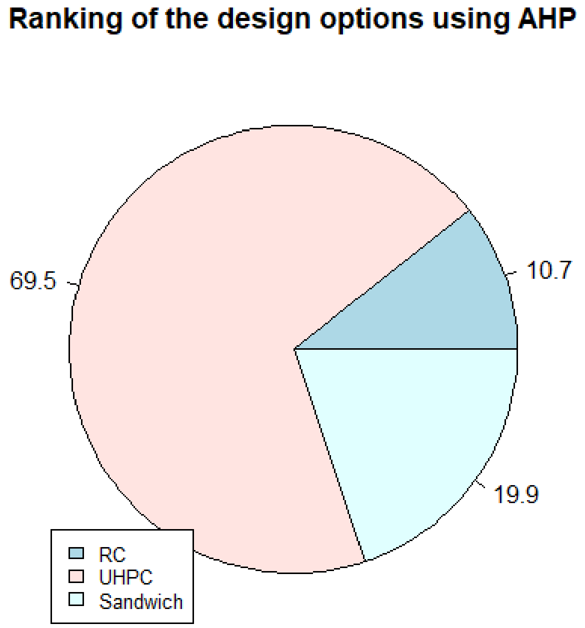

Figure 10. AHP-based ranking of retaining wall alternatives

8. Conclussion

In this study, the environmental performance and life cycle sustainability of three different retaining wall systems were comparatively evaluated using Life Cycle Assessment (LCA) and Analytic Hierarchy Process (AHP) methods. Four key environmental indicators (embodied energy, CO_2, NO_x, and SO_2 emissions) were considered in the study, and maintenance and repair activities over a 100-year service life were included in the model based on equivalent material replacement rates.

According to the results obtained from the AHP analysis, the UHPC retaining wall showed the highest sustainability performance with a weight value of approximately 69.5%. This is due to the reduction in cross-section dimensions thanks to the high strength of UHPC, the decrease in maintenance frequency due to its low permeability, and consequently, a significant reduction in both energy consumption and CO_2 emissions. The sandwich panel wall ranked second with approximately 19.9%. Although the efficiency of prefabricated production processes and reduced concrete volume provided energy advantages, additional emissions from core materials and metal fasteners partially offset this advantage. The traditional RC wall achieved the lowest sustainability score (10.7%) due to its high cement and reinforcement usage, large concrete volume, and frequent maintenance requirements.

In general, the use of UHPC material in retaining wall designs offers significant advantages in terms of both material efficiency and reduced environmental impact. This study demonstrates that high-performance materials such as UHPC can be an effective solution in the development of long-lasting and sustainable infrastructure systems in future engineering designs.

9. References

Tighnavard Balasbaneh, A., Yeoh, D., Juki, M. I., Wan Ibrahim, M. H., & Zainal Abidin, A. R. (2020). *Assessing the life cycle study of alternative earth-retaining walls from an environmental and economic viewpoint.*

American Concrete Institute (ACI). (1991).
Standard practice for selecting proportions for normal, heavyweight, and mass concrete (ACI 211.1-91).
Reported by ACI Committee 211. American Concrete Institute, Farmington Hills, MI, USA.

Nematollahi, B., Voo, Y. L., & Sanjayan, J. (2015).
Design and construction of a precast ultra-high performance concrete cantilever retaining wall.
Center for Sustainable Infrastructure, Swinburne University of Technology, Australia

Precast/Prestressed Concrete Institute (PCI). (2011).
State of the art of precast/prestressed concrete sandwich wall panels (2nd ed.).

ÖKOBAUDAT.
Sustainable construction information portal.
German Federal Ministry for Housing, Urban Development and Building.

Intergovernmental Panel on Climate Change (IPCC). (2023).
Climate Change 2023: Synthesis Report. Geneva, Switzerland.