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Sustainability assessment of geotechnical structures within the framework of the 2nd generation of Eurocode-7

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ABSTRACT: The requirement for geotechnical structures to be designed with sustainability requirements is being implemented internationally. The concept of sustainability involves several variables that are to be carefully identified and analyzed to provide solutions which ensure the short-, medium-, and long-term well-being of society. As per European standards, environmental, economic, and social/functional considerations are mandatory for any and all sustainability assessments. As these considerations (or better yet, requirements) can have different units of measurement, an integrated value model is required to normalize, aggregate, and compare results between solutions. One model (or method) used for this is the integrated value model for sustainable evaluation (MIVES), which allows for a quantitative assessment using multi criteria analysis based on user defined value functions and requirements. The present work covers sustainability assessments of geotechnical structures using MIVES. Special attention is given to the guidelines of the latest revision of the Eurocode 7, particularly in analyzing the weighting of each requirement (taking in consideration classification classes) with respect to the aggregated results.

KEYWORDS: Eurocode, Sustainability, multi-criteria, MIVES, geosynthetics, reinforced soil walls.

1 INTRODUCTION

Sustainability is a multi-variable concept by which geotechnical engineering can and must maintain and improve the world we live in. According to the latest European standards (e.g. EN 1990, 2023; EN 1997-3, 2024) environmental, economic, and social/functional aspects (or requirements) must be thoroughly evaluated as to label a structure as sustainable. These requirements must also be taken in consideration when designating the consequence class of the structure, thus, are critical during the design process. Each requirement must be assessed through individual indicators which take in consideration the scope of the structure (e.g., EN 17472, 2022).

The environmental requirement involves the use of resources and generation of emissions, during and after the service life of the structure. The economic aspect is based on a life cycle cost analysis of all materials, personnel, transportation, and construction activities. The social/functional aspects can cover a wide array of conditions, including health and safety, accessibility, public opinion, and resilience, among others. Assessments should be carried out considering the complete life cycle of the structure, including raw materials, transportation, construction, and operation of the structure, as well as possible deconstruction scenarios.

Designing more sustainable geotechnical structures involves thinking outside the box, considering novel materials and construction methods. In this regard, geosynthetics (or polymeric) materials (e.g., polypropylene, polyethylene, and polyester) are an attractive solution to improve engineering practice in a sustainable manner. These materials are engineered to resist aggressive conditions, such as high load or temperature conditions, extreme in-soil pH, and saturated environments for extended periods of time. Nowadays, polymeric materials are being extensively used in the fields of civil-, mining-, and geotechnical-engineering (e.g., with draining, filtration, and reinforcement functions, among others). As described by Dixon et al. (2017), the use of geosynthetic materials can play a key role in meeting several of the United Nations sustainability goals. Reinforced soil walls (RSWs), commonly used as earth retaining structures, are a specific application of polymeric materials in the field of geotechnical engineering. RSWs are composed of horizontal reinforcement elements embedded in a compacted soil material. Reinforcement can be of inextensible (i.e., steel) or extensible (i.e., polymeric) nature and can have various geometries (e.g., straps, grids, mats, or ladders, among others). A key advantage of RSWs is the use compacted soil as one of the main structural components, resulting in considerably lower emissions than, for example, concrete-, masonry, or steel-based solutions. Previous studies have evidenced the sustainability-related advantages of RSW over concrete- and steel-based solutions using multi-criteria analyses (e.g., Damians et al., 2018; Lee et al., 2015, 2018, among others).

The paper focusses on, first, a thorough description of the sustainability-related requirements of the latest generation of the Eurocode-7, followed by a thorough description of a multi-criteria model for sustainable evaluation in which a sample sustainability assessment of idealized geosynthetic RSWs with different facing elements alternatives is provided. Environmental and cost assessments are based on the authors' previous work (Moncada et al., 2024a, 2024b). The social/functional requirement was covered by survey forms answered by students from geotechnical engineering masters' program and professionals in the field of geotechnical engineering. Due to the nature of retaining wall as a rather permanent solution, the assessment is limited to cradle-to-built considerations.

2 SECOND GENERATION EUROCODE-7

Historically, economic and functional requirements have determined the structure's design. The latest EN guidelines aim to incorporate environmental and social aspects to the current economic-oriented design process of geotechnical structures. The incorporation of environmental and social consequences aims to promote the use of renewable materials, and re-use of structural elements and excavated material, as well as consider the impact in society within the influence zone of the structure, among other positive consequences.

In the latest revision of EN 1997-3 (2024), sustainability requirements for geotechnical structures are based of EN 1990 (2023), where the consequence class for a given structure is based on either the expected loss of human life or personal injury, or, economic, social or environmental consequences (Table 1). The consequence class provides a consequence factor, which is directly used in the design phase of all structures following EN standards, including geotechnical structures.

Table 1. Qualification of consequence classes (adapted from **EN 1990-1:2023**)

Consequence class	Indicative qualification of consequence	
	Loss of human life or personal injury*	Economic, social or environmental consequences*
CC4 – Highest	Extreme	Huge
CC3 – High	High	Very great
CC2 – Normal	Medium	Considerable
CC1 – Low	Low	Small
CC0 - Lowest	Very low	Insignificant

*: Consequence class is chosen based on the more severe of these two columns.

The basic framework for the sustainability assessment of civil engineering works, including geotechnical structures, is EN 15643 (2021). The evaluation of economic, social, and environmental consequences is the basis for a thorough sustainability assessment. Each of these categories (or requirements), should be evaluated using different set of indicators (e.g., EN 17472, 2022; ISO 15392, 2019).

Before the measurement of individual indicators, system boundaries must be defined. These boundaries determine the processes and stages that will be included in the assessment. For this, the complete life cycle of the project shall be considered (Figure 1). The life cycle is composed of; a pre-construction stage (Module A0), product stages (Modules A1 to A3), construction stages (Modules A4 and A5), use stages (Modules B1 to B8), and end of life stages (Modules C1 to C4). Additionally, supplementary information beyond the life cycle (Module D), shall be included.

Environmental indicators can include global warming potential (kg CO_2 eq.), ozone depletion (kg CFC 11 eq.), human toxicity (CTUh), ionizing radiation (kBq U235 eq.), freshwater eutrophication (kg PO4 eq.), and energy use and sourcing (MJ), among many others. Economic indicators include the cost of materials, construction, use, maintenance, and demolition, as well as the possible impacts on the local economy, and externalities, among others. Social indicators can include categories such as accessibility, connectivity, health and wellbeing, impact on the neighborhood, resilience, safety and security, job creation, and cultural heritage elements, among many others. Each of the listed aspects can be subdivided in more specific indicators, for example, impact on neighborhood can include noise generation, shocks and vibrations, light pollution, and changes to microclimate, among others.

Depending on the nature of the project, different indicators for each requirement can become relevant (or not). As such, evaluations must be project specific and include a thorough examination of all indicators that are to be included or excluded from the analysis.

While environmental and economic indicators can be straightforward to measure and quantify (e.g., calculating total construction costs or equipment energy usage), social indicators usually require a more complex analysis. Social indicators such as job creation can be simple to measure (e.g., number of people to be employed and types of employments). While indicators such as resilience against consequences of climate change (e.g., risks resulting from hazards and extreme weather events) or changes of microclimate (e.g., impact on local temperature, changes in winds and/or precipitations), can require extensive analysis where several assumptions must be made. Some social indicators will require the survey of local communities and/or experts in the field to measure, albeit, in a qualitative manner, different impact indicators.

3 SUSTAINABILITY EVALUATION

Guidelines such as EN 17472 (2022) state which indicators should be evaluated under each sustainability requirement. Different indicators will have different units of measurement (e.g., kg and € or $), thus, are only comparable between themselves. In the case of cost requirements, most indicators are expected to be measured in a specific currency (e.g., euros, €), so the total cost (or impact) can be easily aggregated. On the other hand, environmental and social indicators will have different units of measurement, thus, are only comparable between themselves and the aggregation process is not trivial. This can lead to evaluations being carried out using single indicators, as is currently the case with several modern environmental impact calculators, which rely solely on global warming potential or carbon footprint as environmental indicator.

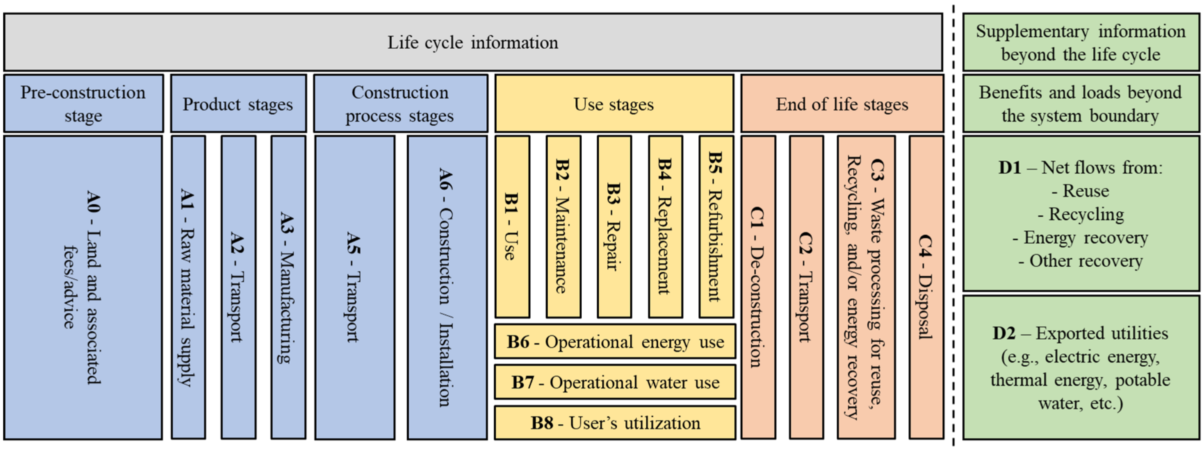


Figure 1. Boundaries of life cycle stages to be used when quantifying sustainability indicators (Adapted from **EN 17472, 2022**)

While useful, using a single indicator can lead to overlooking additional impacts (in social and environmental requirements).

To properly evaluate each requirement (i.e., carry out a successful sustainability assessment), multi-criteria tools which allow for the aggregation of several different indicators must be used. Examples of these tools are the Integrated Value Model for Sustainability Assessment (MIVES, due to its acronym in Spanish) (Josa et al., 2008) and the Quantitative Assessment of Life Cycle Sustainability (QUALICS) (Reddy et al., 2019). A key characteristic of multi-criteria models such as MIVES, is the ability to prioritize (or rather, make a decision), based on well-defined decision trees, which incorporate different criteria (with different measuring units and/or scales) as an aggregated value. The MIVES methodology has been previously used in several engineering-related assessments (e.g., Josa et al., 2020; Zubizarreta et al., 2019)

Figure 2 shows the flow chart of the multi-criteria sustainability assessment using MIVES. A multi-criteria sustainability assessment begins with the definition of requirements, criteria, and indicators. Based on EN definitions, these requirements must include economic, environmental, and social aspects.

Through the use of value functions, each indicator (e.g., direct costs, global warming potential, or noise generation) is converted from a quantitative or qualitative value to a dimensionless scale between 0 (minimum satisfaction) and 1 (maximum satisfaction), defined as $V_{indicator}$. Value functions can have several shapes (Figure 3), positive or negative slopes, and are defined for each indicator individually. $V_{indicator}$ are then weighted ($W_{indicator}$) and summed to obtain the criteria value ($V_{criteria}$) for each requirement. If the $V_{indicator}$ array is defined by a single value (e.g., total cost of the alternative only), then the weighting factor for said requirement will be 1.0. On the contrary, for different categories, different weighting factors can be defined (e.g., using different environmental impact indicators scores). Following this, $V_{criteria}$ are weighted ($W_{criteria}$) and summed in order to obtain a single score for each requirement ($V_{requirement}$). Finally, the MIVES score for each alternative (V_{final}), also named Sustainability Index (SI), is the sum of each weighted requirement ($W_{requirement}$).

The assignment of weights is fundamental. Values should be carefully assigned to not overly favor any $V_{indicator}$ and/or $V_{criteria}$. One way of doing this is by using ratios which take in consideration the relevance of each aspect. A more thorough alternative is the use of an analytical hierarchy process (AHP). In an AHP, weights are obtained by undertaking paired-comparison of all elements that are to be weighted. This allows to determine a relevance scale considering all element permutations. For requirements, the final weighting can be understood as a reflection of the stakeholders' preferences.

In short, the MIVES method relies on five core steps: (1) hierarchization, in which the requirement tree is defined; (2) evaluation, where indicators are defined and measured; (3) value generation, in which scores and measurements are transformed into value; (4) weighting, where the decision making scenarios are defined; and (5) aggregation, in which values and their respective weights are summed to obtain a final score.

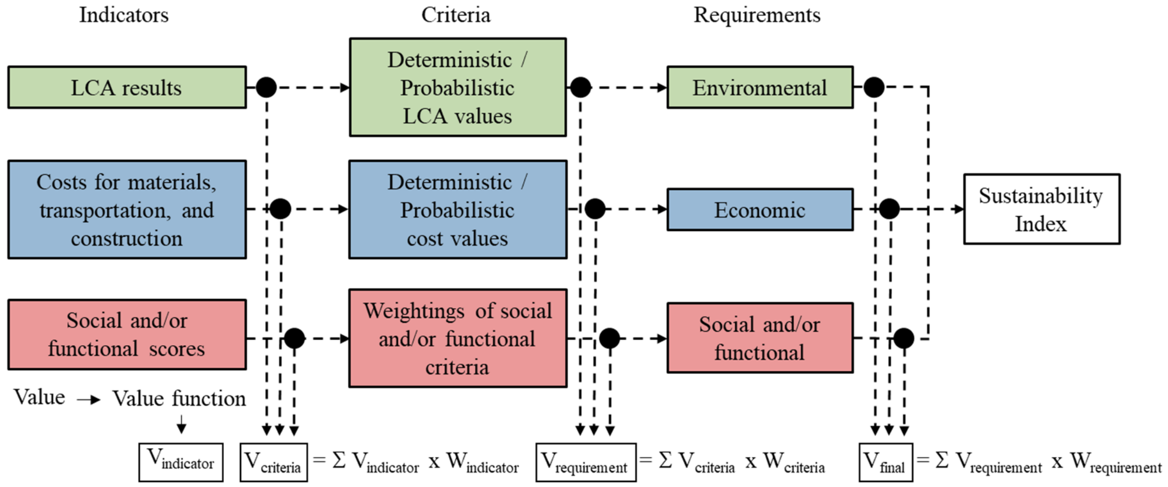


Figure 2. Conceptual workflow of the MIVES methodology (Adapted from **Damians et al., 2018**).

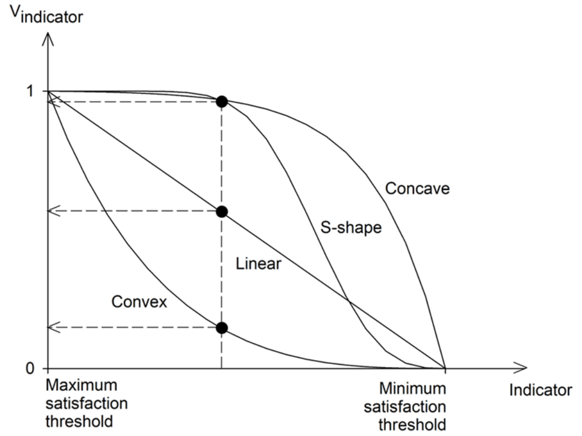


Figure 3. Schematic representation of decreasing (or negative slope) value functions.

4 PRACTICAL EXAMPLE

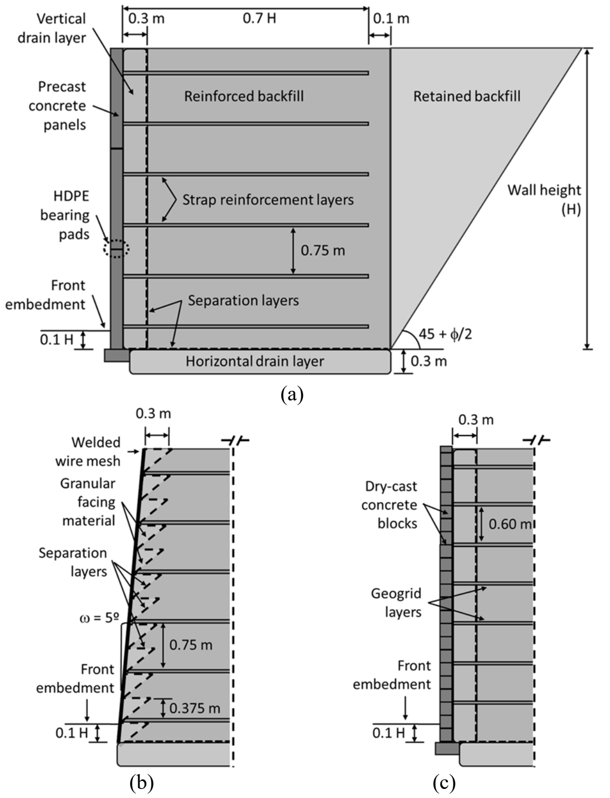
4.1 *Geosynthetic reinforced soil wall case*

In the following section, three distinct reinforced soil wall scenarios (RSWs) are used to exemplify the use of multicriteria tools in sustainability assessments. The structures consist of RSWs with variable height (H = 3, 6, 9 m) with polymeric reinforcement layers and a quarried high-quality granular backfill ($c = 0$ kPa, $\phi = 36º$). Facing elements include three different alternatives, namely, 1.5-m-high by 0.15-m-wide precast concrete panels (PCP) (Figure 4a), welded wire mesh with a batter angle (ω) of 5º (WWM) (Figure 4b), and 0.2-m-high, 0.3-m-deep (toe to heel), and 0.2-m-precast discrete concrete blocks (DCB) (Figure 4c). Structures consider a minimum reinforcement length of 0.7 H. Discrete concrete blocks use geogrid reinforcements, while concrete panels and welded wire mesh facings use polymeric strap reinforcements.

All walls have a front toe embedment of 0.1 H, as well as a nonwoven geotextile separation layer towards the front and bottom of the structure. The purpose of this layer is to avoid any migration to and from the fill material due to water infiltration.

The functional unit is defined as 1-m of running length of a RSW with a design life of 120 years. Further details on life cycle inventories, and environmental and cost analysis, can be found in the authors' previous work (Moncada et al., 2024a, 2024b).

Environmental and economic indicators were quantified using a probabilistic definition. For every scenario (i.e., facing material alternative and wall height), a base, minimum, and maximum quantity cases were considered to obtain triangular frequency distributions with a minimum, modal, and maximum results. Minimum and maximum scenarios aim to represent e inventory uncertainties (e.g., material losses) as well as possible variations in the construction process. Materials and construction activities use the nominal quantity plus the average of the proposed variations for the base scenario (also called modal quantities), while transport activities consider the nominal quantity as the base case. Minimum scenarios use the nominal value plus the minimum variation (which can be negative for transport distances). Maximum scenarios use the nominal values plus the maximum variation. Said methodology allows for triangular frequency distributions with a minimum, modal, and maximum value for environmental and cost analysis. This methodology has been previously used by the authors to evaluate different backfill materials for RSWs (Moncada et al., 2025). In the case of costs, minimum, modal, and maximum quantities are multiplied by a minimum, modal, and maximum costs to obtain the triangular distribution. For each scenario, a random cost and environmental impact value was obtained using Monte Carlo simulations based on each triangular frequency distribution function.



(a)

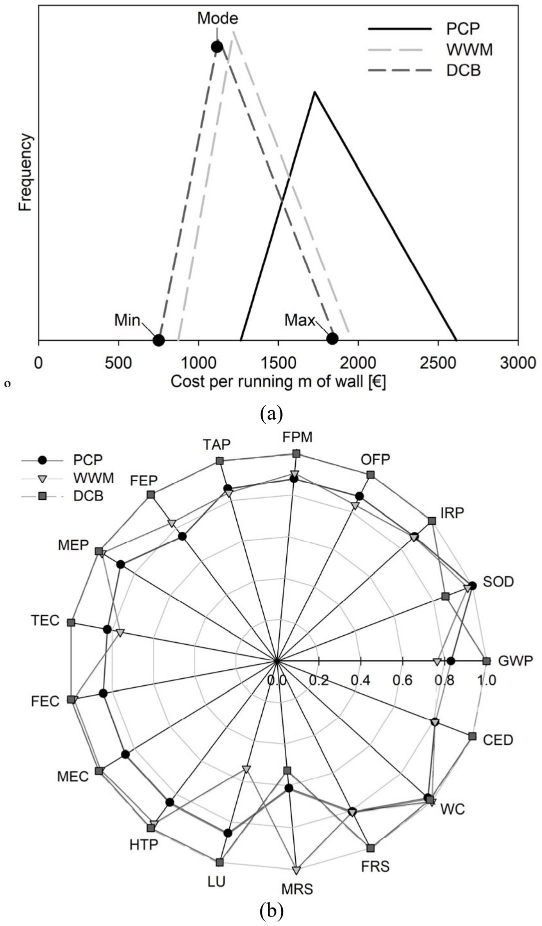
(b) (c)

Figure 4. Schematic representation of the idealized geosynthetic reinforced soil walls with (a) precast concrete panels and with (b) welded wire mesh facing and (c) dry-cast concrete block facing elements.

Figure 5a shows the triangular frequency distribution for cost for the three facing alternatives and a wall height of 6 m. Figure 5b shows the relative value of seventeen environmental indicators obtained using the ReCiPe 2016 v1.1 (Huijbregts et al., 2017) and the CED v1.11 (Althaus et al., 2010) methods. Relative values are calculated as the ratio between the highest value over each alternative's value for each indicator individually. Results show that the most impactful solution can vary depending on the environmental indicator, evidencing the need to analyze more than a single indicator.

For the sustainability assessment, all environmental indicator were aggregated in what is called endpoint indicators using the ReCiPe method. As with cost indicators, calculated endpoint environmental indicator consists of a modal, minimum, and maximum scenarios.

Each random indicator value is used as an input of the value function, which results in a set of random $V_{indicator}$ for both requirements (economic and environmental). The mode of the $V_{indicator}$ array is then used to obtain the resulting $V_{criteria}$. The described methodology has been used in the past to evaluate the impact of structures when there is limited data available (Damians et al., 2018).



(a)

(b)

Figure 5. (a) Triangular cost frequency distributions and(b) relative value of midpoint environmental impact indicators, both for modal quantities and wall height of H = 6 m. *Note: GWP: Global warming, SOD: Stratospheric ozone depletion, IRP: Ionizing radiation, OFP: Ozone formation, FPM: Fine particulate matter formation, TAP: Terrestrial acidification, FEP: Freshwater eutrophication, MEP: Marine eutrophication, TEC: Terrestrial ecotoxicity, FEC: Freshwater ecotoxicity, MEC: Marine ecotoxicity, HTP: Human toxicity (includes carcinogen and non-carcinogen), LU: Land use, MRS: Mineral resource scarcity, FRS: Fossil resource scarcity, WC: Water consumption, CED: Cumulative energy demand.*

The social/functional requirement is defined in a deterministic way using results from an online survey handed out to students and professionals related to the field of geotechnical engineering and reinforced soil structures. For nine out of eleven social/functional indicators, the modal answer is used as the indicator value. For the remaining two indicators, an AHP is used to quantify the indicators' value.

Value functions were selected based on the work of Damians et al. (2020). A concave shape (see Figure 3) was used for the environmental and economic requirements, while a linear shape was used for the social/functional requirement. For environmental indicators, maximum satisfaction (Vindicator = 1.0) is set as the lowest mean value across alternatives for each wall height. The minimum satisfaction (Vindicator = 0.0) is set as 1.75 times the minimum modal value across alternatives.

For the economic indicator, maximum satisfaction (Vindicator = 1.0) is set as 1.25 times the lowest possible value among all alternatives (i.e., the minimum value among the lowest quantity and lowest cost combination). The minimum satisfaction (Vindicator = 0.0) is set for 2.0 times the minimum modal cost among all alternatives.

For the social/functional requirement, minimum (Vindicator = 0.0) and maximum (Vindicator = 1.0) satisfaction is achieved for the lowest (i.e., 1) and highest (i.e., 5) scores, respectively. Some indicators are more favorable for lower values, for which the satisfaction criteria are inversed. For the two indicators evaluated using AHP, minimum and maximum satisfaction levels are adjusted to a 0 to 1 scale, respectively.

4.2 *Results*

A total of nine sustainability assessments were carried out (three heights and three facing materials alternatives). Requirements have equal weights for all assessments (i.e., $W_{economic} = W_{environmental} = W_{social/functional} = 1/3$). Sustainability assessments for each alternative are quantified using a sustainability index (SI) score. A higher SI value means a more sustainable alternative.

Figure 6a shows the final mean SI score for all facing material alternatives for all wall heights. PCP is the most sustainable solution, but only by a small margin. The PCP alternative has a higher score in environmental and social/functional requirements, while WWM and DCB have higher scores for the economic requirements. When comparing mean ± one deviation SI scores (Figure 6b), the three facing alternatives give comparable results across all wall heights.

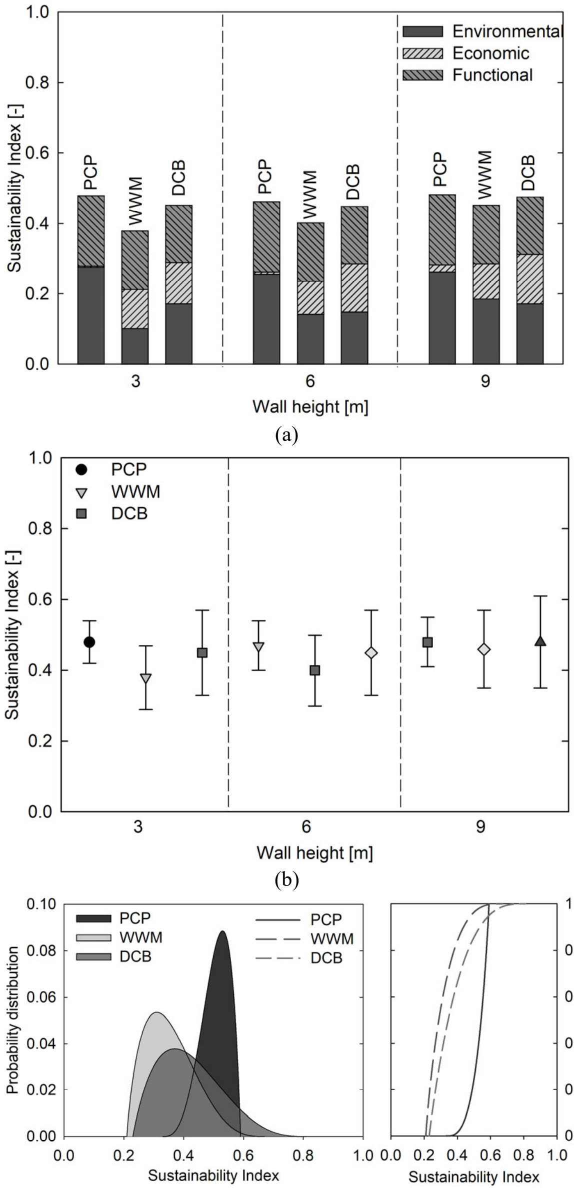
Figure 6c shows the probability and cumulative distribution functions for facing alternatives for a wall height of 3 m using. WWM and DCB show a larger spread across all wall heights, compared to PCP. The use of PCP appears to be slightly more favorable. By using a probabilistic approach, distribution functions allow to better understand uncertainties and negative cornerstones in the analysis.

5 CONCLUSIONS

The present work focusses on describing the sustainability approach of the newly published Eurocode 7, which incorporates sustainability requirements based on economic, environmental, and social aspects. Each requirement is to be evaluated in order to assign a consequence class to the structure prior to its design Sustainability requirements compete with loss of human life or personal injury in this regard. The process through which each sustainability requirements is quantified is explained. The Integrated Value Model for Sustainability Assessment (MIVES) methodology is explored for the sustainability assessment of geotechnical structures. Geosynthetic reinforced soil structures with different facing element alternatives are used as example.

Each sustainability requirement is to be evaluated using sets of indicators relevant to the structure's scope. Indicators will have different units and can be quantitative and/or qualitative. Indicators must be compared and, ideally, aggregated to analyze the best possible solution.

Aggregation of indicators requires the use of multi-criteria models, in which a weighting system, based on stakeholders' preferences, indicators relevance, or other criteria, enables to calculate an aggregated, final score. An example of these models is the MIVES methodology. This method begins with a hierarchization scheme, followed by and evaluation, weighting, and final aggregation process through which a single Sustainability Index is obtained for each alternative being analyzed.



(c)

Figure 6. (a) mean Sustainability index results and (b) final sustainability index (mean value ± one standard deviation) for all cases and wall heights, as well as (c) Sustainability index probability distribution (left) and cumulative distribution (right) for a wall height of H = 3 m

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