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Prediction of shallow landslide occurrence: Validation of a physically-based approach through a real case study

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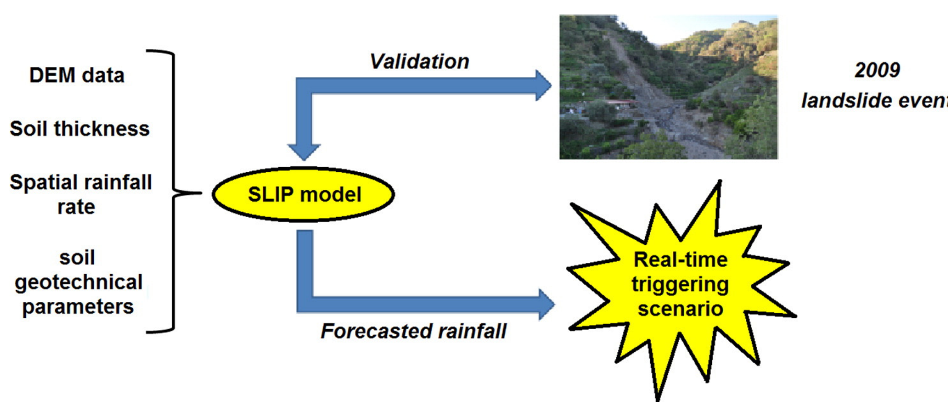
HIGHLIGHTS

- Rainfall-induced shallow landslides cause human casualties and significant damage.
- Numerical models are useful tools for the prediction of these phenomena.
- SLIP model is able to predict the space-time evolution of shallow landslides.
- SLIP is used within an operating procedure for the real-time prediction of landslides.

GRAPHICAL ABSTRACT



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ABSTRACT

In recent years, physically-based numerical models have frequently been used in the framework of early-warning systems devoted to rainfall-induced landslide hazard monitoring and mitigation. For this reason, in this work we describe the potential of SLIP (Shallow Landslides Instability Prediction), a simplified physically-based model for the analysis of shallow landslide occurrence. In order to test the reliability of this model, a back analysis of recent landslide events occurred in the study area (located SW of Messina, northeastern Sicily, Italy) on October 1st, 2009 was performed. The simulation results have been compared with those obtained for the same event by using TRIGRS, another well-established model for shallow landslide prediction. Afterwards, a simulation over a 2-year span period has been performed for the same area, with the aim of evaluating the performance of SLIP as early warning tool. The results confirm the good predictive capability of the model, both in terms of spatial and temporal prediction of the instability phenomena. For this reason, we recommend an operating procedure for the real-time definition of shallow landslide triggering scenarios at the catchment scale, which is based on the use of SLIP calibrated through a specific multi-methodological approach.

1. Introduction

Rainfall-induced landslides often occur as relatively shallow (1–2 m) failures, usually in areas where a residual or colluvial soil profile has

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developed over a bedrock interface (Collins and Znidarcic, 2004; Rahardjo et al., 1995). Although these phenomena typically involve a small volume of earth and/or debris, they are characterized by high velocity and high impact energy. Furthermore, the typical extension of rainfall events frequently causes the almost simultaneously triggering of many shallow landslides over large areas (Cascini et al., 2010; Giannecchini et al., 2012). For these reasons, such events frequently cause substantial damage to infrastructure and human life, thus it appears relevant to assess their spatial and temporal occurrence with the aim of reducing the impact of these natural disasters on the society. In this respect, in the last years different real-time early warning systems have been developed following the improvements of measuring and monitoring networks (Alfieri et al., 2012). The basis of early warning is coupling the susceptibility analysis, which provides the spatial information about landslide occurrence, with measurements or forecasts of intense rainfall events for the prediction of the possible triggering time (Hong and Adler, 2007). These systems rely on the definition of rainfall thresholds (i.e. critical rainfall values beyond which a high probability of landslide occurrence exists), that can be generally determined through empirical (e.g. Aleotti, 2004; Brunetti et al., 2010; Caine, 1980; Corominas and Moya, 1999; Guzzetti et al., 2008) or physical models (e.g. Baum et al., 2008; Iverson, 2000; Liao et al., 2011; Montgomery and Dietrich, 1994). In the latter case, the rainfall thresholds are usually described with the help of numerical models that consider the relation between rainfall, pore-pressure and slope stability. Most of the models adopt an infinite-slope geometry to balance the resisting and the driving forces acting on the sliding mass, using an infiltration model to determine the effect of rainfall on pore-water pressure changes (Raia et al., 2014). This type of models also accounts for the spatial variability of the involved parameters (e.g. physical-mechanical parameters of the slope material, rainfall intensity), thus they appear suitable in determining the shallow landslide occurrence on a regional scale. However, a detailed knowledge of the input parameters over large areas is not generally available (Aleotti, 2004; Berti et al., 2012). In fact, although they are usually calibrated through back-analysis of preceding landslide events, these models are generally characterized by a complex parameterization of hillslope properties and drainage patterns, so requiring detailed field data (Merritt et al., 2003; Rosso et al., 2006).

For these reasons, in this paper we propose the application of SLIP (Shallow Landslides Instability Prediction) (Montrasio, 2000; Montrasio and Valentino, 2007; Montrasio and Valentino, 2008), a simplified physically-based model aimed at spatial and temporal prediction of shallow landslide occurrence. The model calculates the slope stability conditions, in terms of Safety Factor (FS), simulating the saturation process of the soil due to the rainfall infiltration, on the basis of the physical and mechanical parameters of slope materials and rainfall amounts. The specific characteristics of SLIP allow to take into account the contribution to the soil shear strength due to the partial saturation and the effect of the preceding rainfalls. For its features, including the recent implementation at the basin scale (which allows the model to handle geospatial datasets), SLIP has been adopted by the Department of National Civil Protection as a prototype early-warning system for rainfall induced shallow landslides at a national scale (Montrasio et al., 2014). The first objective of this work is to assess the performance of the model by reproducing via back-analysis the landslide event occurred in 2009 in north-eastern Sicily (Southern Italy), for which a comprehensive landslide inventory is available (as well as detailed rainfall and DEM data). At the same time, the reliability of the approach used for the calibration of the model will be evaluated. In a recent publication (i.e. Schilirò et al., 2015a), the same landslide event has been simulated with TRIGRS (Baum et al., 2008), a Fortran program which combines the transient, one-dimensional analytic solution for pore-pressure response to rainfall infiltration with an infinite slope stability calculation (Savage et al., 2003). Therefore, in order to obtain a quantitative comparison with a well-established physically-based model, the reconstruction of the event predicted by SLIP has been compared with that previously obtained from TRIGRS simulations.

Finally, with the aim of evaluating the predictive capability of SLIP as early warning tool, a simulation over a 2-year span period has been performed for the same area, verifying the response of the model to rainfall events alternated by periods of drying. In this respect, some considerations are provided upon the application of the model in the framework of an operating procedure for the real-time definition of shallow landslide triggering scenarios at the catchment scale.

2. The case study

2.1. Introduction to the study area

The area under study (Fig. 1a) extends over approximately 8 km^2 and is located in the north-eastern part of the Sicily Region (Southern Italy), approximately 20 km SW of Messina, on the eastern side of the Peloritani mountain ridge. This chain represents the inner sector of the Apennine–Maghrebide mountain belt (Amodio Morelli et al., 1976; Bonardi et al., 1982) and was formed by the superimposition of several tectonic Alpine units. In particular, two main tectonic stratigraphic units crop out in the study area, consisting of pre-Alpine crystalline basement rocks: the Mandanici Unit (Bonardi et al., 1976), represented by phyllites and metarenites, and the Aspromonte Unit (Bonardi et al., 1979), characterized by the presence of paragneisses, micaschists and small outcrops of gneisses. The result of the weathering of these rocks is a thin (0.5–2 m) cover of eluvial and colluvial deposits that overlays the majority of the slopes. Since the late Miocene, the development of a regional scale NE-SW extensional fault system caused a general uplift of the area (Rust and Kershaw, 2000; Tortorici et al., 1995), as well as an intense seismic activity which is still ongoing (Catalano et al., 2008). The interaction between tectonic activity and eustatic sea-level fluctuations during the late Quaternary is reflected in the landforms that characterize the landscape. The topography is very rugged, with sharp ridges that reach approximately 700 m a.s.l. and steep slopes, on which small outcrops of marine terraces can be found at different elevations (Catalano and De Guidi, 2003). Catchments are generally small (5–10 km^2) and are drained by deeply-incised streams locally named '*fiumara*'. These streams typically have high gradient, short length and a torrential regime (Sabato and Tropeano, 2004). In fact, due to the Mediterranean climate that characterizes the area, rainfall is concentrated almost exclusively during the autumn/winter period, when extreme rainfall events usually occur. Such events (mainly convective) frequently have short duration and very high intensity: as a consequence the streams, which are completely dry for most of the year, rapidly swell and large amounts of coarse material, coming from the riverbed or supplied by the surrounding slopes through lateral gullies, move downslope as debris flows. Regarding land use, the area is characterized by the presence of forests and sparse shrubs in the upper part of the basins and widespread agricultural terraces, nowadays mostly abandoned, in the lower one. Pastures and natural grassland are also common in the study area and often resulted in a significant reduction of vegetation cover and intense erosion (Trigila et al., 2015). The urbanized area is generally concentrated along the coast, often near the mouth of the rivers.

2.2. Summary of the October 1st, 2009 event

On October 1st, 2009 a short but intense rainfall event developed in north-eastern Sicily, hitting with particular severity the southern Messina area. According to the rainfall data (Fig. 1b), approximately 225 mm of rain fall in just 8 h (i.e. between 3.00 pm and 11.00 pm), during which extremely high rainfall peaks were recorded (e.g. 22.7 mm of rain measured by the Santo Stefano di Briga station between 7.00 and 7.15 pm). Beyond the severity of the event, the low rainfall values recorded in two rain gauge stations approximately 20 km from the study area (i.e.