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RELEVANT ASPECTS TO SUSTAINABILITY ASSESSMENTS OF GEOTECHNICAL STRUCTURES

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ABSTRACT

The concept of sustainability includes a multiplicity of variables which must be carefully quantified and analysed to provide solutions which ensure the short-, medium-, and long-term well-being of society. Based on European standards, sustainability assessments must encompass environmental, economic, and social/functional requirements (or pillars). Results from each individual evaluation can yield different conclusions, particularly for the social/functional aspects, thus, multi-criteria methods are required to quantify global scores between comparable solutions. One alternative is the integrated value model for sustainable evaluation (MIVES, for its acronym in Spanish). Said methodology allows for a quantitative assessment using multi-criteria analyses based on user-defined requirements. The present work describes the use of MIVES applied to geotechnical structures. The basis of the methodology is described, including the definition of requirements, use of value functions, and effect of stakeholders' preferences or design requirements via weightings. Example scenarios using idealized reinforced soil walls are provided.

Keywords: sustainability, multi-criteria decision making, MIVES, geosynthetics, reinforced soil.

INTRODUCTION

Sustainability is a complex, multi-variable concept through which geotechnical engineering can improve the world we live in (Basu and Lee, 2021). Sustainability assessment must include environmental, economic, and social and/or functional pillars (or requirements) (EN 15643, 2021). The environmental pillar involves understanding the use of resources and impact to the environment during the life cycle of the system. The economic pillar requires a life cycle cost analysis of all materials, personnel, transportation, and construction and/or deconstruction activities. Finally, the social/functional aspects can cover a wide array of conditions, including health and safety, adaptability and accessibility, and resilience against damaging or catastrophic events such as those expected to occur due to climate change.

This work covers a specific multi-criteria methodology for sustainability assessments, including a thorough step-by-step explanation and a practical use example considering reinforced soil walls.

INTEGRATED VALUE MODEL FOR SUSTAINABILITY ASSESSMENT (MIVES)

The Integrated value model for sustainability assessment (MIVES, for its acronym in Spanish) was developed to quantify and compare how sustainable different engineered solutions are (Josa et al., 2008). Example of its use within geotechnical engineering can be found in the literature (e.g., Damians et al., 2018; Josa et al., 2021). The MIVES method begins with a requirement tree (or hierarchization process). Figure 1a shows the decision tree of a proposed multi-criteria sustainability assessment. While the calculation process goes from indicators to requirements, the decision tree must be defined from requirements to indicators to avoid any bias prior to the analysis. Figure 1b shows a sample decision tree used in the following section.

Once the requirement tree is defined, indicators for each criteria and subsequent requirement must be defined. Indicators are the measurable inputs of the method (e.g., direct and indirect cost, global warming potential, among others). Once the whole decision tree has been defined, user can proceed with the assessment of indicators. Indicators with quantitative or qualitative units are transformed to value scores ($V_{\text{indicator}}$) using value functions.

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Figure 2 shows a schematic representation of decreasing value functions of different shapes. Functions are defined by a minimum and maximum satisfaction threshold, assigned individually to each indicator. These values are selected based on the expected or required scores for each indicator. Calculated $V_{indicator}$ scores, be it a single value (defined by a single indicator) or an array (defined by multiple indicators) are then weighted ($W_{indicator}$) and added to obtain a $V_{criteria}$ value. For multiple indicators, weights can be evenly distributed, or determined by an analytical hierarchy process (AHP). A AHP consists of a pair-wise comparison of all alternatives, thus, provides a weighting value which includes the relative importance of each component.

$V_{criteria}$ are then weighted ($W_{criteria}$) to obtain the value of each requirement ($V_{requirement}$). $V_{requirements}$ values are aggregated to obtain a final sustainability index (SI) for each alternative. Weighting scenarios ($W_{requirement}$) should be based on stakeholders' preferences, be it by predefined values or AHPs. The assignment of weights is fundamental, as the final results will heavily depend on favouring or disfavouring a specific indicator, criteria, or requirement. It is highly encouraged to undergo sensitivity analysis of weighting scenarios to properly assess how SI scores vary. As a standalone value, the final SI score has no physical meaning. It is only relevant as a comparison tool to aid in a decision-making process.

PRACTICAL EXAMPLE: REINFORCED SOIL WALL FACING ELEMENTS

Sustainability assessments were carried out for vertical facing elements of reinforced soil wall (RSW). For this purpose, a functional unit was defined as 1 m of running length of RSW with polymeric reinforcements constructed over competent foundation soil with a design life of 120 years.

As retaining walls are expected to have little to no maintenance during their service life (given no catastrophic event occurs), a cradle-to-built timespan was considered. Three wall heights were considered: 3, 6, and 9 m tall. Backfill material is considered the same for all alternatives. Facing elements include 1.5 m high and 0.15 m thick pre-cast concrete panels (labelled as "PCP") placed over discrete high-density polyethylene (HDPE) bearing pads (Figure 3a); 0.75-m-high segmental, welded wire meshes (labelled as "WWM") with a battering angle (ω) of 5° (Figure 3b); and 0.2 m high, 0.3 m deep, and 0.2 m wide dry-cast concrete blocks (labelled as "DCB") (Figure 3c).

Requirements were defined as environmental, economic, and social/functional (Figure 1b). A life cycle inventory was defined for all alternatives and used for the environmental and economic assessment. The environmental requirement consists on a combination of endpoint indicator (aggregated value of 18 midpoint indicators) obtained via a life cycle assessment, together with

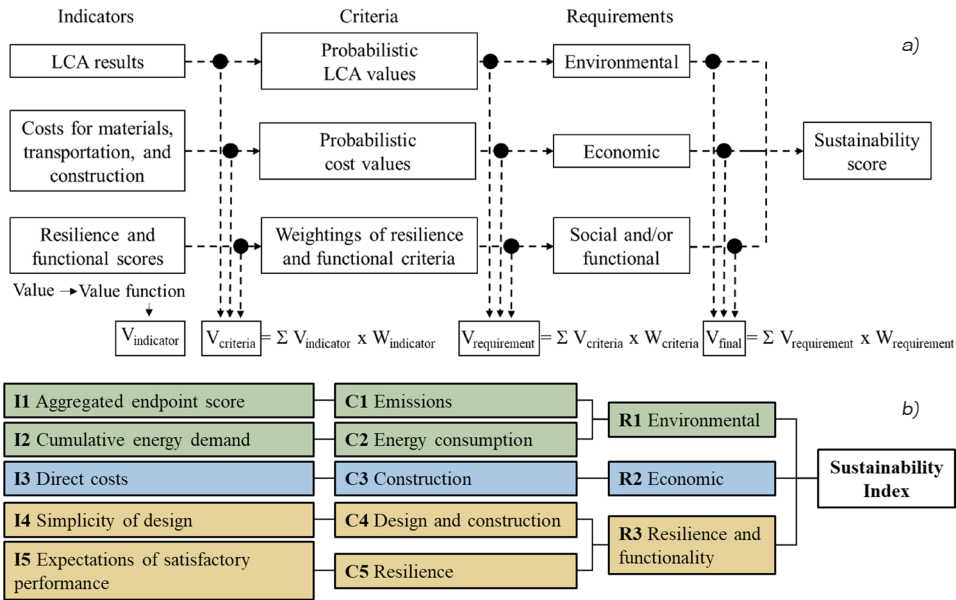


Figure 1 (a) Schematic representation (modified from Damians et al., 2018) and (b) practical example of the decision tree used in a sustainability assessment process.

cumulative energy demand indicator. The economic requirement includes only the direct costs. For the purpose of this paper, the social/functional requirement considered two indicators extracted from an online survey-form carried out by the authors, answered by professionals in the soil reinforcement field and civil engineering Master's program students.

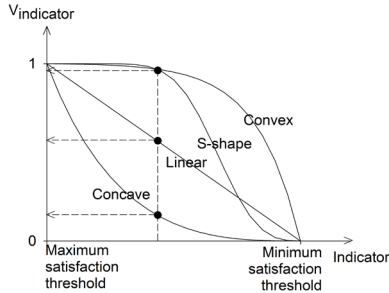


Figure 2 Decreasing value function shape schematic

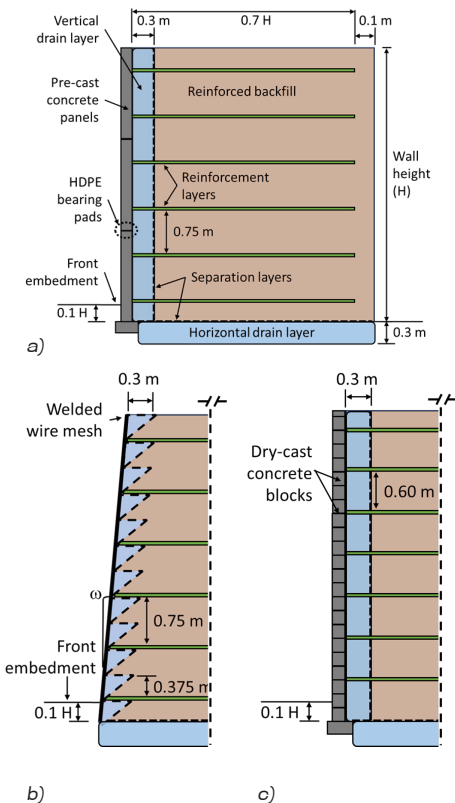


Figure 3 Schematic representation of the idealized RSWs with (a) precast concrete, (b) welded wire mesh, and (c) dry-cast concrete facing elements.

For value functions, the environmental maximum satisfaction ($V_{\text{indicator}} = 1.0$) was set as the lowest mean value across alternatives for each wall height. The minimum satisfaction ($V_{\text{indicator}} = 0.0$) was set as 1.75 times the minimum modal value across alternatives. The economic maximum satisfaction was set as 1.25 times the lowest possible value among all alternatives (i.e., the minimum value among the lowest quantity and lowest price combination). The minimum satisfaction was set for 2.0 times the minimum modal cost among all alternatives. The functional minimum and maximum satisfaction were achieved for the lowest (i.e., 0) and highest (i.e., 1) scores, respectively. A concave shape was used for the environmental and economic requirements. A linear shape was used for the functional/social requirement.

Environmental and economic indicators follow a probabilistic definition. For every alternative, a base (or modal), minimum, and maximum quantity cases allow to define triangular frequency distributions. Minimum and maximum variation aim to include inventory uncertainties (e.g., material losses) in the analysis. 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. Each random indicator score is then used as an input of the value function, resulting in a set of random $V_{\text{indicator}}$. Consequently, the final SI score can be analysed following a probabilistic approach. In the present work, SI were calculated using evenly distributed weights among all requirements (i.e. $W_{\text{environmental}} = W_{\text{economic}} = W_{\text{functional/social}} = 33\%$).

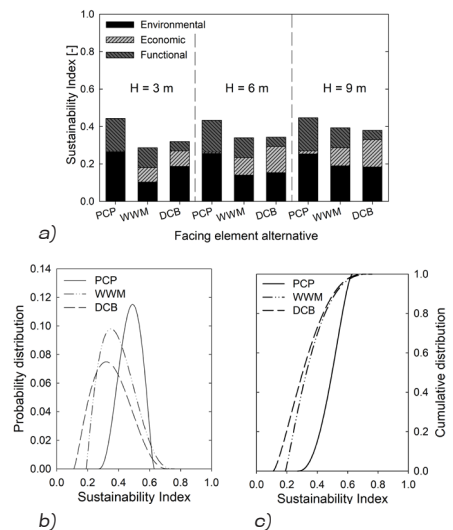


Figure 4 Sustainability index (a) mean values for all wall heights, (b) probability and (c) cumulative distribution functions of a wall height of 9 m.

Figure 4a shows the mean SI results for all alternatives across all wall heights divided by requirements. Using mean values, the PCP alternative shows as the most sustainable solution across all wall heights, mainly by the contribution of functional and environmental requirements scores. Differences between alternatives are reduced with increased wall heights. WWM and DCB alternatives have comparable score across all wall heights, where WWM is slightly above only for $H = 9$ m.

Figure 4b and 4c show the probability distribution and cumulative distribution, respectively, for the SI of the three alternatives, for a wall height of 9 m. Probabilistic results are characterized using a PERT distribution (asymmetrical continuous probability distribution, akin to a smoothed triangular distribution), defined by a minimum, maximum, and modal value. Given the considered uncertainties, results show considerable overlapping of the probability distribution. The PCP alternative shows to be the most probable sustainable alternative. Further project-specific details would allow to reduce results uncertainties.

Depending on the selection of value functions and weighting scenarios, results are expected to vary. Concave functions are more punishing for lower indicator scores, while linear functions allow for proportional increments. A convex or S-shape functions will give similar value to a wider range of indicator scores within the vicinity of the maximum satisfaction threshold. As for requirement weights, favouring a specific requirement would alter results. For example, as the economic requirement score is considerably lower for the PCP alternative across all heights, increasing Weconomic over the other requirements would benefit the WWM and DCB alternatives.

CONCLUSIONS

In this work, a multi-criteria methodology to carry out sustainability assessments of civil and geotechnical structures is presented. The Integrated value model for sustainability assessment (MIVES) is based on the definition of hierarchized requirements, criteria, and indicators which allow for a comprehensive assessment. Indicator scores, be it quantitative or qualitative, are transformed to dimensionless value score through value functions. Value scores are then aggregated considering different weight scenarios to obtain a final sustainability index, used to compare different alternatives and aid in decision-making processes.

Sustainability assessments of vertical facing elements of reinforced soil walls are used as example. Facing alternatives include precast concrete panels, welded wire mesh, and dry-cast concrete blocks. Precast concrete panels were found to be the most probable sustainable solution. Nevertheless, depending on value functions shapes and requirement weighting, results are expected to vary. Distribution functions were used to present

model uncertainty and highlight the relevance of project specific data to properly evaluate different alternatives.

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