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Recent innovations in the LaRiMiT risk mitigation tool: implementing a novel methodology for expert scoring and extending the database to include nature-based solutions

Abstract This paper presents recent innovations implemented in the LaRiMiT (Landslide Risk Mitigation Toolbox) webtool. These include an innovative methodology for utilising experts' scoring of landslide risk mitigation measures directly within the decision support tool, and updating of the tool's database over structural measures to include many nature-based solutions (NBS) for mitigating landslide risk. Landslides are a common and treacherous natural hazard, and due to the effect of climate change on the frequency and intensity of extreme weather events, climate-driven landslides are expected to become more frequent. This negative trend is a driving factor for developing decision-support solutions for risk mitigation, and the LaRiMiT toolbox and the expert scoring methodology presented in this article contribute to meeting these needs. Selecting suitable structural measures is complicated due to factors such as site-specific conditions, local knowledge and resources, socio-economic constraints, and environmental considerations. LaRiMiT uses user-input attributes of site-specific slope movements combined with expert scoring of the suitability of various mitigation solutions to identify and select appropriate mitigation measures from an extensive database of structural solutions. While the LaRiMiT database initially included only conventional (grey) solutions relying on traditional methods, it has been recently expanded to include nature-based solutions (NBS), which are sustainable techniques for managing erosion and mitigating shallow landslides using vegetation and the use of natural materials. NBS and conventional solutions can also be combined to provide hybrid solutions. The proposed methodology for implementing expert scoring is dynamic and iterative, consisting of statistical pooling of experts' scores collected via online surveys, and consolidating these into an expert scoring utility embedded in the LaRiMiT web portal engine. An initial application of this methodology has been tested by surveying a set of landslides experts, mostly in Europe, and applying it to the structural measures database in the LaRiMiT tool. Although the number of experts in this initial application is limited, dynamic updating of the scoring allows the tool to continuously improve as additional experts contribute.

Keywords Landslide risk mitigation · Web-based toolbox · Expert scoring · Nature-based solutions · Mitigation measures · Soil bioengineering

Introduction

Landslides pose a major threat to human life, infrastructure, and the natural environment in many hilly and mountainous regions of the world (Nadim et al. 2006). Climate changes are leading to increased intensity and frequency of severe rainfall events, which combined with expanding urbanisation leads to greater exposure of people to the danger of rainfall-induced landslides (e.g. Gariano and Guzzetti 2016; Jaedicke et al. 2011).

Mitigation measures are needed; however, the decision process to select appropriate mitigation measures can be complex, with decision-makers likely having to consider a range of criteria other than purely technical ones. For example, commonly addressed criteria are related to the reliability or the suitability of the candidate measure within site-specific socio-economic and environmental constraints. Risk mitigation strategies often entail suitable structural or non-structural measures to reduce risk to acceptable/tolerable levels. Structural measures can be active or passive, where active measures are aimed at reducing the likelihood of a landslide and passive measures are aimed at decreasing the vulnerability and/or the exposure of the elements at risk. Non-structural measures are policies or actions such as insurance schemes and landslide early warning systems (LEWS), which are increasingly implemented worldwide (Piciullo et al. 2018; Pecoraro et al. 2019).

The LaRiMiT web portal (<https://www.larimit.com/>) is an ongoing research and development project resulting from several research programmes, and earlier versions of the portal are presented by Vaciago et al. (2013) and Uzielli et al. (2017). The web portal was developed to help practitioners during early phase management of rainfall induced landslides. Although the initial implementation is focused on Europe, the portal itself is not region specific and can be extended to include mitigation measures and experts from other regions. Many of the structural mitigation measures already presented in the database are widely adopted outside of Europe.

At that point in development, LaRiMiT included expert-assigned scores and ratings from a limited expert group for conventional mitigation measures, e.g. the measures most used and accepted by the scientific community (Margottini and Spizzichino 2020). NBS methods were not considered in this limited scoring regime. The

expert scoring was based on parameters such as landslide criteria, site conditions, and socio-economic aspects, and these scores were provided by only one or two experts depending on the measure considered.

Technical developments since 2017 include updating of the underlying programming environment (Django), the addition of many nature-based solutions (NBS) to the platform's structural measure database and implementation of the internal utilities supporting an expert scoring system as part of the systems tools. In late 2019, further development of the tool aimed at expanding the expert scores database for existing measures and establishing scoring of the new categories of NBS and hybrid solutions (the latter resulting from the combination of conventional and nature-based solutions). This process relied on the compilation of a survey by a group of selected international landslide experts and developing a methodology for collecting expert opinions and incorporating them into the LaRiMiT web portal. This approach is possibly the first-ever structured survey sent to experts in landslide risk mitigation for the purpose of developing statistical pooling of expert scores for each of the mitigation measures.

The LaRiMiT portal and database

Introduction of the LaRiMiT web portal

LaRiMiT is a collaborative, web-based landslide risk mitigation portal providing an expert-assisted tool for the case- and site-specific ranking and best-practice selection of landslide risk mitigation measures among a growing database of mitigation measure alternatives (currently 80). LaRiMiT focuses on three stakeholder groups: users, experts, and administrators.

Users and experts provide inputs to LaRiMiT, albeit in very different ways: User input is case/site specific and occurs in real time through dedicated forms on the LaRiMiT portal, whereas expert input is related only to the mitigation measures and this is collected in advance of any user input. Users are asked to give quantitative evaluations, for example the relative importance of economic aspects, environmental suitability, or a number of other key parameters.

User inputs include case-specific information regarding:

- The type of movement and relevant physical conditions at the site (i.e. mode of analysis (triggering/runout); type of movement; material type; depth of movement; rate of movement; ground water conditions; surface water conditions);
- The user's quantitative rating (on a scale 0–10, with 0: not relevant and 10: extremely relevant) of the relevance of the economic suitability of the mitigation measures to be implemented in the specific case under investigation: how important are the economic aspects (affordability, cost of design, realisation, and maintenance) in the selection of the mitigation measure? For instance, how important is it, in the specific case, that a mitigation measure is affordable and does not require high maintenance costs?
- The user's quantitative rating (on a scale 0–10, with 0: not relevant and 10: extremely relevant) of the relevance of the environmental suitability of the mitigation measures to be imple-

mented in the specific case under investigation: How important are environmental, landscape-related, aesthetic, and sustainability-related aspects in the selection of the mitigation measure? For instance, how important is it, in the specific case, that a mitigation measure has a low environmental impact?

- The user's quantitative rating (on a scale 0–10, with 0: low relevant and 10: extremely relevant) of the relevance of the timeliness of implementation of the mitigation measure. How important is the time factor for the implementation of the measure on site.

Expert inputs to LaRiMiT reflect technical knowledge regarding both the physical interactions between landslides and mitigation measures and other factors related to the implementation process as well as economic and environmental aspects of the measures themselves. Expert inputs from the reference rating database include:

- the set of candidate measures;
- quantitative technical suitability ratings (on a scale 0–10, with 0: not suitable and 10: fully suitable), including type of movement, material type, depth of movement, rate of movement, groundwater conditions, and surface water conditions;
- quantitative relevance ratings (on a scale 0–10, with 0: not relevant and 10: extremely relevant), expressing the relevance of each suitability factor with respect to movement-specific factors and case-specific factors (economic suitability, environmental suitability, timeliness of implementation).

The selection process is two-staged. Mitigation measures are initially filtered using quantitative scoring to remove unsuitable measures. The user then subjectively selects candidate measures for the next phase of the analysis, where the analytic hierarchy process (AHP) is used to determine a set of suitability scores for all candidate options. The AHP is a structured technique for organising and analyzing complex decisions, based on mathematics and subjective assessment (Golden et al. 1989; Vaidya and Kumar 2006; Saaty 2008). The output from this stage is three distinct output ranking systems for landslide risk mitigation measures: likelihood-based ranking, consequence-based ranking, and risk-based ranking. The AHP was implemented into the LaRiMiT tool by Uzielli et al. (2017). Figure 1 clarifies the synergy between administrators, experts, and users in the compilation and utilisation of the LaRiMiT toolbox.

The reliability of the ranking system is based on the scores provided by the experts. At the time of the first launch of the tool, the scores for each mitigation measure were provided only by one or two experts, mostly the LaRiMiT developers themselves or, in some cases, experts invited by the LaRiMiT developers. Thus, there was a need to improve the scoring system by involving more experts in landslide risk mitigation. The aim of this article is to fill this gap and propose a suitable approach for data analysis for a possible re-iteration of the scoring assessment as new inputs from experts become available.

The purpose of the web portal is to provide a structured tool for accessing, ranking, and selecting mitigation measures. The database of mitigation measures currently contains 80 structural solutions (as of September 2021); these can be easily browsed via the "Mitigation measures" tab in the web portal. The mitigation measures address

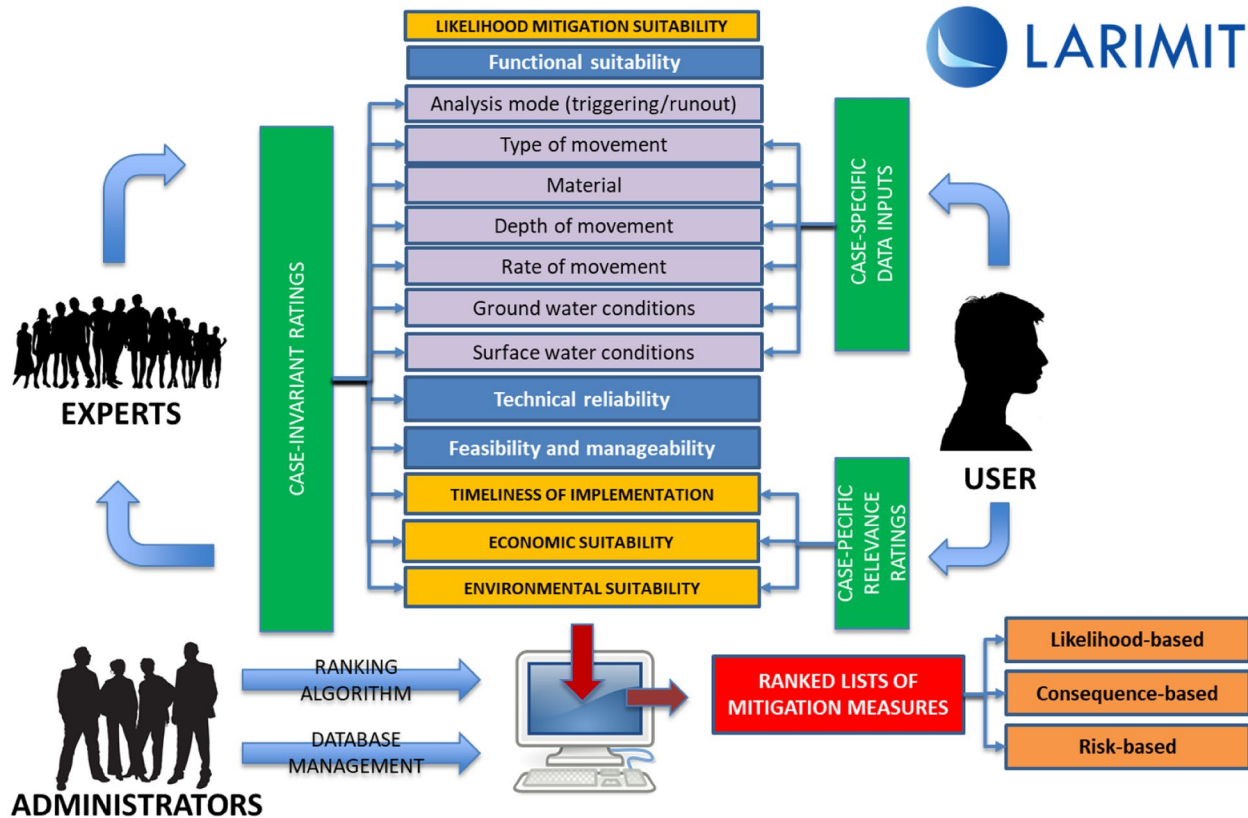


Fig. 1 Synergy between LaRiMiT administrators, experts, and users (from Uzielli et al. 2017)

landslide risk reduction, by reducing either the hazard or the consequences of a wide range of landslide types, namely, falls, topples, slides, spreads, flows, according to the classification provided by Varnes (1978) and later modified by Hungr et al. (2014). The structural measures include conventional engineering solutions but have also recently been expanded to include NBS and hybrid measures.

The database of mitigation measures is an open database for practitioners and academics. The mitigation measures are first divided into two main groups: reduction of landslide hazards (active measures) and reduction of landslide consequences (passive measures). The 80 mitigation measures in the toolbox are sorted into 11 categories describing either the reduction of predisposing factors (e.g. modifying ground water regime) or the improvement of physical processes (e.g. retaining structures to improve slope stability). Currently, there are from 4 to 9 individual measures in each category (Table 1), also in including a general classification of each measure as “grey” (i.e. conventional engineering measures), “green” (i.e. NBS), and “hybrid” (i.e. grey and green solutions combined).

Introduction of the new categories: nature-based solutions and hybrid solutions

A significant technical development of the database since Uzielli et al. (2017) summary has been the addition of NBS and hybrid mitigation measures.

Nature-based solutions are “solutions supported by nature that simultaneously provide environmental, social, and economic benefits and help build resilience” (Bauduceau et al. 2015). In fact, NBS is a broader concept that also accounts for non-technical aspects. The concepts defining what is (and is not) a NBS are evolving, and an attempt to define how to get the NBS message right has been done by Seddon et al. (2021).

NBS applied to landslide hazard mitigation are mostly soil bioengineering practices aimed at reducing the potential of shallow failures and/or erosion by using natural materials alone (living approach) or combined with inert materials (combined living/not living approach). With the increasing climate change challenges, soil bioengineering can be considered a good compromise to reconcile civil engineering practices with nature. Although soil bioengineering approaches found their roots in ancient applications (Evette et al. 2009) and have been used as engineering practices since the early 1980s (Gray and Leiser 1982) and before, they are nowadays receiving increased attention since they are considered nature-based solutions for risk mitigation.

Soil bioengineering interventions have demonstrated effectiveness mostly for surface erosion control and shallow soil stabilisation (Morgan and Rickson 2003), as well as for the stabilisation of existing debris flow scars (Florineth et al. 2002).

Soil bioengineering measures for landslide mitigation are sometimes mistaken for restoration practices aimed only at improving the ecological situation of the site. The threshold between soil

Table 1 List of the categories and the mitigation measures available in LaRiMiT

| Risk reduction | ID | Category | ID | Mitigation measure | Grey | Hybrid | NBS | Update status* | | |
|-----------------------------------|----|---|-----|--|------|--------|-----|----------------|---------|-------------|
| Reduction of the landslide hazard | 1 | NBS for erosion control — living approach | 1.1 | Hydroseeding | | | x | Updated | | |
| | | | 1.2 | Turfing | | | x | Updated | | |
| | | | 1.3 | Tree bushes direct/pit planting | | | x | Updated | | |
| | | | 1.4 | Live/inert fascines and straw wattles | | | x | Updated | | |
| | | | 1.5 | Brush mattresses | | | x | Updated | | |
| | | | 1.6 | Brush layering | | | x | Updated | | |
| | | | 1.7 | Live stakes (live poles) | | | x | Updated | | |
| | | | 1.8 | Live smiles | | | x | Updated | | |
| | 2 | NBS for erosion control — living/ not living approach | 2.1 | Geotextiles (rolled erosion control products) | | | | x | Updated | |
| | | | 2.2 | Drainage blankets | | | | x | Updated | |
| | | | 2.3 | Beach replenishment/nourishment | | | | x | Updated | |
| | | | 2.4 | Rip-rap | | | | x | Updated | |
| | | | 2.5 | Rock dentition | | x | | x | Updated | |
| | 3 | Modifying slope geometry or mass distribution | 3.1 | Removal of unstable soil/rock mass | | x | | | Updated | |
| | | | 3.2 | Removal of loose/unstable blocks/boulders | | x | | | Updated | |
| | | | 3.3 | Removal of material from driving area | | x | | | Updated | |
| | | | 3.4 | Substitution of material with lightweight fill | | x | | | Updated | |
| | | | 3.5 | Addition of material to the area maintaining stability | | x | | | Updated | |
| | | | 3.6 | Terracing (NBS) | | | | | x | Updated |
| | 4 | Modifying surface water regime — drainage | 4.1 | Surface drainage works (ditches, channels, pipes) | | x | | | Updated | |
| | | | 4.2 | Local regrading to facilitate run-off | | x | | | Updated | |
| | | | 4.3 | Sealing tension cracks | | x | | | Updated | |
| | | | 4.4 | Impermeabilisation (geomembranes, impervious facing) | | x | | | Updated | |
| | | | 4.5 | Vegetation — hydrological effects | | | | | x | Updated |
| | | | 4.6 | Hydraulic control work (channel lining/check dams) | | x | | | | Updated |
| | | | 4.7 | Diversion channels | | x | | | | Not updated |

Table 1 (continued)

| Risk reduction | ID | Category | ID | Mitigation measure | Grey | Hybrid | NBS | Update status* |
|----------------|---|----------|--|--------------------|------|--------|-----|----------------|
| 5 | Modifying groundwater regime — deep drainage | 5.1 | Shallow trenches filled with free-draining material | x | | | | Updated |
| | | 5.2 | Deep trenches filled with free-draining material | x | | | | Updated |
| | | 5.3 | Sub-horizontal drains (conventional drilling) | x | | | | Not updated |
| | | 5.4 | Sub-horizontal drains (directional drilling) | x | | | | Not updated |
| | | 5.5 | Wells** | x | | | | Updated |
| | | 5.6 | Vertical small diameter (< 800 mm) wells — siphoning | x | | | | Updated |
| 6 | Modifying mechanical characteristics of the unstable mass | 6.1 | Vegetation — mechanical effects | | | | x | Updated |
| | | 6.2 | Substitution | x | | | | Not updated |
| | | 6.3 | Compaction from surface | x | | | | Not updated |
| | | 6.4 | Deep compaction | x | | | | Not updated |
| | | 6.5 | Mechanical deep mixing with lime and/or cement | x | | | | Not updated |
| | | 6.6 | Low pressure grouting with cements/chemicals | x | | | | Not updated |
| | | 6.7 | Jet grouting | x | | | | Not updated |
| | | 6.8 | Modification of ground water chemistry (lime piles) | x | | | | Not updated |
| 7 | Transfer of loads to more competent strata | 7.1 | Counterfort drains (intersecting trench drains) | x | | | | Updated |
| | | 7.2 | Piles | x | | | | Not updated |
| | | 7.3 | Barrettes (diaphragm walls) | x | | | | Not updated |
| | | 7.4 | Caissons — mechanical effects | x | | | | Not updated |
| | | 7.5 | Soil nailing | x | | | | Updated |
| | | 7.6 | Dowels and harnessing | x | | | | Not updated |
| | | 7.7 | Rock bolting | x | | | | Updated |
| | | 7.8 | Strand anchors | x | | | | Updated |
| | | 7.9 | Soil nail and root technology — SNART | | | | x | Updated |
| 8 | Retaining structures to improve the slope stability | 8.1 | Reinforced soil structure | x | | | | Updated |
| | | 8.2 | Gabion walls | x | | | | Updated |
| | | 8.3 | Crib walls | x | | | | Updated |
| | | 8.4 | Drystack masonry walls | x | | | | Updated |
| | | 8.5 | Mass concrete or masonry walls | x | | | | Updated |

Table 1 (continued)

| Risk reduction | ID | Category | ID | Mitigation measure | Grey | Hybrid | NBS | Update status* | |
|---|----|--------------------------------------|-------------------|---|------|--------|-----|----------------|---------|
| Reduction of the landslide consequences | 9 | Deviating the path of landslides | 8.6 | Reinforced concrete stem walls | x | | | Not updated | |
| | | | 8.7 | Vegetated gabions | | x | | Updated | |
| | | | 8.8 | Live crib walls | | | | x | Updated |
| | | | 8.9 | Vegetated slope gratings | | x | | | Updated |
| | 10 | Dissipating the energy of landslides | 9.1 | Deflection structures (berms) | x | | | Updated | |
| | | | 9.2 | Rock sheds | x | | | Updated | |
| | | | 9.3 | Channelisation structures (lateral walls) | x | | | Updated | |
| | | | 10.1 | Debris racks | x | | | Updated | |
| | | | 10.2 | Baffles (impediments) | x | | | Updated | |
| | | | 10.3 | Check dams | x | | | Updated | |
| | 11 | Arresting/containing landslides | 10.4 | Attenuator system | x | | | Updated | |
| | | | 10.5 | Afforestation | | | | x | Updated |
| | | | 10.6 | Live gully breaks | | | | x | Updated |
| | | | 11.1 | Rigid barriers | x | | | | Updated |
| 11.2 | | | Flexible barriers | x | | | | Updated | |
| | | | 11.3 | Ditch and embankment | x | | | Updated | |
| | | | 11.4 | Debris retention basin | x | | | Updated | |

*Update status after the survey, see document section “Measures with updated scorings” for an explanation

** 5.5 Wells is further split into subcategories 5.5a to 5.5 h based on well type, dimension, and function. However, these are considered as a single category for the purpose of scoring

bioengineering works for ecological restoration and solutions for natural hazard protection is at times hardly perceptible. In fact, there are still many issues concerning the design, implementation, and monitoring to be considered for reconciling natural hazard control and ecological restoration through soil bioengineering practices (Rey et al. 2019). Another important aspect is related to the durability of the natural materials used, such as the wood decay or the vegetation development (Bischetti et al. 2021).

However, soil bioengineering techniques for natural hazard control that simultaneously provide additional benefits (such as ecological restoration) are at the base of the concept of NBS (Preti et al. 2022). A recent study formulated some recommendations to help civil engineers embrace the multidisciplinary nature of soil bioengineering and effectively address climate change challenges in the future (Mickovski 2021).

Using nature-based solutions instead of grey infrastructure enhances the biodiversity and improves the ecosystem services with many collateral benefits, for instance by increasing the awareness among citizens to enhancing the local economy or the

landscape-related aspects, or in some cases improving the touristic attractions of an area. Evidence-based examples that document the effectiveness of these interventions compared to traditional measures are still lacking and these examples are much needed to overcome deeply rooted cultural barriers and to facilitate a political green shift, and finally promote the use of NBS (Ruangpan et al. 2020; Chausson et al. 2020; Solheim et al. 2021).

Many projects financed by the European Research Programme Horizon 2020 have aimed to demonstrate that NBS can be a cost-effective and robust alternative for rural areas, and that these have potential for up-scaling. The EU demonstration project “PHUSICOS—According to Nature” (coordinated by NGI) is implementing NBS in three main demonstrator sites to mitigate different hydro-meteorological hazards linked to landslides. The NBS proposed and implemented in PHUSICOS includes terracing and re-vegetation for erosion control, or afforestation for reducing the risk of snow-avalanche. Assessment frameworks have been introduced within these EU projects to quantify potential benefits of NBS (Watkin et al. 2019; Pugliese et al. 2020).

In this article, an attempt to identify and categorise the key NBS measures for erosion control and shallow landslide mitigation was conducted for the LaRiMiT database. The first two categories in Table 1 are *NBS for erosion control (living approach)* and *NBS for erosion control (combined living/not living approach)*. These two categories were recently added to the LaRiMiT web portal. The classification of categories is based on the guidelines provided by the Geotechnical Engineering Office (GEO), Civil Engineering and Development Department (CEDD), Government of Hong Kong S.A.R., which has introduced these techniques for the treatment of erosion and landslide scars in Hong Kong Territory (Cambell et al. 2008). Some of the mitigation measures belonging to the new *category 2* (e.g. 2.1 Geotextiles (rolled erosion products), 2.2 Drainage blankets, and 2.4 Rip-rap) were already present in the previous version of the database, but after the introduction of NBS categories, they were re-updated and integrated with additional information.

Other NBS reduce the hazard of shallow landslides, through means that sometimes differ from erosion control. *Terracing* for example is mostly aimed at modifying the slope geometry or mass distribution (*category 3* — Table 1) to reduce slope instability.

The vegetation in terms of roots of trees, shrubs, or grass can provide both hydrological (Pollen-Bankhead and Simon 2010; Capobianco et al. 2021) and mechanical reinforcement (Wu 2013; Dias et al. 2017; Foresta et al. 2020) to the shallower soil layers and is included as a mitigation measure in *category 4 — Modifying surface water regime — drainage* and *category 6 — Modifying mechanical characteristics of the unstable mass*. *Live crib walls* are the nature-based version of the crib walls used to retain unstable soil masses. The main structure is made by using timber to form a wall-like framework. Live cuttings or branches are then planted into the structure as it is built, similarly to brush layering, to exploit an additional reinforcement when roots gradually take over (Morgan and Rickson 2003; Gray and Sotir 1996). The effectiveness of this measure can decrease proportionally with the progressive decay of wood over time; this time dependence of strength is accounted for in the design (Tardío and Mickovski 2016).

NBS mitigation measures aimed at reducing the consequences of a triggered landslide belong to *category 10 — Dissipating the energy of a landslide* and can be, e.g. *afforestation*. This category includes using trees, protection forests, or best-practice forest management (Brang et al. 2001), and *live gully breaks*, which are live cuttings placed in the gullies to control water flow and prevent the initiation of debris torrenting (Polster 2003).

A key advantage of NBSs over other approaches is that they can be implemented as stand-alone measures or in combination with other engineered solutions (Cohen-Shacham et al. 2019). When used as landslide mitigation measures, since there are still many key issues to be addressed (Stokes et al. 2014), a good compromise is to implement NBS together with grey infrastructures and form “hybrid” solutions. These are increasingly recognised as being both cost-effective and environmentally friendly options for the mitigation of risks associated with natural hazards and minimise negative effects of traditional mitigation measures, also visually (Kalsnes and Capobianco 2019).

Among hybrid solutions, the LaRiMiT web portal contains those engineered measures that can be covered or combined with vegetation to reduce their ecological impact. Soil nailing with the use of

vegetation (*Soil nail and root technology* in Table 1) is an example of a combined solution in which the engineered measure transfers load to more competent strata, and vegetation reinforces the mechanical characteristic of the shallowest layers (Bo et al. 2015), while enhancing biodiversity. *Vegetated gabions* are gabion walls covered with vegetation whose function is to retain the unstable mass, for example along stream banks (Brunet and Shuey 2005). In case of failed slopes, *vegetated slope gratings* are wooden structures backfilled with soil and revegetated, which can provide additional support to the failed area (Florineth et al. 2002).

Methodology for establishing and updating expert scores

Survey to landslide risk mitigation experts

In 2019, a collaborative effort involving a pool of international experts in landslide risk management from practice and academia was launched, with the aim of updating and integrating the scores established for the initial configuration of the LaRiMiT platform in 2018. The initial scores relied on the compilation of a survey and on the subsequent processing and pooling of the scores. This section presents the steps undertaken in 2019 and 2020 to update the scores. Specifically, it details (a) the criteria for the selection of the experts in the pooling group; (b) the character, structure, and timeline of the survey; and (c) the algorithm used in the statistical processing of the survey responses. Results of the statistical polling are illustrated and discussed in a subsequent section.

Invitation of experts

The experts invited to compile the survey were selected from three sources:

1. Contacts of the authors of this paper, with expertise in landslide risk mitigation;
2. Contacts from former or on-going EU projects and the KLIMA 2050 CRI;
3. Experts on NBSs and soil bioengineering.

The authors’ personal networks of contacts with relevant experience in landslide risk mitigation were invited to participate. Among these were the practitioners and researchers working in landslide risk assessment and management at the Division of Natural Hazards at NGI, members of the European Large Geotechnical Institutes Platform (ELGIP), and contacts established during workshops and conferences. Partners in the earlier EU—FP7 financed project SafeLand (<https://www.ngi.no/eng/Projects/SafeLand>), as well as current partners of the on-going KLIMA 2050—Centre for Research Innovation (CRI) — (<http://www.klima2050.no/>), were also contacted, and experts in NBS with a focus on soil bioengineering were identified from the authors’ networks and, at a second stage, members of the European Federation for Soil Bioengineering (EFIB — <http://www.efib.org/>). All the experts mentioned above were reached by email for voluntary input and were also asked to forward this survey to their network in order to reach as many experts as possible.

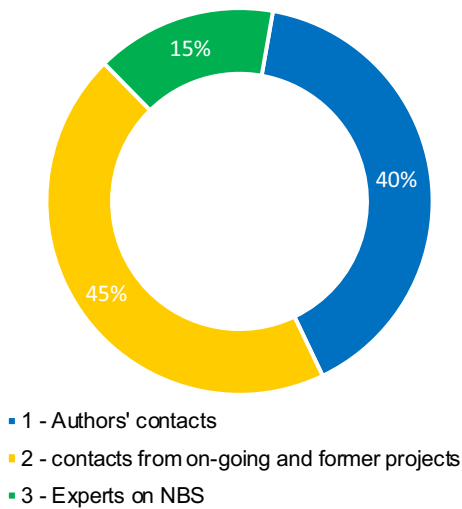


Fig. 2 Distribution of the invited experts for the 2020 pooling

Out of the total 153 invited experts, those selected from criteria 1 and 2 were the most numerous, while 15% of the participants were associated with criterion 3 (Fig. 2).

The experts were mostly affiliated to European Countries (94%), while only 5% were from Asian (China especially), and 1% from American (US especially) affiliations (Fig. 3a). The countries contributing the highest number of invited experts are Italy and Norway (Fig. 3b). This is due to three main reasons: (1) the nationalities and affiliations of the authors of this paper; (2) the webtool

was initiated during the Safeland project, in which Studio Geotecnico Italiano (SGI, <https://www.studiogeotecnico.it/>) developed the initial mitigation measure database and NGI developed the first toolbox; and (3) the updated LaRiMiT tool was developed by NGI in Norway as part of the KLIMA 2050 CRI.

Following Italy and Norway, Spain, France, and China were the other countries with the most invited experts. It is worth mentioning that Spain and France are the countries where most of the NBS experts contacted exercise their profession, followed by Austria and Portugal (based on the list provided by the EFIB).

Structure and timeline of the survey

The survey was conducted using Microsoft Forms. All experts were provided with a registration form in which they were asked to accept specific privacy terms and to specify their professional profile and affiliation. Professional profiles were grouped into 5 categories: PhD/post-doc, researcher, practising professional engineer, professor, other. In addition, each expert could express a preference on whether or not to be listed openly as contributing expert in the LaRiMiT website (those that have accepted have been acknowledged in this contribution).

The surveys were sent by email by the survey managers, with general instructions and a guide to the compilation of the survey itself. The survey questions were identical for all mitigation measures. Experts were asked to evaluate the suitability of as many measures as they wished or were comfortable with. Scoring was strictly anonymous.

The survey was sent out at the end of November 2019, with deadline set at the beginning of January 2020 (Fig. 4). As the first deadline was right after the Christmas period, a second deadline

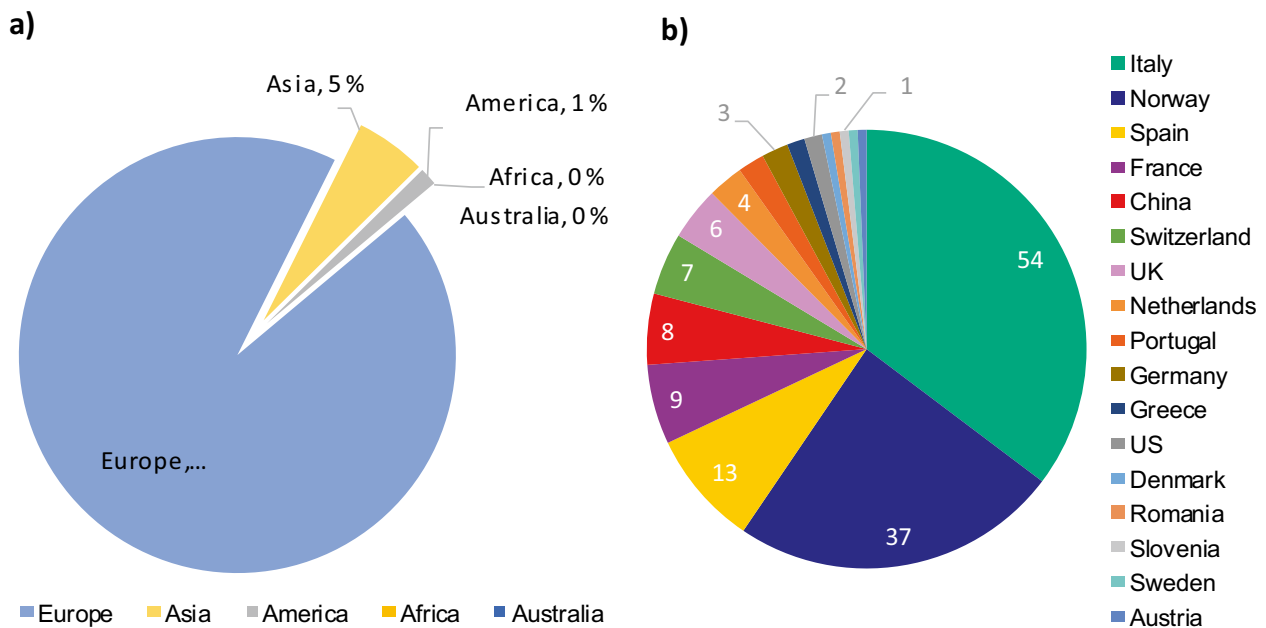
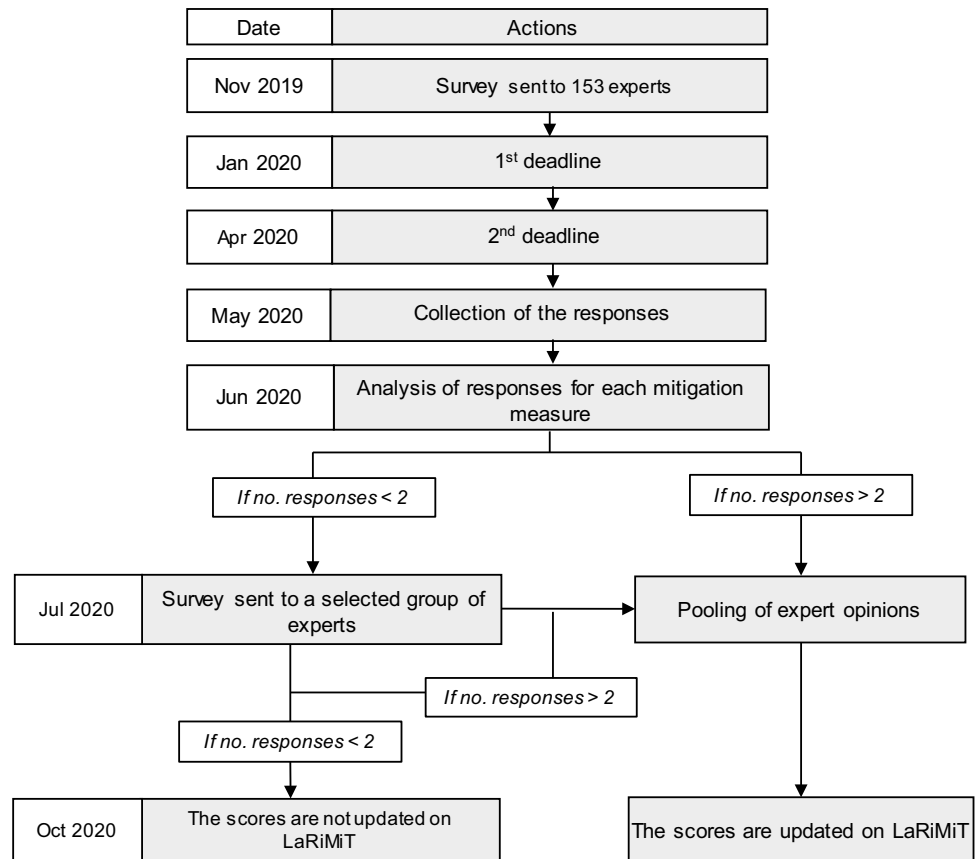


Fig. 3 Provenance of invited experts: **a** by continent; **b** by country

Fig. 4 Flowchart and timeline of the updating process



was set to April 2020, including a reminder at the end of February. Responses were collected in May 2020, and the pooling results on the mitigation measures were analysed in June 2020.

The pooling process was conducted for those measures that had received responses from at least two experts. For the remaining measures, a second, more targeted round of surveying was initiated. Measures belonging to the categories of NBS and hybrid solutions had received still very few responses during the first round. Hence, during the second round, the targeted survey was sent to the experts in NBS and members of the EFIB. Scores for those measures which still had less or equal to 2 responses following the second round of survey were not updated. The overall process ended in October 2020.

Parameters evaluated in the survey

The experts were provided with a table containing all the mitigation measures subdivided into categories (Table 1). Each measure was linked to a dedicated response page on Microsoft Forms through a hyperlink, and each expert could submit as many individual responses as desired. For each mitigation measure selected, the experts were asked to assess the measure by scoring the 33 parameters listed in Table 2 on a scale from 0 to 10. The parameters refer to the set of indicators first proposed by Vaciago et al. (2013) and supplemented by Uzielli et al. (2017) on the basis of existing landslide classifications with regard to the type of movement (Varnes 1978), material type (Hung et al. 2014), and rate of movement (Cruden and Varnes 1996).

Often landslides entail compound motions and more than one type of material, aside from involving different volumes depending on the magnitude and the return period of the events. LaRiMiT is a simplified concept development tool aimed at providing a preliminary, expeditious evaluation and ranking of likely suitable mitigation measures given a broader (and more general) set of parameters and considerations. Thus, when a complex landslide entails, for example more than one type of material and is triggered by a complex mechanism, LaRiMiT parameters refer to the predominant types of material and movement of that landslide.

For each criterion, an initial question asking whether the expert considered it technically pertinent to that specific measure was asked. If the expert replied “no”, the survey would skip the question related to the parameters of that criterion and proceed directly to the next criterion, starting with the same question.

It was also possible for experts to return comments for the criterion along with scores to the parameters belonging to that criterion. For example, when assessing the technical pertinence of parameters according to the criterion “Type of movement” for a measure, they could also provide a general comment for that criterion.

The first category, functional pertinence, is related to the technical aspects that a mitigation measure must address for a landslide case, while the remaining 4 categories provide an information on the socio-economic and environmental aspects that a user should consider in the selection of the most suitable mitigation measure for a specific context.

Table 2 List of the categories, criteria, and parameters used in the survey

| Categories | Criteria | Parameters |
|-----------------------|--|---|
| Functional pertinence | Type of movement | Fall Topple Slide Spread Flow |
| | Type of material | Earth Debris Rock |
| | Depth of movement | Superficial (< 0.5 m) Shallow (0.5–3 m) Medium (5–8 m) Deep (8–15 m) Very deep (> 15 m) |
| | Rate of movement | Very fast Moderate to fast Slow Very slow Extremely slow |
| | Groundwater conditions | Artesian (pressurised zone) High hydrostatic water level Low hydrostatic water level Absent (no water table) |
| | Surface water conditions | Rain Snowmelt Localised Stream Torrent River |
| | Technical reliability | Maturity of technology, reliability of design, reliability of performance |
| Manageability | Ease of construction, safety during construction, durability, ease of maintenance | Feasibility and manageability of the measure Timeliness of implementation |
| Economic impact | Relevance of design, construction, maintenance, indirect costs | Economic suitability |
| Environmental impact | Relevance of impact on the environment from geological, geomorphological, hydrogeological, and ecological viewpoints | Environmental suitability |

Practitioners and decision-makers usually base their decision on mainly technical and economic aspects, i.e. how suitable is the measure for the specific case and how costly it is. A unique feature of LaRiMiT is that importance is also given to the societal and environmental aspects, which is an increasingly important factor to include in the decision-making process, in particular related to NBS and hybrid solutions.

Proposed framework for statistical pooling

The flowchart illustrated in Fig. 5 was devised and implemented for the statistical pooling of expert scores and for the calculation of the final score for each of the parameters listed in Table 2, for

each mitigation measure. The final score describes the suitability of a measure with respect to each parameter. As mentioned, the updating was done only for the parameters that received more than 2 scores.

The first step of the flowchart involves *Data analysis*, whereby for each parameter θ_i ($i = 1, 2, \dots, 33$), salient sample statistics; specifically, the minimum (min) ($\theta_{i,\min}$), maximum (MAX) ($\theta_{i,\max}$), first quartile (Q_1 — 25th percentile) (θ_{i,Q_1}), and third quartile (Q_3 — 75th percentile) (θ_{i,Q_3}) of the scores provided were calculated. Subsequently, the range, Δ ($\Delta_i = \theta_{i,\max} - \theta_{i,\min}$) was derived. The *data* were then *filtered* according to the following criteria: (1) if $\Delta_i > 6$ and $\theta_{i,Q_1} - \theta_{i,\min} > 3$, $\theta_{i,\min}$ was excluded from the dataset; (2) if $\Delta_i > 6$ and $\theta_{i,\max} - \theta_{i,Q_3} > 3$, $\theta_{i,\max}$ was excluded from the dataset.

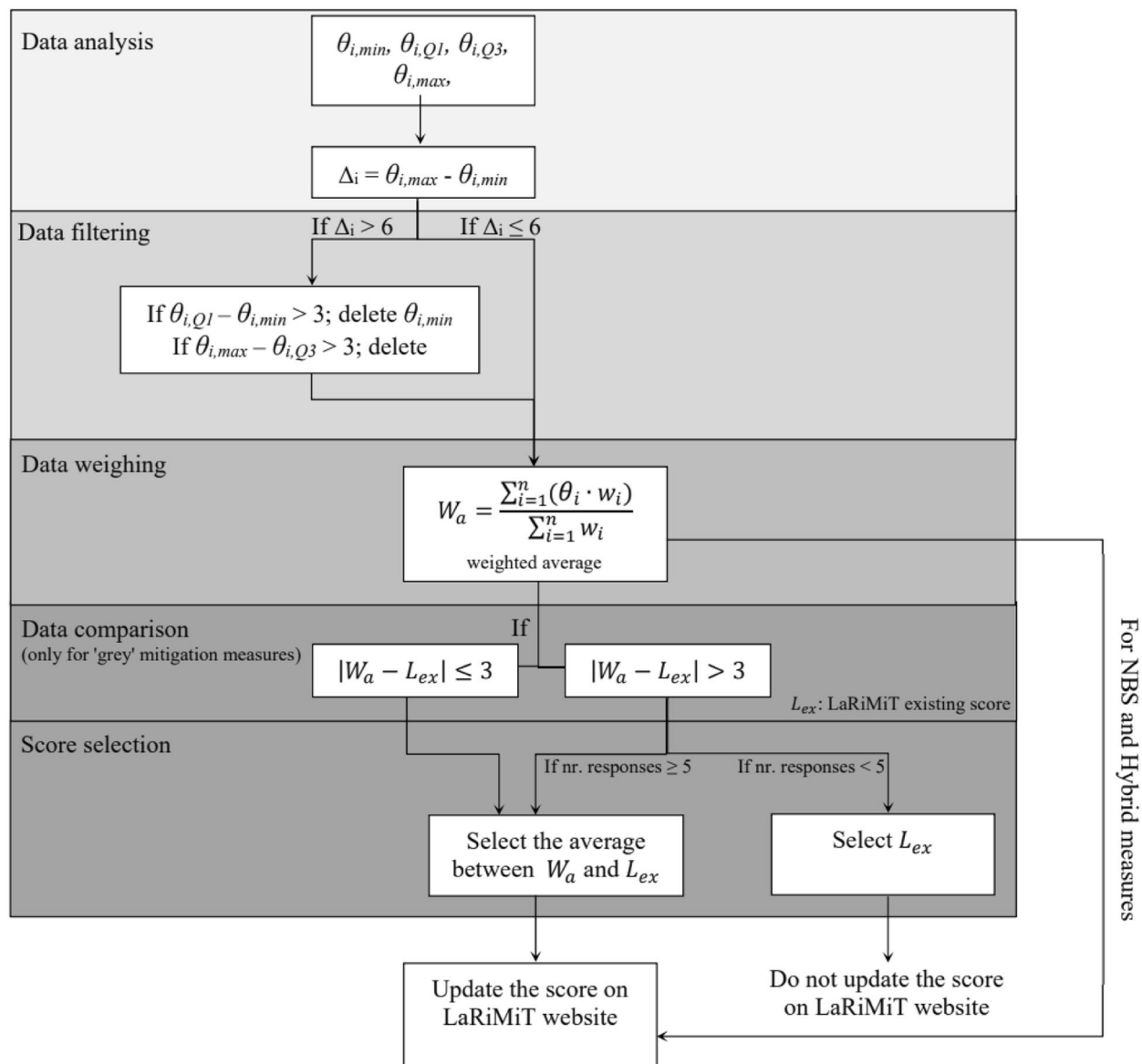


Fig. 5 Algorithm adopted for the statistical pooling of experts' scores

Filtered data subsequently underwent *Data weighing*, whereby the weighted average of the scores for each parameter was calculated on the basis of the weights (w_i) assigned subjectively to each expert category by the survey managers with the aim of conveying greater importance to practitioners' scores. More specifically, the following weights were assigned: $w_i = 5$ for practising professional engineers, $w_i = 3.5$ for professors, $w_i = 2$ for researcher, $w_i = 1.5$ for PhD/post-doc students, $w_i = 2.5$ for others, being these mostly experts in NBS and thus having a priori an overall less broad expertise of landslide mitigation measures. The authors were faced with the fundamental choice of either objective or subjective weight factors, i.e. whether a fixed factor should be assigned to each category of experts, or whether individual responders should be assigned factors subjectively, for instance through self-assessment. The latter option was discarded in this

initial phase because the self-assessment process introduces additional uncertainty due to the lack of objective criteria, and to the consequent introduction of bias and dispersion in weights. After careful consideration and extensive discussion, the decision was to assign fixed factors to various expert categories. Furthermore, it was decided to put more weight to the category of professors, since many of the professors involved are also practising the profession. The choice of the weight factors is not to be considered definitive; rather, it will be assessed observationally through future follow-up initiatives focusing on the comparative validation of case-study applications of the LaRiMiT tool.

The score obtained by the *Data weighing* process was compared with the existing score available on LaRiMiT (L_{ex}) for mitigation measures belonging to the category of "grey" solutions, for which scores were previously available (Uzielli et al. 2017). The L_{ex} scores

available on the database were not the product of any statistical pooling, but a simple average of scores provided by a limited group of experts during the compilation of the database.

The criterion for updating the existing score for the “grey” solutions was established by calculating the difference between the weighted average (W_a) and the LaRiMiT existing score (L_{ex}). If this difference was smaller or equal than 3 (out of 10, deemed subjectively by the survey managers to represent the threshold for a “moderate difference”), an average between the two scores was accepted as the final score. If this difference was higher than 3, an additional step was carried out considering the total

number of responses: if 5 or more scores were available, the average between W_a and L_{ex} was assigned as the output of the score selection phase. Otherwise, the LaRiMiT existing score (L_{ex}) was not updated.

As NBS and hybrid solutions were not previously present in the database, data comparison could not be performed for these measures, and the weighted average was accepted as final score and included in the revised dataset. In addition, given the iterative nature of the proposed approach, the scores derived by this first survey will be re-introduced into the pooling process again (as L_{ex} scores) as new scores will be provided.

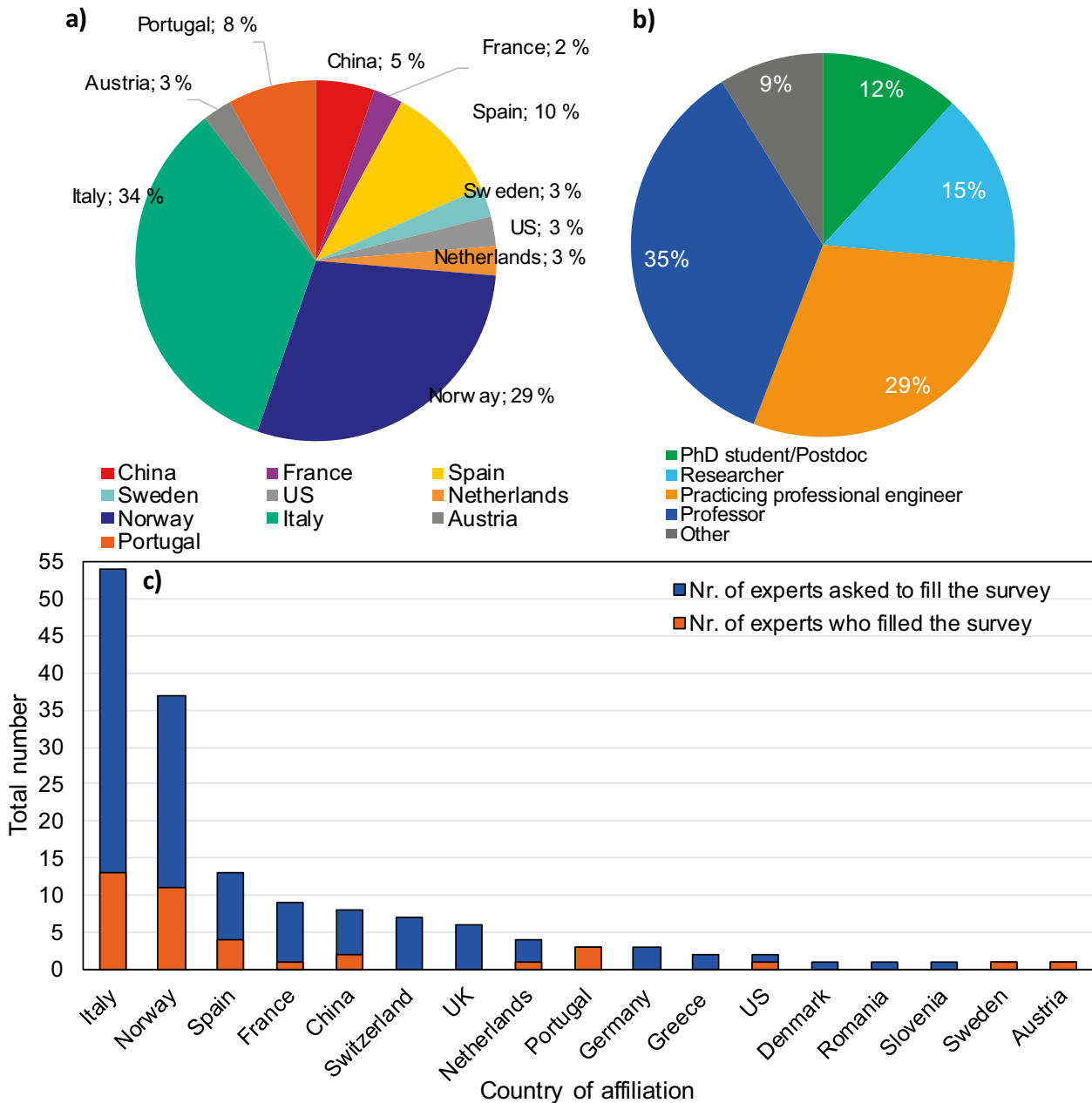


Fig. 6 Responding experts: **a** country of affiliation of responding experts; **b** professional qualification; **c** number of responding vs. invited experts by country of affiliation

Responses from the experts

A total of 38 out of the 153 invited experts (corresponding to just over 25%) contributed scores for at least one mitigation measure. The majority of responding experts were Italian (34%), Norwegian (29%), Spanish (10%), Portuguese (8%), Chinese (5%), Austrian, French, Swedish, USA, and Dutch affiliations as shown in Fig. 6a. With regard to professional profile, experts qualified themselves as professors (39%), practising professional engineers (30%), researchers (15%), and PhD or post-doc students (6%). The remaining 9% who placed themselves in the “other” category (Fig. 6b) were mostly agronomists, ecological engineers or plant ecologists, and experts in NBS.

Since experts could contribute feedback on any number of mitigation measures, the number of total responses received from each country was also recorded. Norway provided the highest total number of scores (95), followed by Portugal (67), Italy (42), USA (35), and Spain (17). This means that while many Italian experts responded, on average, they responded to fewer mitigation measures per person compared to, for example Norway and Portugal.

Number of responses

In total, 296 responses were received of which 172 were for “grey” mitigation measures, 111 for NBS, and 13 for hybrid solutions (Fig. 7).

The number of responses received provided an indication about the general level of familiarity of the expert group with the measures as well as with individual parameters. All the NBS measures received between 3 and 9 responses. This confirms that the NBS measures listed were known to most of the experts who participated. Twenty mitigation measures received from 6 to 10 survey responses each, where 9 of the measures are grey solutions and 11 are NBS. Only one grey mitigation measure received more than

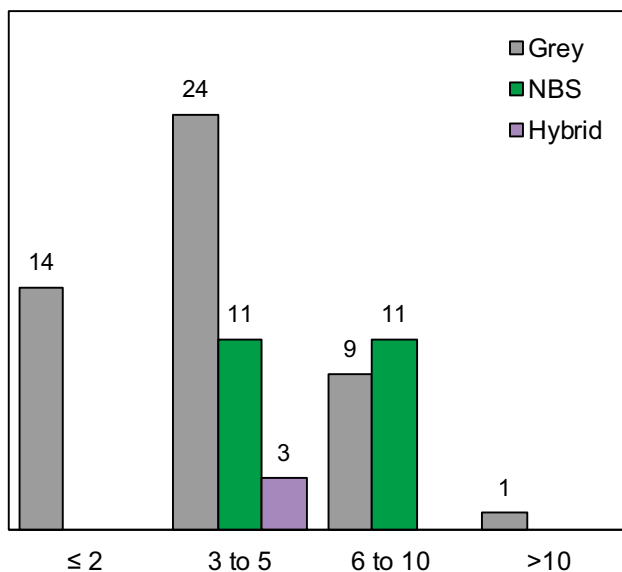


Fig. 7 Response frequency for the three mitigation measure categories

10 responses. Among the measures that received between 3 and 5 responses, 24 were grey solutions, 11 were NBS, and 3 were hybrid solutions (Fig. 8). These represented enough responses to apply the statistical pooling process previously described. Fourteen measures did not receive enough responses to be subjected to the statistical process (Fig. 8).

The measure that received the highest number of responses was the 3.1 — Removal of (actual or potentially) unstable soil/rock mass, with a total of 13 responses, while those that received the fewest responses belong mostly to categories 5 — Modifying groundwater regime — deep drainage, 6 — Modifying mechanical characteristics of the unstable mass, and 7 — Transfer of loads to more competent strata.

Each measure could be scored through 33 parameters. Experts could provide scores to the parameters which they felt confident to express an opinion or which they considered of technical pertinence for the measure being assessed without necessarily having to complete scoring of all 33 parameters. The parameters received varying numbers of scores, indicating that some parameters were more familiar to the experts, while others were less familiar, or were not considered of relevance for the assessment. The variability in the number of scored parameters may also indicate that experts might be experienced in applying certain measures in specific conditions.

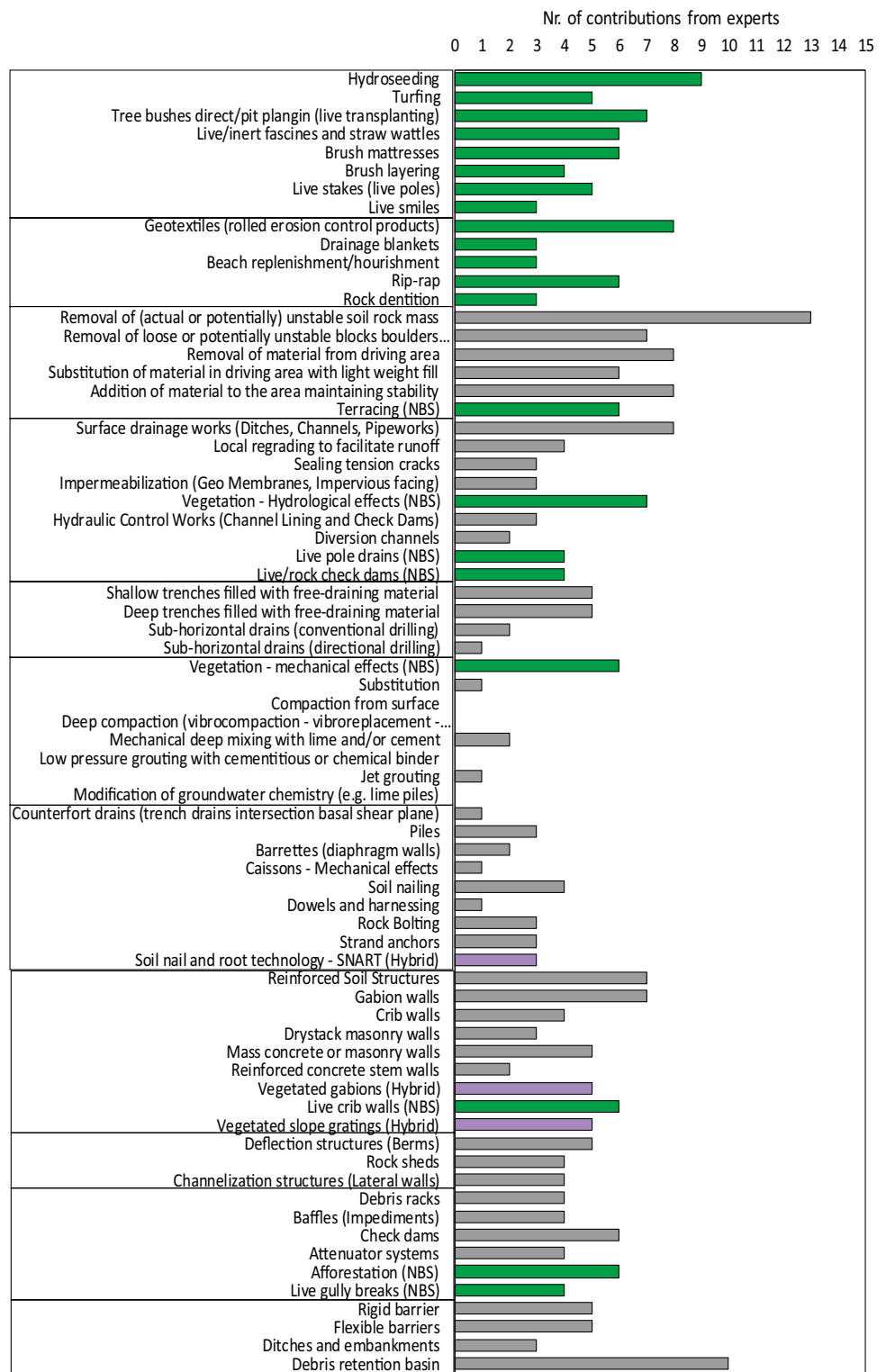
Some experts also provided additional comments when assessing the scores. For grey measures, most of the comments were additional explanations to the score given, while for green measures, most of the comments reflected aspects related to the vegetation selection. Many of the comments were experts’ recommendations on the use of adequate vegetation species or use of shrubs rather than trees for some measures. This highlights how NBSs are site specific and knowledge of aspects other than geotechnical engineering are needed to select the measure most suitable to a certain climate and geo-environmental context.

Response margin in parameter evaluation

An indicator of possible differences in the experts’ opinion about a measure assessed is the difference between $\theta_{i,min}$ and $\theta_{i,max}$ scores (Δ_i in Fig. 5). The measures that received from 3 to 5 responses were also those that had the lowest number of parameters with $\Delta_i > 6$. When the responses ranged from 6 to 10, the number of parameters with $\Delta_i > 6$ increased and had larger variability (Fig. 9). The one measure that received the maximum number of responses (>10) registered also among the highest number (20 out of 33) of parameters with $\Delta_i > 6$. This means that even though a measure receives a high number of responses, the scores are inherently subjective and may be region specific. The wide scatter of some scores for a measure could be related to the different degree of effectiveness of that measure in different regions.

The number of abstentions (i.e. unscored parameters) can be indicative of the experts’ assessment of which attributes of landslides are either irrelevant for the specific measure, or of the degree of confidence on the part of experts. Figure 10 shows the number of abstentions normalised by the total number of responses for each of the three macro-categories of mitigation measures (grey, hybrid, and NBS). It is interesting to note that the magnitude of hesitancy for technical criteria was greater than those related to feasibility

Fig. 8 Overview of number of responses for each mitigation measure (grey colour — traditional engineering measures, violet — hybrid measures, green — NBS and soil bioengineering)



aspects, timeliness of implementation, reliability of the measure, and environmental suitability. In terms of movement types as classified by Varnes (1978), fall, topple, and spread received the highest number of abstentions for functional suitability criteria, regardless of the type of mitigation measure.

For traditional grey solutions, *ground water conditions* and *surface water conditions* represent the criterion with the highest number of abstentions, possibly indicating that there is either a lack of confidence in expert assessments regarding how to account for pore water pressure conditions in the selection of the most suitable

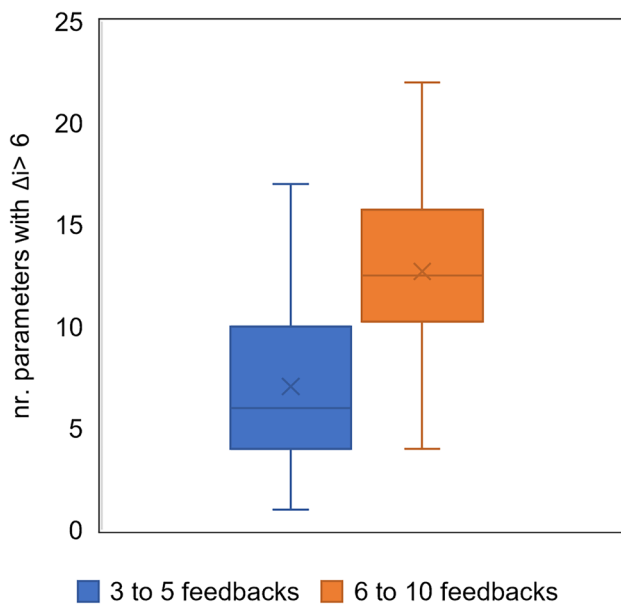


Fig. 9 Number of parameters for which $\Delta_i > 6$, grouped by number of expert responses received for each mitigation measure

landslide mitigation measure, or that the experts did not consider this criterion relevant for mitigation measures. On the other hand, the *surface water conditions* seem to be a criterion which is less irrelevant for NBS measures, since most of them are adopted along streams or riverbanks.

For hybrid solutions, the abstentions broadly replicated those found for grey solutions, albeit with less variability in socio-economic criteria (i.e. *reliability of the measure, feasibility, timeliness of implementation, environmental suitability, economic suitability*).

For NBS, many abstentions were recorded for the *depth of movement*, as in most of the cases, these measures are not suitable for deep-seated landslides, and for the *rate of movement*. In fact, soil bioengineering measures are not intended to mitigate landslides but are rather used to protect from soil erosion problems or shallow instabilities. The level of abstentions was also significant for parameters such as *timeliness of implementation, environmental suitability, and economic suitability*. One possible explanation for this could be that most of these measures involve the use of vegetation which requires many factors to be considered. For example, the timeliness of implementation depends on the vegetation establishment, and this is dependent on species, climate, type of soil involved... a point brought up by many experts in their comments to the survey. At the same time, effectiveness depends on multiple factors, including the age of vegetation and whether it is alive or decaying (Ni et al. 2019; Yamase et al. 2021; Foresta et al. 2020).

Measures with updated scorings

The framework illustrated in Fig. 5 was used to update the scores for 56 measures. Among these are 21 NBS, 3 hybrid, and 32 to grey solutions (Table 1).

Among the measures for which existing scores were not updated due to the lack of responses from the experts, 3 of them belong to

category 5 — *Modifying the groundwater regime — deep drainage*, one belongs to category 4 — *Modifying the surface water regime*, only measure 7 to category 6 — *Modifying the mechanical characteristics of the unstable mass*, 5 to category 7 — *Transfer of loads to more competent strata*, and one to category 8 — *Retaining structure to improve slope stability*.

Application to a real case: comparison with the 2019 database

Study case in Bodø, Norway

The study site is located in the municipality of Bodø (67° 16' 49.2852" N, 14° 24' 17.6976" E), northern Norway, and it is one of the pilot cases of the Centre for Research Innovation KLIMA 2050 (<http://www.klima2050.no/>) used to demonstrate mitigation of risk to society by means of measures designed to adapt to the impact of climate change. The slope is about 400-m long and is running parallel to the rail line on the final leg into the Bodø railway station (Fig. 11). In the past, the slope has experienced several slope instabilities consequent to heavy rainfall. The slope has an inclination of 35° and its stratigraphy consists of a main layer of firm marine clay (12–15 m), covered by a layer of about 1.5 m of heterogeneous silty sand with gravel material.

Four piezometers were installed in 2019 to monitor the pore water pressure conditions into the slope. Measurements indicate a groundwater level at approximately 2 m below the surface in the upper part of the slope, and 1 m below the surface in the lower part. The main instabilities recorded in this area are due to a combination of the following: (1) increased pore water pressure values in the undrained firm clay layer due to rainfall infiltrating through the drainage layer; and (2) concentrated run-off of surface water from the upper part, which in turn can either trigger mass sliding at the interface between the firm marine clay and the coarser layer on top, or severe runoff erosion.

The study area was divided in 5 plots of about 40-m length each, where conventional and alternative (NBS) drainage systems will be tested and compared in terms of cost of implementation and effectiveness. For each plot, a specific erosion protection measure involving a surface drainage solution will be selected. One plot will be intended for NBS. For sake of comparison, a monitoring system will be installed to measure soil moisture at different depths, potential displacements, and detached soil sediments in each of the 5 plots.

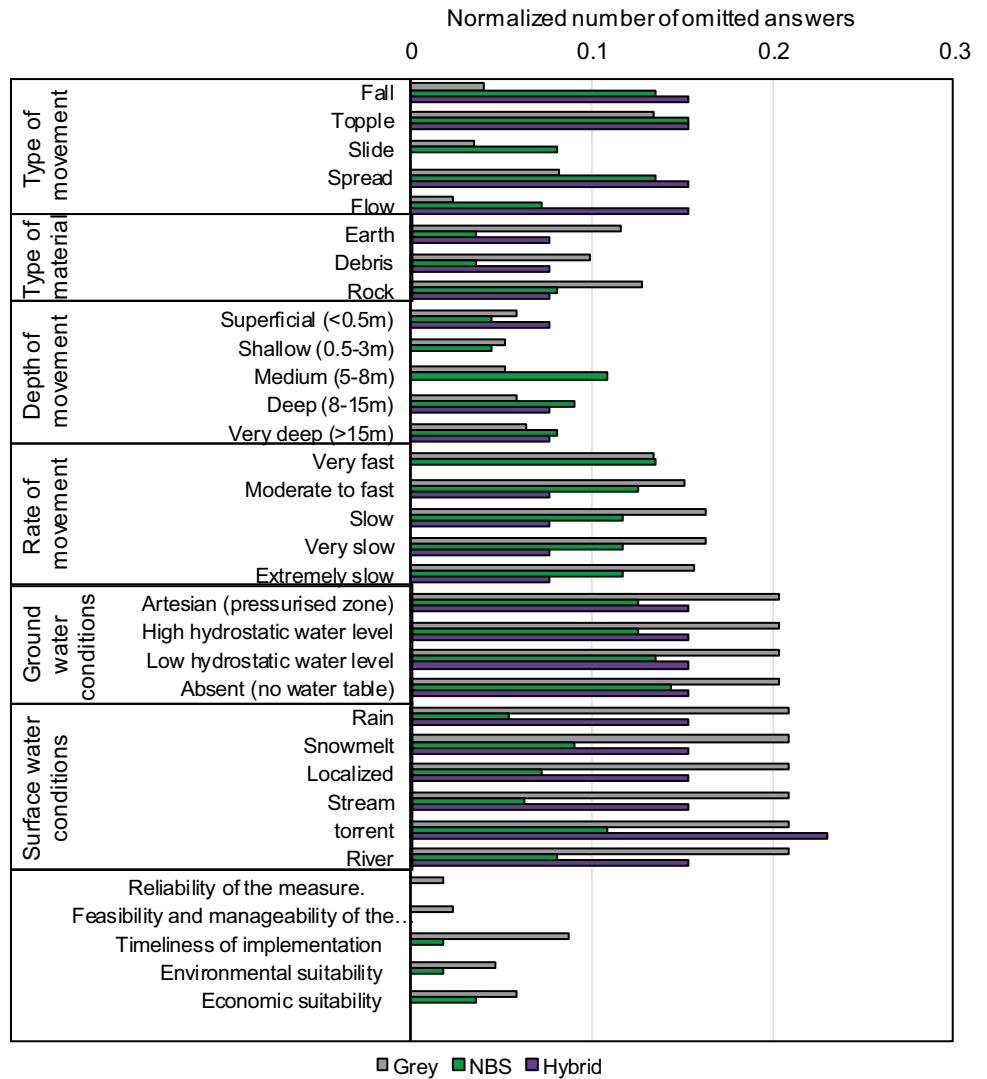
Comparison of the 2019 version with 2020 version of LaRiMiT

The LaRiMiT webtool was applied to gain an overview of the technical suitability of NBS as well as conventional measures to be adopted in the specific case. The input parameters selected for the calculation of the likelihood suitability in terms of technical functionality are shown in Table 3. The same input parameters were used for both the versions of LaRiMiT (i.e. before and after the updating of expert scores).

The top 5 mitigation measures suggested by the webtool in both the pre-score updating and the post-updating version of the tool are listed in Table 4.

The measure 2.4 *Rip-rap* was the most suitable solution provided by the pre-updated version of the toolbox, which is not

Fig. 10 Number of abstentions for the three categories of mitigation measures (grey: traditional engineering measures; green: NBS; purple: hybrid solutions), normalised by the total number of assessments in that group



considered suitable for this case, not being in the vicinity of a river/stream embankment. On the contrary, the measure 4.8 *Live pole drains* (NBS) was suggested from the updated version. Live pole drains consist in cylindrical bundles made of live cuttings with roots used as drain collector against the underground see page rising. Live pole drains can be designed as alternative and sustainable solution to these techniques that provides double effect on both the drain of excess soil moisture and the reinforcement of soil with roots (Pacas 1999). More details on the solution and examples of applications can be found in the LaRiMiT database (https://www.larimit.com/mitigation_measures/1028/).

In addition to the live pole drains, due to the depth of movement given as input, which suggests the need for erosion protection measures, many following mitigation measures suggested by the updated version of the tool belong to the NBS category (1.6 *Brush layering*, 1.7 *Live stakes (live poles)*).

On the base of the available information regarding the study are, implementing measures aimed at improving the surface drainage will be the most appropriate action. Thus, the first conventional

measures belonging to category 4 — *Modifying the surface water regime — surface drainage* that appeared in the ranked lists of LaRiMiT pre- and post-updating were compared.

From the not updated version of the webtool, measure 4.2 *Local regrading to facilitate runoff* is the first measure from category 4 suggested. Differently, the measure 4.1 *Surface drainage works* (such as ditches, channels, pipeworks), which will also be realistically implemented in one of the plots of the pilot case (as traditional drainage solution), rank fifth in the output from the post-scores updating version. The recommendations provided by LaRiMiT have been reviewed by the authors, and our opinion is that the updated version of the database is more accurate in identifying the most suitable measures to be implemented, according to their technical functionality.

An example of overview of the LaRiMiT webpage when the input parameters and site location of the case study site are introduced is given in Fig. 12, specifically for the Bodø pilot case. In addition, the ranked list of mitigation measures provided as output by the tool is shown for the version after scores update (Fig. 12b).

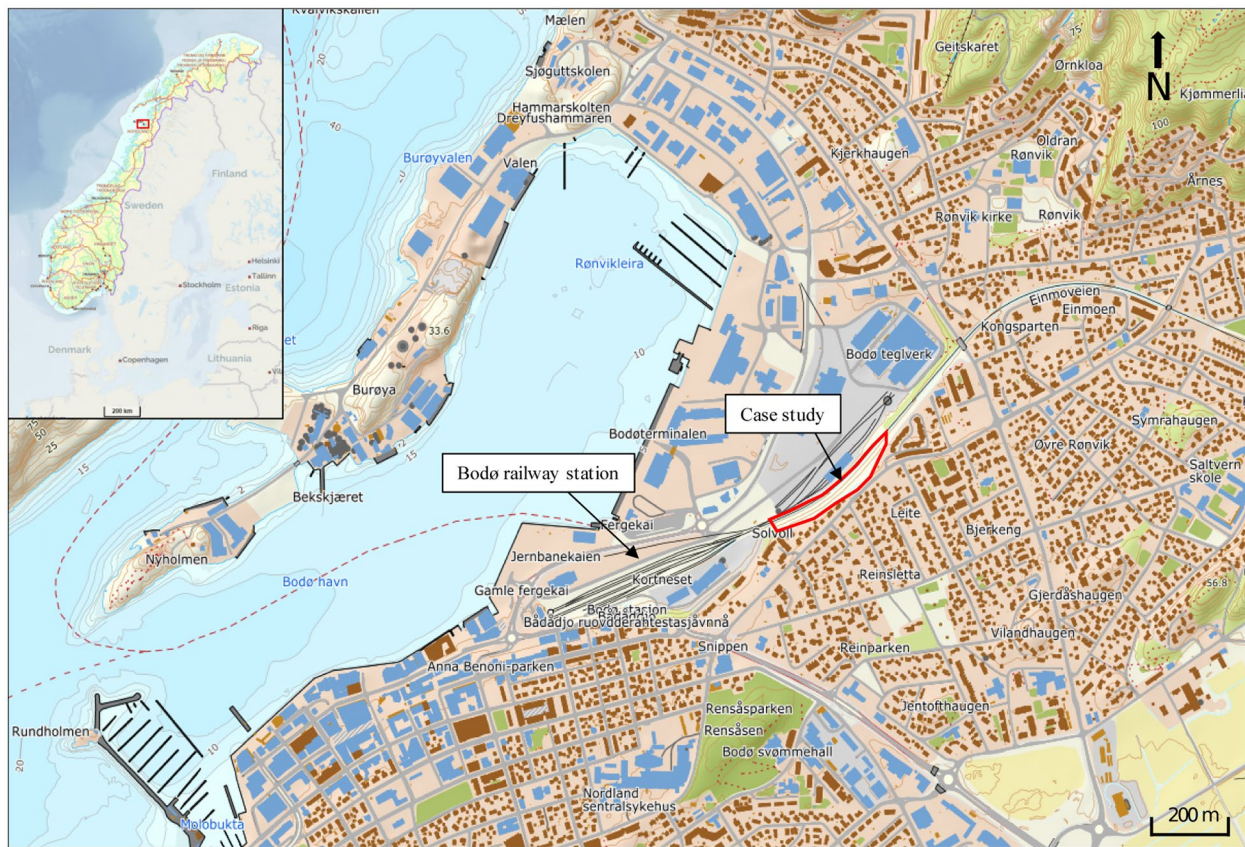


Fig. 11 Location of the case study in Bodø

Assessment and future improvements

It is widely expected by the scientific community that with a warmer and wetter climate and an increased demographical density, landslides triggered by rainfall will increase in frequency and increase the risk to human life, public and private property, infrastructure, and the environment, in many regions worldwide. Based on this expectation and society requiring that greater attention be given to risk mitigation and preparedness, there is a growing need of investing in risk mitigation strategies that will help to reduce

either the frequency, the magnitude, or the consequences of landslides. On the other hand, the need to take rational decisions in adopting more sustainable measures which produce less impact on the ecosystem and the biodiversity is increasingly recognised in many societies.

This paper has illustrated the process by which the database of mitigation measures of the publicly accessible LaRiMiT web portal is updated to account for the outputs of a structured scoring process involving a group of international experts. Sustainable solutions, namely nature-based solutions (NBS), which find their roots in the ancient practice of soil–water–bioengineering (Sangalli et al. 2021; Preti et al. 2022), were also introduced in the database, to provide a “green” alternative to traditional grey solutions, especially for erosion-related and shallow instability-related problems. Hybrid solutions, involving the combination of NBS and grey solutions, were also added to the toolbox. A framework was proposed for the pooling of expert scores for the assessment of the technical suitability of a wide gamut of landslide mitigation measures. The results of the processing of survey feedback are discussed in the paper.

A total of 38 out of the 153 experts contacted provided at least one feedback. Among the 80 mitigation measures assessed, 14 did not receive enough responses (≤ 2) to apply the score updating methodology, while the remaining received between 3 and 13 responses, thus allowing the updating of the suitability scores in the toolbox.

Table 3 Characterisation of the input parameters related to the site

| Parameters | User input |
|-------------------------|---------------------|
| Mode of analysis | Triggering |
| Type of movement | Slide |
| Material type | Debris |
| Depth of movement | Surficial (< 0.5 m) |
| Rate of movement | Slow |
| Ground water conditions | High |
| Surface water | Rain |

Table 4 Top 5 mitigation alternatives from different categories proposed by the webtool, before and after scores update

| Before scores update | After scores update |
|--|--|
| 2.4 Rip-rap | 4.8 Live pole drains (NBS) |
| 2.2 Drainage blankets | 1.6 Brush layering |
| 3.5 Addition of material to the area maintaining the stability | 1.7 Live stakes (live poles) |
| 2.1 Geotextiles (rolled erosion control products) | 3.5 Addition of material to the area maintaining stability |
| 4.2 Local regrading to facilitate runoff | 4.1 Surface drainage works (ditches, channels, pipeworks) |

It should be emphasised here that LaRiMiT is undergoing continuing and progressive development, and hopefully autonomous dynamic scoring by experts from individual logins will be implemented in the future (Uzielli et al. 2017), resulting in the automated implementation of the quantitative score updating process outlined herein. While the present number of responses is insufficient for a

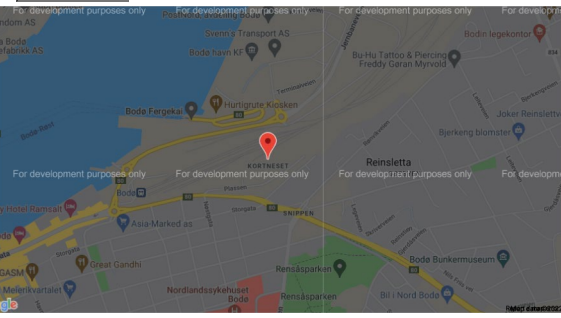
sophisticated statistical analysis, the proposed algorithm allows the transition to a full statistical treatment of dynamic expert scoring as more scores become available. The criteria outlined in the paper allow the calculation of central statistics, a check in sample dispersion through a threshold value of sample ranges, and the identification of statistical outliers. The proposed approach for pooling of

Pilot Bodø after update_n6
Posted by beatrix on June 25, 2021, 5:13 p.m.

[Print](#)

Description
Kortneset

Position
Latitude: 67.28726
Longitude: 14.39933



Description of movement

| | |
|--------------------------|---|
| Mode of analysis: | Triggering |
| Type of movement: | Slide |
| Material type: | Debris |
| Depth of movement: | Surficial (< 0.5 m) |
| Rate of movement: | Slow (from 5 x 10-5 mm/sec to 5 x 10-3 mm/sec) |
| Ground water conditions: | High |
| Surface water: | Rain |

Likelihood mitigation suitability ranking

37 measures are eligible for this analysis among a total of 80 measures

| Measure ID | Measure description | Functional suitability index (FSI) | Feasibility and manageability index (FMI) | Technical reliability index (TRI) | Likelihood mitigation suitability index (LMI) |
|------------|--|------------------------------------|---|-----------------------------------|---|
| 4.8 | Live pole drains (NBS) | 8.3 | 10 | 8 | 8.7 |
| 1.6 | Brush layering | 8.2 | 10 | 8 | 8.6 |
| 1.7 | Live stakes (Live poles) | 8.2 | 10 | 8 | 8.6 |
| 3.5 | Addition of material to the area maintaining stability | 6.7 | 10 | 10 | 8.3 |
| 4.1 | Surface drainage works (Ditches, Channels, Pipeworks) | 7.5 | 10 | 8 | 8.2 |
| 1.3 | Tree bushes direct/pit planting (Live transplanting) | 7.5 | 10 | 8 | 8.2 |
| 4.4 | Impermeabilization (Geo Membranes, Impervious facing) | 7.2 | 10 | 8 | 8.1 |
| 1.1 | Hydroseeding | 7.0 | 10 | 8 | 8.0 |
| 1.5 | Brush mattresses | 8.0 | 8 | 8 | 8.0 |
| 4.2 | Local regrading to facilitate runoff | 6.8 | 10 | 8 | 7.9 |
| 4.3 | Sealing tension cracks | 6.8 | 10 | 8 | 7.9 |
| 2.1 | Geotextiles (Rolled erosion control products) | 6.8 | 10 | 8 | 7.9 |
| 3.6 | Terracing (NBS) | 6.8 | 10 | 8 | 7.9 |
| 3.1 | Removal of (actual or potentially) unstable soil/rock mass | 6.7 | 10 | 8 | 7.8 |
| 1.4 | Live/inert fascines and straw wattles | 6.7 | 10 | 8 | 7.8 |
| 2.2 | Drainage blankets | 6.7 | 10 | 8 | 7.8 |
| 4.9 | Live/rock check dams (NBS) | 7.5 | 8 | 8 | 7.8 |
| 5.1 | Shallow trenches filled with free-draining material | 7.5 | 8 | 7 | 7.5 |

Fig. 12 a Input parameters and site location of the Bodø case in LaRiMiT and **b** likelihood mitigation suitability ranking after the scores update.

expert scores can be re-iterated multiple times, allowing the progressive refinement of the database as new scores become available while accounting for existing scores.

Even though the current version of LaRiMiT can be mostly used for European climates, the framework presented herein could seamlessly accommodate the extension of the LaRiMiT database to other regions and types of climates (e.g. tropical regions, where landslides and debris flows are also very common); this is valid mostly for NBS where the vegetation species is climate dependent, while for traditional structural mitigation measures, the climate does not affect the selection of the construction materials. Another possible extension could be on applications other than landslide mitigation measures, such as pile design or method uncertainty in geotechnical calculations models. In such case, a dedicated survey, specifically involving experts within these fields of expertise, could be conducted to ensure the quality and reliability of the resulting scores.

The high impact of the LaRiMiT tool, despite its “work-in-progress” status, is evident within the academic and practitioners’ communities. Since the launching of the webtool, more than 330 cases studies have been updated in the portal as “new case study sites” from Europe (Norway, Italy, the Alps, and Spain), India, Nepal, China, South America, and North America. Among the registered cases, it is possible to find examples of reported landslides for which mitigation measures have already been implemented, along with references to journal papers or technical reports.

It is also worth noting the importance of LaRiMiT in disseminating examples of NBS for landslide mitigation, which may still be not commonly used in some regions. By suggesting a portfolio (and ranking) of possible mitigation measures, local engineering experts may be presented with solutions and ideas they are not previously familiar with. Indeed, many NBS cases are also reported in the section “Registered cases” of the toolbox, together with relevant literature. LaRiMiT is also routinely used for educational purposes from the University of Florence (Italy) and the Norwegian University of Science and Technology (Norway).

Although the LaRiMiT tool still needs further development, the results so far provide important contributions as a real case of progressive build-up of an expert-based knowledge hub, with its difficulties, successes, and future development strategies. The contributed cases and the adoption of the framework by academia attest to the breadth of the ongoing process aimed at the progressive co-validation of the webtool by developers, experts, and users. The stepwise compilation and improvement of the database, with the inclusion of NBS and hybrid solutions, attest to the scientific significance of the collaborative effort undertaken. In fact, the 2019 survey was possibly the first-ever structured opportunity for experts in landslide mitigation, including academics and practitioners, to collaborate in assessing, quantitatively and within a shared framework, the suitability of structural mitigation measures as a function of both landslide-related criteria, site conditions and socio-economic aspects. The progressive consolidation of the database and of the LaRiMiT tool in general occurs observationally, through the transparent assessment of technical and organisational initiatives. The dissemination of work-in-progress outcomes provides an opportunity for peer review and collaborative improvement among academia and practice.

LaRiMiT is hosted by NGI with the commitment to support the continuing development of the toolbox. The design allows for

continuous development of the toolbox. This includes addition of expert scoring, improving the underlying engine for selecting and prioritising mitigation measures for a case. Involving more professionals to fill out the survey and validating the toolbox are some of the research activities foreseen for the upcoming years.

Link to the survey

The authors encourage additional experts in landslide risk reduction to contribute to the scoring of the LaRiMiT mitigation measures. Please contact the corresponding author if you are able to contribute your expert opinions.

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Declarations

Conflict of interest The authors declare no competing interests.

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