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Cost-based analysis of mitigation measures for shallow-landslide risk reduction strategies

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ABSTRACT

Landslide risk assessments are usually permeated by a certain degree of subjectivity. In order to reduce it, we have developed an original methodology which enables risk assessments to be carried out in fully quantitative terms, integrating both physical and economic science techniques. This risk assessment combines geomorphological studies, probabilistic modelling and cost-benefit analyses (CBA). We applied the methodology to an area of north-west Italy that was affected in 2011 by a dramatic rainfall-induced landslide event, and where a risk management program is necessary for avoiding future losses. We analyzed the cost-effectiveness of several landslide mitigation measures applying the proposed procedure. The results demonstrate that measures previously considered as suitable for mitigating shallow landslides were inappropriate from the economic viewpoint. The applied techniques also served to optimize economically the most appropriate mitigation measure. Moreover, our methodology allowed to calculate the maximum affordable investment on a cost-effective mitigation measure; this result will be a reference for designing innovative solutions to mitigate landslides in the study area.

1. Introduction

Decisions for managing landslide risk are often made just taking into account the available budget: analysis of the economic suitability or even optimization of the proposed mitigation measures are generally not considered. Thus, the application of costly and oversized structural measures for stabilizing slopes are frequent when funding is available; and landslide risk mitigation does not usually happen when the budget is scarce (cf. Winter and Bromhead, 2012). These situations can be avoided by implementing quantitative landslide risk assessments. However, the latter involve difficult tasks and decisions that should take into account a wide range of issues, including hazard analysis, potential loss estimation and design of mitigation measures (Crozier and Glade, 2006; Gutiérrez et al., 2010; Van Asch et al., 2014). To date, this complex evaluation has commonly been carried out using semi-quantitative approaches; applying qualitative or quantitative procedures in different stages of the assessment according to the available data (e.g. Lateltin et al., 2005). However, nowadays there is an increasing need to perform quantitative risk analysis (Corominas et al., 2014) and, in some cases, the conditions are favourable to develop risk assessments totally based on measurable parameters (see e.g. Galve et al., 2012a, 2012b).

Among other options, cost-based approaches can be reliable methodologies for developing landslide risk assessments in fully quantitative terms. These techniques can be applied at local and regional scales. The completion of this type of analysis at those scales depends on (1) the production of a sound landslide hazard map and (2) the estimation of costs generated by landslides and those economic losses saved due to the implementation of specific mitigation measures. Currently, procedures for performing comprehensive landslide susceptibility and/or hazard maps (i.e. hazard zoning) are widespread and well developed (e.g. Brenning, 2005; Chung, 2006; Lee et al., 2007; Rossi et al., 2010; Felicísimo et al., 2013; Piacentini et al., 2012; Lari et al., 2014; Piacentini et al., 2015), primarily because they require information currently accessible or easy to produce (DEMs, land use maps, geological information and landslide inventories). However, the usual absence of available information on costs produced by landslide occurrence prevents the calculation of risk in economic terms. This explains the scarce number of articles that describe quantitative approaches aimed at landslide risk estimation (e.g. Remondo and Bonachea, 2005; Zêzere et al., 2008; Jaiswal et al., 2010). The same problem also concerns the making available of reliable market prices for mitigation solutions. There is a wealth of literature on landslide mitigation measures and their

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technical suitability (e.g. Cornforth, 2005; Glade et al., 2005; Huebl and Fiebiger, 2005; Highland and Bobrowsky, 2008; Andreu et al., 2008; Bromhead et al., 2012; Mavrouli et al., 2014; Bowman, 2015) but it is difficult to obtain information in detail about their implementation costs. This is a common obstacle to analyze the cost-effectiveness of a proposed measure. For this reason, papers describing cost-benefit analysis (CBA) of landslide mitigation alternatives are rare. This deficit of knowledge on cost-based studies may prevent stakeholders from having an overview of optimum solutions for managing landslide risk. The development of quantitative risk assessment methods, capable of managing landslide problems in different settings, represents a crucial need for landslide risk managers. Among the modest number of papers dealing with cost-based landslide risk assessment the following can be highlighted. Fuchs and McAlpin (2005) analyzed the economic benefits of avalanche defence structures and discussed the protection that the public sector should provide. Holub and Fuchs (2008) used the results of a cost-benefit analysis to demonstrate that local structural measures should be considered as additional or alternative solutions to conventional structures for mitigating torrent-related phenomena (flash floods or debris flows). Agliardi et al. (2009) described how to integrate rock fall numerical modelling and CBA to evaluate the cost efficiency of two protection scenarios. Lee and Chi (2011) combined geotechnical calculations with a cursory economical evaluation to assess the cost-benefit ratio of a proposed structural solution for stabilize a slope. Chen et al. (2010) and Narasimhan et al. (2015) provided two similar cost-based analyses of strategies to mitigate damages produced by flow-like phenomena. These authors based their assessment on the cost-benefit ratios obtained by implementing a specific mitigation strategy. Ballesteros-Cánovas et al. (2013) presented a comparable methodology for assessing the best option to reduce flood risk. The cited publications mainly deal with snow avalanches, rock falls and torrent-related hazards that may hit populated areas and describe methodologies aimed at analyzing the cost efficiency of static scenarios (i.e. the proposed protection scenario do not change to achieve the maximum efficiency). The present study attempts to fill a gap on landslide risk assessment and management by describing a methodology based on quantitative techniques to establish appropriate measures for mitigating shallow landslide risk along roads. Moreover, the techniques presented are designed to provide optimized mitigation solutions analyzing dynamic scenarios (i.e. the proposed mitigation solutions can be resized to achieve the maximum efficiency). We applied the procedure to an area of north-west Italy (Vernazza catchment, Cinque Terre National Park), that was affected by an impressive landslide-event on October 2011. The proposed methodology is completely based on measurable parameters and reduces the subjectivity that usually permeates risk assessments. It combines both physical and economic issues that make the study a multidisciplinary and a complex analysis. This complexity produces a significant level of uncertainty, but we also adopted a strategy to narrow it down. The case study shows: (1) how quantitative assessments can change local preconceptions about the best way to manage landslides; and (2) the importance of conducting this type of studies for avoiding to divert resources which could be better used. This research has also shown how the methods previously applied by Galve et al. (2012a, 2012b) for analyzing the economic viability of a structural solution to mitigate sinkholes in a roadway may be adaptable to other geomorphic hazards in different environmental contexts.

2. Materials and methods

The proposed methodology links several logical steps and is derived from both physical and economic science techniques (Fig. 1). The following procedure was implemented: (1) production and validation of a landslide hazard model; (2) estimation of how the implementation of mitigation solutions can influence the areal frequency of landslides; (3) compilation of data on economic losses caused by landslide and calculation of the implementation costs of planned measures to mitigate

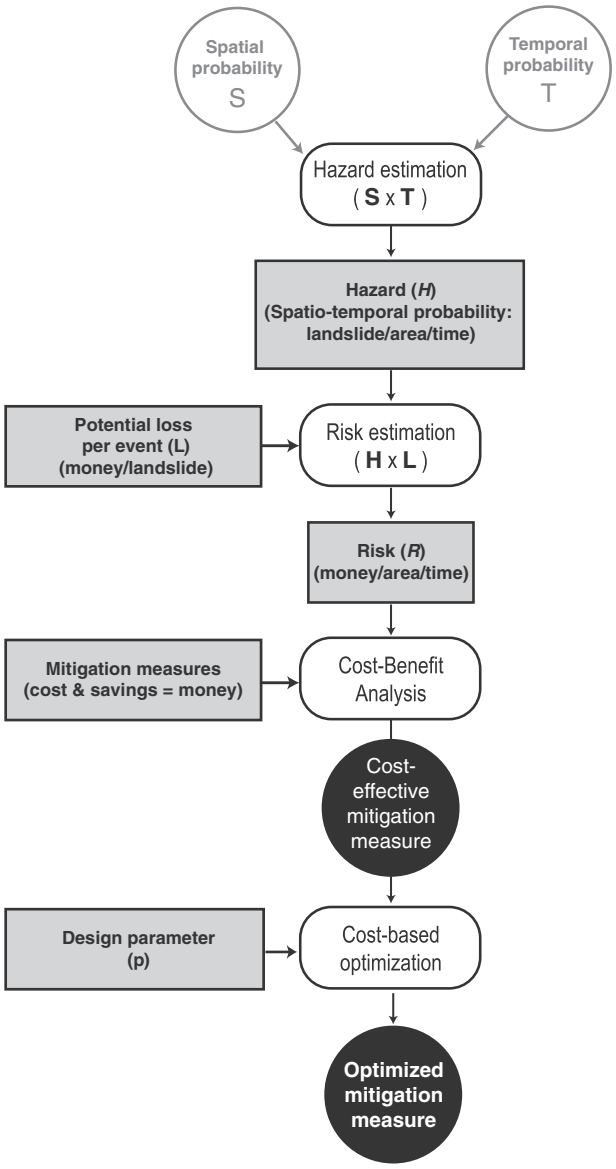

Fig. 1. Methodological flow chart diagram.

them; (4) carrying out of a cost-benefit analysis (CBA) in order to identify the most cost-effective measure and how optimize it from the economic point of view; and finally, (5) analysis of the sensitivity of the CBA results to the variation of the input parameters.

The full description of the methods used to generate the hazard model (1) and to calculate the impact of mitigation measures on landslide areal frequency (2) is reported in Galve et al. (2015). For this reason, in this paper, only a brief outline of (1) and (2) is provided, while a more detailed description of the methodology dealing with the economic analysis (3; 4; 5) is presented.

2.1. Case study

The Vernazza catchment covers approximately 5.7 km^2 and is located in the easternmost part of Liguria (NW Italy) (Fig. 2). This area was declared as a World Heritage Site by UNESCO in 1997 and is included in the Cinque Terre National Park. Cinque Terre is an outstanding example of a man-made landscape comprising centuries-old agricultural terraces retained by dry stone walls (Terranova et al., 2006; Brandolini, in press).

The Vernazza basin is characterized by very steep slopes with a terrain gradient ranging mainly between 30° and 40°. It has very short