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Earthquake-induced rockfall hazard zoning

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ABSTRACT

A methodology for quantitative probabilistic hazard zonation for earthquake-induced rockfalls is presented and demonstrated in the area of Friuli (Eastern Italian Alps) affected by the 1976 M_w 6.5 earthquake. Four rockfall datasets have been prepared both from historical data analysis and field surveys. The methodology relies on a three-dimensional hazard vector, whose components include the rockfall kinetic energy, the fly height, and the annual frequency. The values of the first two components are calculated for each location along the slope using the 3D rockfall runout simulator Hy-STONE. The rockfall annual frequency is assessed by multiplying the annual onset frequency by the simulated transit frequency. The annual onset frequency is calculated through a procedure that combines the extent of unstable areas, calculated for 10 different seismic-hazard scenarios with different annual frequencies of occurrence, and the magnitude relative–frequency relationship of blocks as derived from the collected field data. For each annual frequency of occurrence, the unstable area is calculated as a function of morphometric and earthquake characteristics. A series of discriminant-analysis models, using the rockfall datasets and DEMs of different resolution (1 and 10 m), identified the controlling variables and verified the model robustness. In contrast with previously published relationships, we show that the slope curvature plays a relevant role in the computation of the unstable area.

1. Introduction

Rockfalls are a dangerous hazard where developed areas are near steep, susceptible slopes. Moreover, rockfalls and other landslides are one of the main secondary effects of large earthquakes (Keefer, 1984; Rodrıguez et al., 1999; Hack et al., 2007). Rockfall hazard zoning is therefore important for land-use planning, especially in seismic areas having steep slopes. Landslide hazard zoning is the division of land into homogeneous areas or domains that are ranked according to degrees of actual or potential landslide hazard (Fell et al., 2008). Different rockfall hazard zoning methodologies have been proposed at different scales (Labiouse and Abbruzzese, 2011) through multi-criteria rating approaches (e.g., Pierson et al., 1990) or approaches based on coupling energy and frequency (Rouiller et al., 1998; Raetzo et al., 2002; Corominas et al., 2003; Jaboyedoff et al., 2005). However, most of these approaches assess the rockfall frequency using heuristic approaches, expert judgement, or analysis of relatively small historical datasets. This makes them inapplicable in seismic areas, where the probability of rockfalls is mostly controlled by earthquake events.

A rigorous rockfall hazard assessment for zoning purposes requires the definition of (1) the probability of occurrence and (2) the magnitude and effects of the expected events. We refer to these, respectively, as the onset probability and the reach probability (Cancelli and Crosta, 1993; Corominas et al., 2005; Jaboyedoff et al., 2005; Straub and Schubert, 2008; Agliardi et al., 2009). The onset probability depends on several factors (e.g., geological, geomorphological, and hydrological conditions) that locally control the stability of the slopes and on the probability of possible external triggering events (e.g., rainfall, earthquakes). For seismically triggered rockfalls, the onset probability is regulated by the probability of occurrence of earthquakes having different intensities. For other landslide typology the relationship between earthquake input and landslide occurrence has been extensively studied by means of empirical (Keefer, 1984; Rodrıguez et al., 1999; Lee et al., 2008; Miles and Keefer, 2009) and physically based approaches (Jibson et al., 2000; Wasowski and Del Gaudio, 2000; Capolongo et al., 2002; Del Gaudio et al., 2003; Del Gaudio and Wasowski, 2004; Uchida et al., 2006; Peng et al., 2009; Rapolla et al., 2010; Motamedi and Liang, 2013). Indeed, only a few studies have focused explicitly on rockfalls. For example, based on the Umbria and Marche 1977 earthquake (M_w 6.0), Marzorati et al. (2002) defined a multiple regression equation in which the density of landslides is related to slope angle and peak ground acceleration (PGA).

The reach probability depends on the path followed by rockfalls in their movement along the slope and is controlled by several factors, such as the topographical surface at micro- and macro-scale, the rockfall volume, and the shape and the size of the blocks (Frattini et al., 2012a). For the assessment of the reach probability, a simulation of rockfall run out should be performed by using empirical methods (e.g. the "shadow cone" method, Evans and Hungr, 1993) or by simulating free-fall, impact, bouncing, and rolling motions in a 2D or 3D space, through the

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use of kinematic (e.g., Stevens, 1998), hybrid (Pfeiffer and Higgins, 1990; Jones et al., 2000; Crosta et al., 2004), or dynamic mathematical models (Descoeudres and Zimmermann, 1987; Azzoni et al., 1995; Leine et al., 2013).

The aim of this paper is to develop a simple and readily applicable methodology for earthquake-induced hazard zoning in seismic areas, starting from the "rockfall hazard vector" approach (RHV) proposed by Crosta and Agliardi (2003), and introducing the rockfall probability as a function of seismic hazard and rockfall dynamics. Moreover, the paper identifies the most important variables controlling rockfall triggering, including the role of PGA.

2. Methodology for earthquake induced hazard zoning

The overall methodology adopted in this study for rockfall hazard zoning is presented in Fig. 1.

Rockfall hazard at a given location on a susceptible slope is assumed to be a function of rockfall annual frequency of transit at each location, f_{annual}, maximum block kinetic energy, e_k, and maximum trajectory height, h. This approach assesses hazard by taking into account both rockfall frequency and intensity, as a function of velocity, or energy, and fly height of blocks. The required variables can be computed for each grid cell of a terrain surface by performing 2D or 3D numerical modeling at a suitable level of detail. Similarly to Crosta and Agliardi (2003), rockfall hazard is expressed through an index that represents the magnitude of the modified "rockfall hazard vector" (RHV_{mod}) defined as:

$$|\text{RHV}_{\text{mod}}| = \sqrt{F_{\text{annual}}^2 + E_k^2 + H^2} \qquad (1)$$

where F_{annual}, E_k and H are indices obtained by reclassifying from 1 to 3 (Table 1) the measured values of f_{annual}, e_k, and h, respectively. The threshold of e_k and h classes are defined considering the dimension and energy of typical countermeasures (barriers and embankments) (Crosta and Agliardi, 2003). The class thresholds of f_{annual} have been defined considering individual risk-acceptability criteria. In fact, assuming that the impact of a block on a person is always lethal, the frequency of transit corresponds to the individual risk, defined as the probability that an average unprotected person, permanently present at a certain location, is killed (Bottelberghs, 2000). The f_{annual} class thresholds correspond to the limits of tolerability (10^{-5} per year for new developments, 10^{-4} per year for existing developments) for non-volunteer risk such as rockfalls (Geotechnical Engineering Office, 1998).

Table 1
Interval classification for the variables involved in the modified RHV hazard assessment.

Value	Transit frequency, c (#)	Maximum kinetic energy, e_k (kJ)	Maximum trajectory height, h (m)	Annual transit frequency, f_{annual}
1	0–10	0–1000	0–4	$0–10^{-5}$
2	10–50	1000–5000	4–10	$10^{-5}–10^{-4}$
3	>50	>5000	>10	$>10^{-4}$

The annual frequency of transit for each cell, f_{annual}, is obtained by combining the annual onset frequency, f_{onset} (i.e., the expected number of detachment events per year), with the results of the rockfall propagation model:

$$f_{\text{annual}} = f_{\text{onset}} \frac{c}{N} \qquad (2)$$

where c is the number of transits for each cell and N is the total number of blocks simulated from the entire cliff.

For the calculation of f_{onset} of rockfalls triggered by earthquakes a new procedure is proposed based on a statistical and probabilistic analysis of rockfall triggering:

- Define an empirical function for the probability of rockfall as a function of morphometric variables and PGA, through discriminant analysis;
- Calculate and map potentially unstable rockfall areas for different annual frequencies of occurrences by applying the empirical probability function;

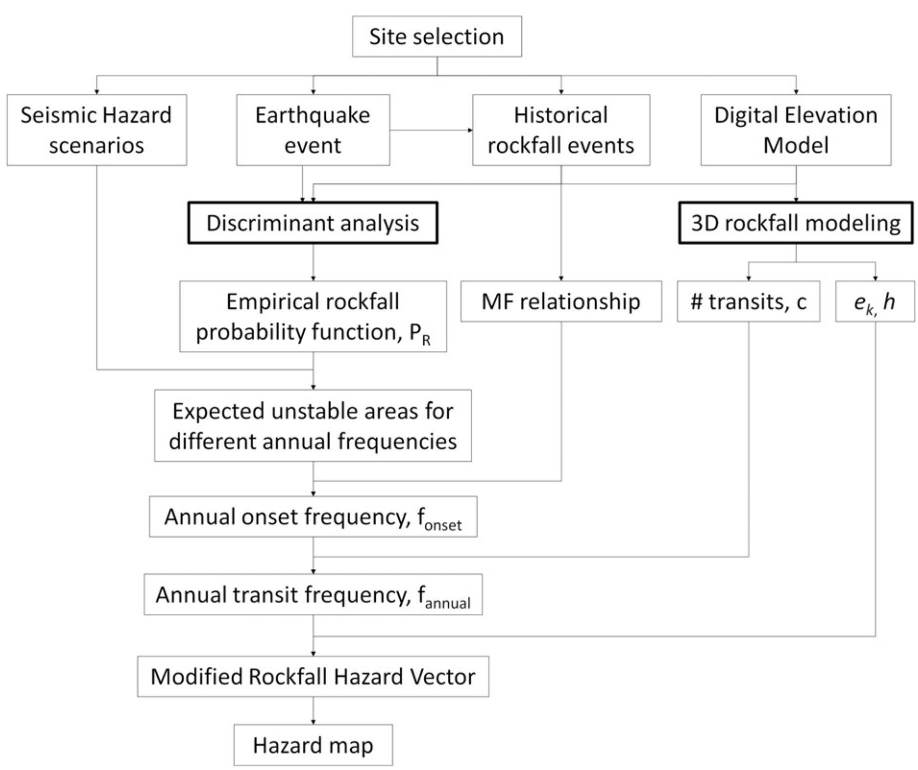

Fig. 1. Workflow of the rockfall-hazard methodology.