

Evaluation of landslide reactivation: A modified rainfall threshold model based on historical records of rainfall and landslides

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Abstract

This study proposes a modification of the conventional threshold model for assessing the probability of rainfall-induced landslide reactivation. The modification is based on the consideration that exceedance of a pre-determined rainfall threshold is a necessary but not sufficient condition to reactivate a landslide. The proposed method calculates the probability of reactivation as a function of the probability of exceedance of a pre-determined rainfall threshold, as well as the probability of occurrence of a landslide after such exceedance. The data for the calculation were obtained from historical records of landslides and rainfall.

The method was applied to two complex landslides (“San Donato” and “La Salsa”) involving fine-grained debris in the southern section of the Apennine foredeep. The minimum rainfall threshold triggering landslide reactivation on the two slopes was determined by examining rainfall patterns during the 180 days preceding the slide events. For the San Donato and La Salsa landslides, the minimum triggering threshold consists of rainfall events lasting 15 days, with cumulated rainfall exceeding 150 and 180 mm, respectively. Based on hydrological and statistical analyses, the annual probabilities of exceeding the thresholds were estimated to be 0.38 and 0.25, respectively. During the period from 1950 to 1987, the minimum threshold was exceeded 14 times, and four reactivations occurred at San Donato; whereas, the threshold was exceeded 10 times and three reactivations occurred at La Salsa. Hence, the probabilities of landsliding after exceedance of the minimum rainfall threshold are 4/14 and 3/10, respectively. Finally, annual reactivation probabilities were calculated to be 0.11 and 0.08, respectively. The reliability of the minimum rainfall threshold was tested by: i) simulating variations in the stress–strain behavior of the slopes as a result of fluctuations in the water table from normal to extreme values; and ii) analyzing the results of continuous multi-year monitoring of pore pressure and rainfall variations on a slope composed of dominantly fine-grained debris.

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1. Introduction

Extensive records of landslide activity in Italy (Guzzetti et al., 1994; Bandis et al., 1996; Iiritano et al., 1998; Guzzetti, 2000; Basenghi and Bertolini, 2002; Calcaterra and Santo, 2004) show that, in many cases, new slides are consequent upon partial or com-

plete reactivation of existing landslide bodies, often triggered by rainfall. Therefore, landslide prediction is closely related to the probability of exceeding given precipitation threshold values. There is a vast body of literature on this topic, which has yielded important results in the past two decades (e.g., Keefer et al., 1987; Cannon, 1988; Capecchi and Focardi, 1988; Finlay et al., 1997; Au, 1998; Glade, 1998; Reichenbach et al., 1998; Domínguez Cuesta et al., 1999; Polemio and Sdao, 1999; Chleborad, 2000; Waltham and Dixon,

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2000; Dai and Lee, 2001; Ibsen and Casagli, 2004; Luino, 2005; Claessens et al., 2006).

However, this simple predictive model, known as “threshold model”, has some inherent drawbacks, if it is applied at regional scale or to a single slope. Although exceedance of the precipitation threshold is necessary for inducing movements, it is not sufficient to trigger a slide, especially when the model is applied to a single slope. In particular, records of rainfall-induced slips and debris flows demonstrate that rainfall thresholds are often exceeded without giving rise to any movement. This uncertainty presumably derives from a “black box model”, where the causal link between rainfall and landslide reactivation is unclear. If these phenomena were thoroughly investigated through coupled hydro-mechanical models at slope scale (Hodge and Freeze, 1977; Reid, 1994; Terlien, 1997, 1998; Crosta, 1998; Ng and Shi, 1998; Rahardjo et al., 2001; Alonso et al., 2003), this uncertainty would be clarified. However, these investigations might be much more complex than those relying on the threshold model.

Historical records of landslides and precipitation may be analyzed more thoroughly while retaining the simplicity of the threshold model (Crovelli, 2000) and mitigating its inherent indeterminacy. We adopted and developed this modified concept of the conventional threshold model in order to investigate the probability of slide reactivation on two landslide-prone slopes in Italy.

2. Improvement of the threshold model

The fundamental input data for the threshold model are the time series of precipitation intensity $X(t)$, expressed in mm h^{-1} or mm day^{-1} . The basic assumption is that there is a function of $X(t)$ which is related to the reactivation of the slide event E :

$$Y(t) = f[X(t)] \quad (1)$$

where the function $Y(t)$ identifies the amount of rainfall in a given period (e.g. hourly, daily, monthly, or n -day cumulated rainfall).

The probability of occurrence of the event $E(P[E])$ is a function of Y . Defining Y_S as the threshold value of Y gives

$$P[E|Y \leq Y_S] = 0 \quad (2)$$

$$P[E|Y > Y_S] = 1 \quad (3)$$

i.e., the slide event does not occur at Y values lower than or equal to Y_S , whereas, the event occurs when Y exceeds Y_S . In the latter case

$$P[E] = P[Y > Y_S]. \quad (4)$$

If the probability $P[Y > Y_S]$ is the probability of occurrence of Y exceeding Y_S in a given year, then the return period T of the threshold, defined by the number of years in which Y_S is exceeded only once on average, is expressed by

$$T = \frac{1}{P[Y > Y_S]}. \quad (5)$$

This basic assumption of the threshold model, on which the probability of occurrence is equal to one at values of $Y > Y_S$ (see Eq. (3)), may not be validated by actual event records. Exceedance of the precipitation threshold appears to be a necessary but not sufficient condition to trigger movement. Apparently, mass movement is induced by another set of complex conditions which are not fully understood and difficult to analyze in probabilistic terms (Aleotti and Chowdhury, 1999).

An alternative solution is to compute both the probability that a given rainfall threshold is exceeded (event A), and the probability of occurrence of actual landslide reactivation (event B) once the threshold has been exceeded. Thus, the probability of rainfall-induced reactivation of a slide is given by the intersection probability

$$P[A \cap B] = P[A]P[B|A]. \quad (6)$$

Eq. (6) states that the probability of occurrence of both events A and B is equal to the probability of A multiplied by the probability of occurrence of B, assuming that A has already occurred.

The determination of $P[A]$ involves

- assessing the hydrological variable $Y(t)$ “justifying” reactivation of slope movement;
- choosing the probability calculation model; and
- determining the “minimum threshold” triggering slide phenomena.

The determination of $P[B|A]$ may rely on the determination of the frequency of landslide reactivations after cumulated precipitation becomes greater than the given threshold. Therefore, it involves the determination of

- return periods of the threshold values; and
- return periods of landslide phenomena.

This paper describes the procedures for assessing $P[A]$ and $P[B|A]$ in two landslide-prone slopes located in the southern Apennine foredeep (Fig. 1): San Donato (Pisticci) and La Salsa (Pomarico). For these slopes, a number of well-documented reactivations

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