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Early warning of rainfall-induced landslides based on empirical mobility function predictor

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ABSTRACT

A stochastic real time predictor of rainfall-induced landslides has been developed. It couples the empirical slope stability model FLaIR with a point rainfall stochastic model. FLaIR model introduces a slope mobility function which links the occurrence of a slide movement to the characteristics of antecedent rainfall. Point rainfall external intermittence, namely the alternation of storms and dry periods, is modeled as an alternating renewal process (ARP). The properties of the ARP allow to assume that, during a storm, the future evolution of the mobility function depends only, in stochastic sense, on the hyetograph observed after the beginning of the ongoing storm (internal intermittence). Thus, the expected value of the mobility function is empirically evaluated by selecting, from the historical data set, only the storms with characteristics similar to the ongoing one. The predictor has been calibrated and validated on the basis of a nearly 48 years long hourly rainfall data record, collected by the rain gauge of Lanzo, in Northern Italy, close to the slope of Pessinetto, where six earth flows occurred during the observation period. The obtained results show that the proposed model provides reliable real time predictions of the slope mobility function up to a lead time of 6 h. The proposed predictor has been also tested as a part of an early warning system against earth flows to be operated at the slope of Pessinetto, by defining two threshold values of the mobility function, corresponding to alert and alarm levels, respectively. The obtained results show that, by properly setting the levels of probability of exceeding the two thresholds, at which the corresponding messages are launched by the system, it is possible, with a low number of false and missing messages, to gain some hours for effectively activating risk mitigation procedures.

1. Introduction

Rainfall-induced landslide risk has been growing all over the world during the last decades, due to fast population increase, often accompanied by uncontrolled urban sprawl. As a consequence, occurrence of landslides more and more often causes damages to buildings and infrastructures and, in some cases, even casualties. This problem is of particular concern in Italy, where unplanned settlement development involves large areas.

Mitigation of such diffuse high risk level cannot be attained with structural interventions and, in most cases, transferring of settlements and infrastructures is also impossible. Therefore, setting up of early warning systems capable to activate prevention measures (i.e. disruption of gas or water supply, electricity cut, road interruption, and evacuation of people) represents in many situations the only viable means for hydrogeological risk management.

Enhancement of early warning systems is indeed part of one of the five priorities of action adopted by the United Nations, International Strategy for Disaster Reduction (ISDR) (UN-ISDR, 2005), in order to enable "individuals and communities threatened by hazards to act in sufficient time and in an appropriate manner to reduce the possibility of personal injury, loss of life and damage to property and the environment" (UN-ISDR-PPEW, 2006).

To this aim, four interrelated key elements of an effective early warning system have been identified (UN-ISDR-PPEW, 2006):

1. risk knowledge;
2. monitoring and warning service;
3. dissemination and communication;
4. response capability.

The first element requires systematic collection and analysis of data, regularly updated to consider the dynamic nature of hazards and vulnerabilities. The last two elements relate, respectively, with setting up communication systems, which must reach people at risk

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with reliable communications, and with preparedness of the community, who should trust warning service and know how to react.

The major contribution of the hydrological scientific community concerns the second element, since prediction and forecasting of hazards implies the development of reliable mathematical models of the relevant hydrological processes. Furthermore, continuous monitoring of hazard parameters and precursors is essential to generate accurate warnings in real time.

For the case of rainfall-induced landslides, warning service should rely on real time observation of hydrological variables (i.e. rainfall height, air temperature and relative humidity, soil suction, and soil water content) and should incorporate models allowing to evaluate in real time, at a given site, the probability of achievement of landslide triggering (hazard assessment), and the possible consequences of the landslide (impact assessment). To this aim, such models should consist of four different parts:

1. rainfall predictor;
2. infiltration model;
3. slope equilibrium model;
4. slide propagation model.

So far, for all of the above mentioned aspects, several modeling approaches are available in literature. The choice of the most convenient for early warning purposes should be advised by taking into account that networks of sensors for monitoring hydrological variables are usually far from being operated (in most cases, only data from rain gauge networks are available). Such limitation, besides the need for building up models capable to perform real time predictions, leads often to prefer simple empirical models rather than computationally expensive physically based models.

In particular, in all the existing warning systems, only the probability of landslide triggering is predicted, while the landslide propagation is not modeled. The extent of the area affected by the consequences of the landslide, and thus by the relevant preventive measures, is therefore not referred to the magnitude of the predicted event, but is evaluated a-priori during the hazard mapping phase, on the basis of historical landslide data heuristically combined with geomorphologic information (Romeo et al., 2006; Castellanos Abella and Van Westen, 2008; Dahal et al., 2008; Galli et al., 2008; He and Beighley, 2008; Sarkar and Anbalagan, 2008; Wu and Chen, 2009).

Therefore, most of the few examples of operating early warning systems of rainfall-induced landslides are based on qualitative weather forecasts integrated with rain gauge measurements, in some cases supplemented by some geotechnical monitoring (Brand et al., 1984; Keefer et al., 1987; D'Orsi et al., 1997; Wilson, 1997; Wieczorek et al., 2000; Wiley, 2000; Ortigao and Justi, 2004; Chleborad et al., 2008; Restrepo et al., 2009). For a review about early warning systems operating in Europe, the reader is referred to Alfieri et al. (2012).

Rainfall is largely adopted as a precursor for early warning of landslides, owing to the large prevalence of landslides induced by rainfalls. In most cases empirical rainfall thresholds for triggering of landslides are used, usually expressed as relationships between rainfall intensity and duration or between cumulated event rainfall and duration (Guzzetti et al., 2007, 2008; Baum and Godt, 2010).

One of the few exceptions is represented by the debris flow warning system of the city of Nagasaki, in which rain gauge data are used as input for a physically based slope infiltration and stability model (Iwamoto, 1990).

The landslide warning system adopted by the civil protection agency of Campania, Italy, is based on the empirical model FLaIR (Forecasting of Landslides Induced by Rainfall). To identify landslide triggering conditions, a slope mobility function is introduced, defined as the convolution integral of rainfall heights, with a transfer function calibrated on the basis of observed slope failures (Sirangelo and Versace, 1996; Versace et al., 2003; Sirangelo and Braca, 2004). Warning levels are defined, corresponding to threshold values of the mobility function.

In order to activate effective prevention measures, rainfall-induced landslides triggering models should be coupled with rainfall stochastic predictors, allowing gaining longer lead times. Such requirement is particularly needed in the case of fast shallow landslides, such as earth flows and debris flows.

In this paper, a stochastic predictor, coupling the empirical slope stability model FLaIR with a simple rainfall stochastic model, is presented. On the basis of available rainfall data, it allows to perform conditional estimates of the probability that, in a future time interval, the slope mobility function overcomes an assigned threshold. The predictions are performed adopting a nonparametric approach: the probability of future values is evaluated making use only of historical mobility function data, which had been observed during storms with characteristics similar to the ongoing one.

The adopted rainfall model describes the external structure of rainfall (i.e., the alternation of storms and dry intervals) through three sequences of random variables (i.e., storm durations, storm total rainfall heights, and dry interval durations) modeled as three renewal processes. In particular, storm durations and dry interval durations, as well as storm rainfall heights and dry interval durations, are modeled as alternating renewal processes (i.e., couples of stochastically independent renewal processes); conversely, the series of storm rainfall heights and storm durations relating to the same storm are assumed to be dependent.

In addition, it is assumed that the internal structure of each storm (i.e., small time scale hyetograph) only depends on what happens after the beginning of the storm.

The proposed model is used to perform real time predictions of FLaIR model mobility function during a storm. To this aim, owing to the adopted rainfall stochastic model features, it is possible to assume that only rainfall data observed after the beginning of the ongoing storm affect, in the stochastic sense, the future evolution of slope equilibrium.

The stochastic predictor of the mobility function is applied to simulate an early warning system of earth flows at the slope of Pessinetto, around 40 km North–West of Turin, in northern Italy, where six earth flows were observed between 01 January 1943 and 15 June 2004. For the entire period, except some out of order intervals, hourly rainfall data of the nearby rain gauge of Lanzo are available for calibration and validation of the predictor.

2. FLaIR model of slope stability

The empirical model FLaIR (Capparelli and Versace, 2011) allows for the identification of rainfall thresholds for landslides triggered by rainfall, without considering the phenomena occurring in the subsoil, such as water infiltration and circulation, pore water pressure changes and their effects on soil strength, but simply linking the occurrence of a slide movement to the characteristics of antecedent rainfall.

The model is formulated by introducing a mobility function, $Y(t)$, defined as a convolution between rainfall intensity, $p(t)$, and a transfer function, $\Psi(t)$:

$$Y(t) = \int_0^\infty \psi(\tau) p(t-\tau) d\tau. \quad (1)$$

The mobility function, which has the dimension of an infiltration height, is to be considered as an empirical indicator of the probability of slope failure. In the presented application, the link between the mobility function value $Y(t)$ and the probability $P[E_t]$ of a new movement E_t at time t is the simple threshold scheme:

$$P[E_t] = \begin{cases} 0 & \text{if} \quad Y(t) < Y_{cr} \\ 1 & \text{if} \quad Y(t) \geq Y_{cr} \end{cases} \quad (2)$$

where Y_{cr} is an empirical threshold value. The choice of the simple decisional rule of Eq. (2) is due to the fact that usually only few observed