

CLIMATE-ADAPTIVITY OF LANDSLIDE RISK MITIGATION MEASURES: FRAMEWORK AND PRELIMINARY VALIDATION

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It is increasingly recognized that climate change significantly impacts civil society, as evidenced by the rise in climate-driven hazards (e.g., rainfall-induced landslides). Therefore, it is important for engineers to explore climate-adaptive and regenerative landslide risk mitigation options, employed stand-alone or in combination with conventional engineering solutions. In this paper the Climate Change Adaptation (CCA) group of the European Large Geotechnical Institutes Platform (ELGIP) presents the preliminary results of a study on assessing the feasibility of applying nature-based solutions (NbS) as climate-adaptive landslide risk mitigation measures. The basis for this study relies on the outcomes from a previous study conducted by the CCA working group regarding the adaptivity of geo-structures to climate change effects.

The paper proposes a three-level sequential evaluation system to assign scores to the climate-adaptiveness of the NbS included in the LaRiMiT (Landslide Risk Mitigation Toolbox) database, a web-based platform for the case-specific selection of landslide risk mitigation measures. The conceptual standpoints and preliminary results from applying the three-level scoring process are presented and assessed critically.

Keywords: geohazards, landslides, climate change adaptivity, risk mitigation, experts scoring, Nature-based Solutions.

1. Introduction

In line with the EU climate adaptation strategy and global efforts toward a climate-neutral economy, the international geotechnical community has been active in the research of more sustainable and climate change resilient design solutions, as recently reviewed by Vitale & Liu (2024). However, this review also shows that significant uncertainties remain regarding the best practice to be used when moving towards the concept of resilient geo-structures. One example of climate-adaptive landslide risk mitigation is the use of nature-based solutions (NbS), which stem from soil bioengineering practices (Preti et al., 2022) and use plants or their parts as building materials for slope stabilization and erosion protection, being cost-effective and providing biodiversity improvement. NbS, when employed as mitigation measures for landslide hazards, also have the potential to prevent or positively act on other foreseeable climate change impacts on geotechnical properties and thermo-hydro-mechanical processes.

Insana et al. (2021) provided an overview of eight primary climate change signals expected for European countries in the future (e.g., increased precipitation, increased air temperature) and their effects on soil geotechnical properties and processes (e.g. increased erosion, increased degradation of material strength due to increased saturation and physical weathering).

The adoption of NbS among practitioners relies significantly on the dissemination of knowledge regarding their suitability and effectiveness in specific geo-hydro-mechanical conditions and climatic scenarios. To support this, [LaRiMiT](#) is a web portal designed to aid practitioners in the early phase of landslide risk management (Uzielli et al., 2017). The portal provides the case-specific rankings of conventional, nature-based and combined landslide risk mitigation measures based on user-provided local data and the expert-assigned suitability scores on a common scale (from 0 - not relevant to 10 – highly relevant). The expert scoring is based on parameters directly dealing with landslide criteria (e.g. material type, type of movement, rate of movement etc.), but also site conditions, environmental constraints, and socio-economic factors, which should be further enlarged with a climate-sensitive judgment. The uniqueness of the portal relies in

the fact that this is the only existing platform for selecting landslide mitigation options based on experts' opinions.

In this study, we propose a procedure to assess the adaptivity of the NbS available in the LaRiMiT database to the climate change effects (CCE) identified by Insana et al. (2021). The paper also illustrates the preliminary results of an initial application of the methodology conducted within the ELGIP Climate Change Adaptation group. The process involves both individual and group activities, allowing the assessment of the effects of collaborative scoring.

2. Materials and Method

2.1. Mitigation measures evaluated

The NbS sourced from the LaRiMiT database are categorized based on their functions, i.e. whether acting on predisposing or triggering factors of physical processes (e.g., erosion control, nature-based retaining structures to enhance slope stability). Additionally, hybrid measures that combine NbS with conventional ("grey") engineering solutions were also considered. The complete list of NbS and hybrid measures available in the LaRiMiT database and evaluated in at least the first phase of the proposed method can be found in Capobianco et al. (2022).

2.2. Proposed workflow

The proposed methodology consists of a three-Level sequential evaluation system, as shown in Fig.1. The three-tiered assessment system is based on the authors' speculation that, due to the topic's novelty, expert experience in individual assessments may be lacking. Group discussions can refine scoring (as testified by novel teaching/learning techniques, such as Team-Based Learning, see Michaelsen (2005)), followed by a literature analysis to resolve discrepancies. Level-1 scoring relies on the individual compilation of an identical online survey to be sent to experts in the field. Survey takers are requested to provide an expert opinion regarding the impact of the evaluated mitigation on the anticipated future effects of climate change on geotechnical properties and processes, identified by Insana et al. (2021). The survey is divided into sections, each focusing on a specific Climate Change Signal (CCS), such as increased precipitation or increased air temperature, and the associated anticipated effects (CCE) on the geotechnical and geological properties of a system. For instance, the CCS *Increased precipitation*, results in CCEs such as *A.1 Increased degradation of material strength due to increased saturation and physical weathering*, *A.2 Increased mineral dissolution due to increased chemical weathering*, among others. The complete list of CCSs and their associated CCEs is available in Insana et al. (2021). For consistency, the original CCE coding is maintained.

The impact of the mitigation measure on each CCE is scored on a scale from 0 to 10, where 0 = negative impact (no reduction or worsening of the CCE) and 10 = highly positive impact. A blank score may be awarded if the measure evaluated is believed to not influence the impact on that CCE. As this scoring is solely dependent on the expert's opinion, they are asked at the end of the survey, to specify the confidence level (LC) in their overall assessment on a scale from 1 (low confidence) to 3 (high confidence). Subsequently, salient sample statistics for the scores from Level-1 are calculated. In addition, the weighted average of the scores for each CCE (W_a) is calculated by weighting the assigned CCEs by the expert's self-assessed LC values and rounding to the nearest integer (Fig.1).

Level-2 scoring addresses the same questions given in the Level-1 survey. However, scoring is now conducted collegially through experts' team discussions, which can take place either online or in person, with preferred in-person meetings. Level-2 scores are denoted by T_i . The distribution of Level-1 scores W_a and Level-2 scores T_i for each CCE and for each mitigation measure can be visualized using box-whisker plots and assessed comparatively. Subsequently, both, the team final scores (T_i) and the weighted average (W_a), are categorised into three Score Categories (SC); namely, low (SC_L), medium (SC_M), and high (SC_H). Details of the criteria and outputs of the comparative assessment are given in the upper right box of Fig.1. Based on the outputs of this comparison, and in case of high discrepancy between Level-1 and Level-2 scores for the same measure, the procedure moves to Level-3.

In Level-3, which relies on literature, scores from Level-2 are either confirmed or further adjusted. To this purpose, outputs from both, the literature screening and Level-2 analysis, are used as inputs to enter the matrix provided in the bottom part of Fig.1. Specifically, the number of scientific publications addressing that specific CCE and the SC of the T_i after Level-2 analysis are to be used to enter the matrix and obtain as output the new SC and the literature-based score (L_i).

The query string for the literature screening, carried out by making use of the SCOPUS database, is based on two main keyword concepts: MM (name of mitigation measures evaluated) "AND" CCE (keyword of the climate change effect). The Boolean operator "OR" is used to link complementary keywords describing the same CCE.

The queries are constructed to search within index terms and metadata, specifically in the “titles, abstracts and keywords” fields of the Scopus database. For example, the query string for the mitigation measure (MM) “Hydroseeding” and for the Climate Change Effect (CCE) “Decreased surface and groundwater level and flow” are: TITLE-ABS-KEY (“Hydroseeding”) AND (“groundwater” OR “pore-pressure”), and TITLE-ABS-KEY (“Hydroseeding”) AND (“groundwater” OR “pore-pressure”) AND (“slope*”). In this case the keywords used for the CCE are “groundwater” and “pore-pressure”.

A threshold of three publications confirming a positive or negative impact was adopted. Given the novelty of the research topic and the relative paucity of technical literature, the mutual consistency between the content of three papers was considered sufficient to suggest their reliability. By combining the input values from Level-2 scoring with the number of publications, a new score category (L_i) is assigned. This score parameterizes the relevance awarded to a given measure in literature.

For example, if three or more publications consistently confirmed the positive impact of the studied measure on the specific CCE, this would raise its SC to High, regardless of its previous score category but, depending on its initial score category, the L_i will have a certain final value.

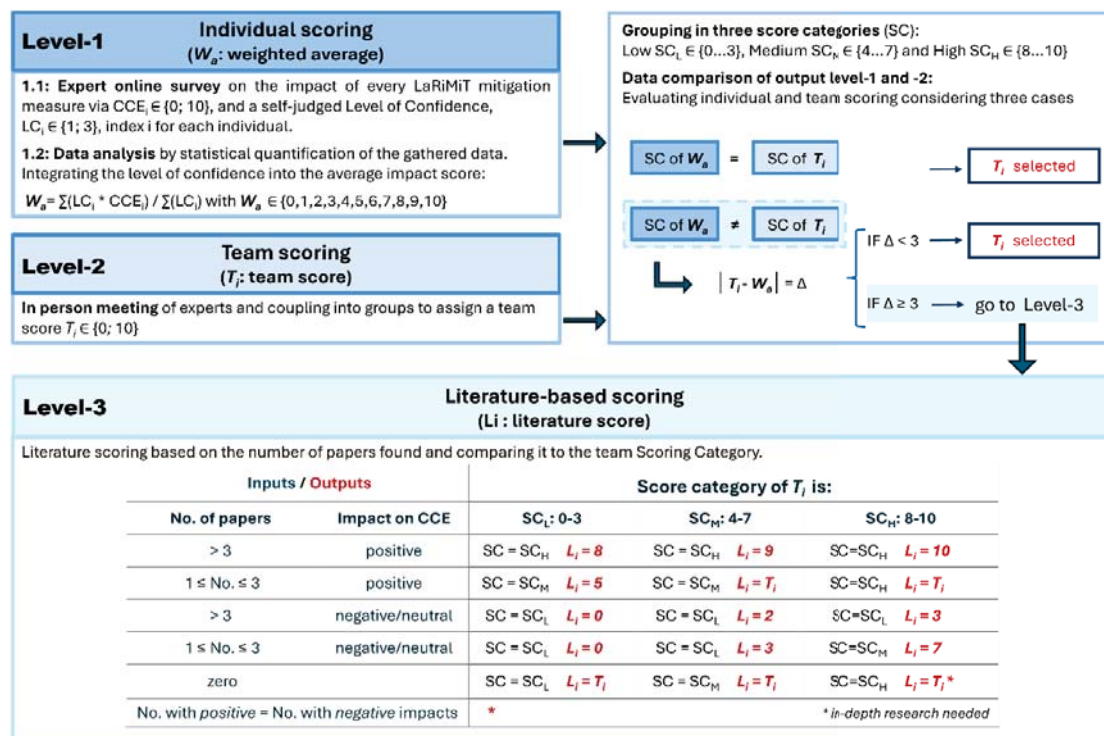


Fig. 1. Overview of the proposed three-Level scoring evaluation workflow, highlighting key steps at each scoring Level.

3. Preliminary validation of the procedure

The three-Level evaluation approach was partially tested by the members of the ELGIP CCA group, which represents a diverse array of institutes across Europe. These experts are involved in both the industrial and academic sectors of geotechnics, providing a comprehensive and well-rounded perspective on the subject.

For Level-1 scoring, an individual online survey was created using Microsoft Forms and distributed to group members, resulting in the evaluation of 24 measures, including both NbS and hybrid solutions, available in Capobianco et al. (2022). An in-person meeting took place during the collegial gathering of the ELGIP CCA group at the University of Florence in February 2024. During the meeting, the same participants who completed the online survey individually were divided into three groups of four members. Groups were diversified to optimize the equal distribution of researchers, PhD students, faculty members and practitioners. Group discussions were conducted to allow collegial insights into the measures to be scored at Level-2.

Due to time constraints, only 9 out of the 24 measures underwent additional evaluation with Level-2 team scoring. These measures were: 1.1 Hydroseeding, 1.2 Turfing, 1.4 Live/inert fascines and straw wattles, 1.5 Brush mattresses, 1.7 Live stakes (Live poles), 1.8 Live smiles, 4.5 Vegetation - Hydrological effects, 6.1 Vegetation - mechanical effects and 8.8 Live crib walls, following the original coding assigned in the LaRiMiT portal.

An example visualizing the results is shown in Fig.2.a for Hydroseeding which compares the distribution of scores and the calculated W_a from Level-1 scoring, with T_i scores from Level-2 scoring (16 out of 30 CCEs are shown for the sake of space). The extract from the data analysis shown in Fig. 2a demonstrates with green

boxes two out of the five CCEs with a discrepancy of ≥ 3 . This is shown in Fig. 2b, where the number of CCEs for each mitigation measure which required Level-3 analysis based on Level-2 outputs are listed. The Level-3 scoring procedure was conducted separately and involved only measure 1.1.

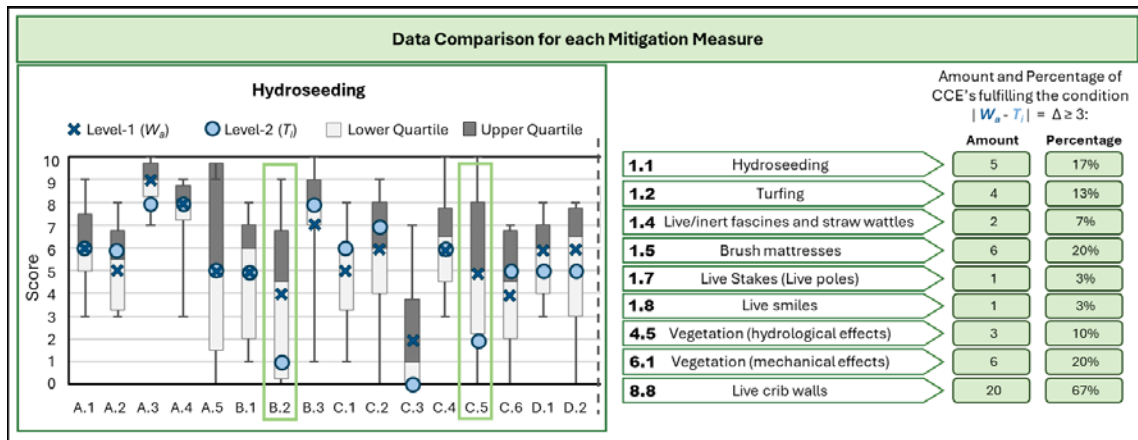


Fig. 2. a) Extract of data comparison results of Level-1 (W_a) and Level-2 (T_i) for the mitigation measure Hydroseeding, evaluated for Climate Change Effect (CCE) adapted from Insana et.al. (2021)e.g. A.4: Increased surface runoff due to increased precipitation; Quartiles are calculated only for the results from Level-1 scoring, before rounding the W_a to the nearest integer number. b) Required Level-3 analysis evaluated for each mitigation measure based on Data Comparison of outputs Level-1 and Level-2.

4. Discussion and Conclusions

This paper introduces a three-Level sequential evaluation procedure for scoring the impact of nature-based landslide risk mitigation measures on the effects of climate change. Key insights from its initial application demonstrate the flexibility of the procedure (e.g. the option to conclude scoring after Level-1) and show that team discussions enhance understanding and interpretation.

For all mitigation measures, except 8.8 Live Crib Walls, over 80% of climate change effects (CCEs) did not require Level-3 analysis, as Level-1 and Level-2 scores aligned closely ($\Delta < 3$), indicating consistency between individual and team scores. Discrepancies between individual and group scoring may arise from differences in personal experience, for example specific geographical contexts in which participants operate, among others.

Future work could include comparing the Level-1 and Level-2 scores using a smaller Δ , which may reveal additional CCEs requiring further literature analysis. Additional focus may also be placed on the calibration of the threshold number of papers required in Level-3 scoring to ensure sufficient confidence and coherency in literature scoring. In addition, a deeper analysis of the discrepancies between Level-1 and Level-2 scoring could lead to a more nuanced understanding of regional differences and the varied impacts that each measure could have on different climate change effects.

This work supports the EU climate adaptation strategy and provides a structured approach that combines expert insights and literature evidence on NbS effectiveness, addressing the current gap in documented efficacy for climate impact mitigation.

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