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A probabilistic approach for landslide hazard analysis

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ABSTRACT

We present a general framework for probabilistic landslide hazard analysis. With respect to other quantitative hazard assessment approaches, this probabilistic landslide hazard analysis has the advantage to provide hazard curves and maps, and to be applicable to all typologies of landslides, if necessary accounting for both their onset and transit probability.

The method quantifies, for a given slope location, the exceedance probability of being affected by a landslide with a specific local intensity within a reference time interval, i.e. the hazard curve, under the common assumption that landslides behave as a Poisson process. Hazard maps are calculated, reducing the hazard curve to single values by choosing a fixed probability of exceedance following standards or regulation requirements. The method is based on the assessment of a landslide onset frequency, a runout frequency for long-runout landslides, and the local definition of landslide intensity, which can be expressed through different parameters, according to landslide typology. For long runout landslides, the runout and spatially-varying intensity and uncertainty are considered.

Hazard curves and maps play a fundamental role in the design and dimensioning of mitigation structures, in land planning and in the definition of risk and hazard management policies. Starting from the general framework, we apply the methodology for rockfall hazard analysis, and we test it in an area affected by the Christchurch 2011 earthquake, New Zealand, which triggered a large number of rockfalls, killing five people.

1. Introduction

Landslide hazard expresses the probability that a landslide with a certain intensity can occur in a certain location within a given period of time [*ISSMGE Glossary of Risk Assessment Terms,* http://140.112.12.21/issmge/2004Glossary_Draft1.pdf]. This definition underlines that hazard is a function of intensity. This function is usually known as hazard curve, in the literature generally related to seismic risk (Frankel et al., 1996), windstorms and floods (Grünthal et al., 2006) and tsunamis (PTHA, González et al., 2009; Annaka et al., 2007; Liu et al., 2007; Geist and Parsons, 2006). While the concepts of intensity and magnitude are well defined for these threats, the terms are not always really and easily formalised for landslides. A formalization was proposed by Hungr (1997), and some clarifying advices have been expressed in some recommendations for landslide risk assessment (e.g. OFAT-OFFE-OFEP, 1997; AGS, 2007; Fell et al., 2008; Corominas et al., 2014). In most cases, however, intensity is used as a general term, which can include different concepts, such as size, volume, velocity, energy. Magnitude is frequently used to describe the size of a landslide in terms of volume (e.g. Hungr et al. 1999; Marchi and D'Agostino, 2004; Jakob and Friele, 2010; Santana et al, 2012) or area (e.g.: Hovius et al, 1997; Stark and Hovius, 2001; Dussauge et al, 2003; Malamud et al., 2004; Guthrie and Evans, 2004).

A low consensus on the use of terms derives from the fact that landslides include different phenomena, which can be described by different parameters. Due to the objective difficulty to generate hazard curves for landslides, a reason why they are extremely rare in the landslide risk literature, the selection of an intensity parameter is still an important issue. Intensity should correspond to a measure of "damage potential". Hence, it should not express the size of a landslide, but its destructive power. On the other hand, the frequency of landslides is often related to their size and not necessarily to their destructive power, expressing the magnitude of the events, more than the intensity (e.g., Hungr et al, 1999; Dussauge et al, 2003).

The concepts of magnitude and intensity applied to landslides can be clarified referring, in analogy, to earthquake engineering. For earthquakes, the magnitude expresses the energy released by the single event, and can be considered a description of earthquake "size". Magnitude–Frequency relationships (also known as Gutenberg–Richter's law) are used to characterize the frequency of occurrence of earthquakes with different magnitude (Gutenberg and Richter, 1942). However, ground motion parameters or functions (e.g., peak ground acceleration, peak ground displacement, spectral acceleration), expressing the local intensity of the earthquake, are needed to assess damages by using fragility curves (i.e., the probability of exceeding a given

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damage state as a function of a ground motion parameter) (Syner-G, 2011). To calculate the local ground motion, attenuation relationships as a function of distance from the earthquake epicenter and magnitude, are used, also accounting for uncertainty.

Techniques to derive hazard for each location along a slope can be different as a function of the typology of the landslide and the scale of the analysis. For local scale analysis of single landslides it is possible to simulate various scenarios considering different volumes (but also displacement or velocity, especially for already existing landslides with known volume) and associated probabilities (i.e., M–F relationships) through numerical models in order to determine the spatial distribution of intensity during landslide movement (Archetti and Lamberti, 2003; Friele et al, 2008). Hence, for each location along the slope it is possible to build the hazard curve by adopting the frequency values provided by M–F relationships and the intensities calculated by the model. This approach is also adopted for snow avalanches (Keylock et al, 1999; Keylock and Barbolini, 2001). In these methodologies, however, the uncertainties involved in modeling the landslide dynamics are not taken into account. If uncertainty is considered, the intensity at each location along the slope cannot be expressed as a single value for each magnitude scenario, but as a frequency distribution of values. To characterize this distribution, a simple statistic is normally used, such as the arithmetic average (Agliardi et al 2009), the maximum value (Gentile et al, 2008; Calvo and Savi, 2009), or a specific percentile (95th in Spadari et al., 2013; 90th in Lambert et al., 2012). In these cases, the hazard curves are obtained by associating these unique values of intensity to corresponding scenario frequencies derived from M–F relationships. However, these approaches introduce a strong assumption about the distribution of intensity, because the arithmetic mean is representative only for normally distributed intensity, the maximum value can reflect outliers of the distribution, and the percentiles may strongly overestimate the actual hazard.

The aim of the paper is to propose a probabilistic methodology for the assessment of hazard connected to all typologies of landslide, quantifying the probability of exceeding various intensities at a site (or a map of sites) given all possible events. In the second section we present the general framework for landslide probabilistic hazard analysis. In the third section, we discuss its applicability to all landslide typologies. In the fourth section, we decline the methodology to rockfall hazard analysis and we investigate the nature of the intensity distribution for rockfalls by means of parametric numerical modeling. In the fifth section, we present an application of the methodology to the area of Richmond Hill, Port Hills, Christchurch, New Zealand.

2. A general framework for landslide hazard analysis

The landslide hazard assessment methodology here proposed is conceptually derived from the numerical/analytical approach formalized by Cornell (1968) for probabilistic seismic hazard analysis (PSHA), which integrates over all earthquake scenarios, allowing to estimate the likelihood of exceeding selected ground motion parameters (generally peak ground acceleration, PGA) at a given site, within a reference time interval.

For each position along the slope, z, the probability of exceeding a certain value of landslide intensity, i, is

$$P(I>i) = \int_{I_c}^{\infty} p(I)dI \tag{1}$$

where $p(I)$ is the probability density function of landslide intensity at the position z. This function reflects the stochastic nature of intensity, whose values can vary for each position along the slope, due to the uncertainty about the models used to simulate the intensity, and the temporal and spatial variability of the landslide behavior. The shape of the probability density function can be different (e.g., normal, log-normal), based on both the nature of the physical processes and the types of uncertainty.

Multiplying the exceedance probability by the annual frequency of occurrence f, we obtain the annual rate at which i is exceeded, $F(I>i)$ as:

$$F(I>i) = f \cdot P(I>i) \tag{2}$$

The annual frequency of occurrence, f, can be calculated for landslides by direct or indirect approaches (Picarelli et al., 2005; Corominas and Moya, 2008). Direct approaches are based on the analysis of available historical data of past landslides, which can also be related to geology, geomorphology, and other factors (Moon et al., 1992; Cruden, 1997; Jaiswal et al, 2011; Geist et al, 2013). Indirect approaches derive the landslide frequency from triggering factors, such as rainfall intensity and duration (Sidle et al., 1985; Crozier, 1997; Dai and Lee, 2001; Schuster and Wieczorek, 2002; D'Odorico et al., 2005; Rosso et al., 2006; Salciarini et al., 2008; Frattini et al., 2009), or earthquake (Del Gaudio et al., 2003; Rathje and Saygili, 2008).

In case landslides scenarios with different magnitude potentially occur in a certain position along the slope, the total annual rate at which i is exceeded, $F_{tot}(I>i)$, derives from the sum of all scenarios, s.

$$F_{tot}(I>i) = \sum_{s=1}^{N} f_s P_s(I>i) \tag{3}$$

By assuming a homogeneous, stationary Poisson process for the occurrence of the events (Crovelli, 2000), the probability of exceeding each intensity i in the next T years from this annual rate, P_{poiss}, is:

$$P_{poiss}(I>i, T) = 1 - e^{-F_{tot}T} \tag{4}$$

This represents the hazard curve for each position along the slope.

In order to represent hazard through a hazard map, it is necessary to reduce the hazard curve to a single value for each position. This is typically done by choosing the intensity value having a 10% (or 2%) chance of exceedance in 50 years (as done for earthquakes, Frankel et al, 1996). As a consequence, a map of these values for the region of interest can then be generated.

In the literature, the probability of landslides is frequently expressed in terms of annual frequency (e.g. Hungr et al., 1999) or return time, implicitly assuming a binomial occurrence probability model, for which, in fact, the exceedance probability equals the annual frequency. While this assumption holds in case of rare events (e.g. large rock avalanches), it can be violated for frequent events (e.g. rockfalls, debris flows, landslide reactivations) (Crovelli, 2000).

The use of a stationary Poisson process for the occurrence of the events implies the assumptions that the rate of occurrence of landslides is constant in time, and that the probability of more than one event in a small time interval is order of magnitudes lower than the probability of just one event (Straub and Schubert, 2008). The recurrence time of landslides deviates from that expected for a stationary Poisson process at short recurrence times, due to a temporal clustering effect, resulting from climatic conditions and/or seismic triggers (Geist and Parsons, 2008; Tatard et al, 2010; Witt et al, 2010). In this case, the occurrence rate may increase slightly immediately after an event, but is that of a stationary Poisson process on a larger timescale.

A time-varying occurrence rate however may be introduced, with an increase of the complexity of the analysis, as done for other hazards (Ogata, 1999; Parsons, 2008).