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Control of hydrological seasonal variability of ash-fall pyroclastic deposits on rainfall triggering debris flows in Campania (Southern Italy)

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Abstract

Ash-fall pyroclastic deposits covering Campanian mountain slopes (southern Italy) are very prone to instability under heavy and prolonged rainfall. In such a geo-hazard framework, to understand hydrological dynamics of pyroclastic mantle is a further step toward the assessment of rainfall thresholds and landslide hazard. In this research, the hydrological and stability modelling of representative ash-fall pyroclastic soil mantled slopes of the Sarno Mountains is proposed to assess the role of seasonal hydrological variability of the pyroclastic cover on rainfall triggering debris flows. The approach is based on the numerical modelling, from seasonal to inter-annual timescales, of unsaturated/saturated flows occurring into the pyroclastic mantle upslope of a source area of a debris flow. Modelling results were calibrated by means of field measurements achieved by a monitoring station equipped with tensiometers and Watermark sensors. Among the main results, the recorded pressure head time series showed a dominant unsaturated condition and a very relevant decrease in the summer season, whose effects are not limited to the root zone but extended down to the bedrock interface, about 4 meter deep. This seasonal hydrological regime of the ash-fall pyroclastic mantle was correlated both to the distinctive water retention properties of pyroclastic soils and to the existence of a deciduous forest, which concentrates the evapotranspiration demand during the dry season. Hydrological and stability modeling of the representative slopes allowed the reconstruction of deterministic rainfall thresholds for both dry and wet seasons and the assessment of the significant predisposing role of antecedent hydrological conditions to slope instability during short and heavy rainstorms.

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Keywords: Ash-fall deposits, Debris flows, Hydrological modelling, Hydrological thresholds, Rainfall-triggered landslides.

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1. Introduction

Mountainous areas nearby the Somma-Vesuvius volcanic complex (Campania, southern Italy) are among the areas of Italy with the highest geo-hazard owing to the recurrence of rainfall-induced debris flows along slopes covered by ash-fall pyroclastic deposits. In such a peculiar geomorphological context, to set up an early warning system, finalized to civil defense purposes, several studies were carried out adopting empirical approaches to assess rainfall conditions triggering debris flows [1; 2; 3], given a consistent record of landslide occurrences and the availability of rainfall measurements by a rain gauge network. Nevertheless, further advances of knowledge should concern the understanding of hydrological dynamics occurring within pyroclastic cover at different temporal scales and physically-based approaches. On these bases, it is possible to define rainfall thresholds by calculating critical values of rainfall capable to trigger landslides and to set a suitable early warning system. Moreover, the temporal probability for a landslide to occur [4; 5] can be assessed by connecting rainfall thresholds to statistical hydrological analyses. Consequently hazard to landslide triggering can be estimated. It is clear how to figure out the amount of precipitation needed to trigger slope failures is a problem of scientific and social interest.

Rainfall is a recognized trigger of landslides, indeed direct connections between rainfall patterns and shallow landslides occurrences are widely recognized in the scientific literature [6; 7; 8; 9; 10]. Indeed, hillslope hydrological processes such as infiltration and unsaturated throughflow determine an increase of pore pressures with a consequent redistribution along the slope, which drops the slope stability as a consequence of several combined mechanisms which chiefly determine the reduction of resisting forces by reduction of apparent cohesion and of effective stresses [11].

We present the outcomes of an experimental study based on the integration of hydrological and slope stability modeling and in situ hydrological monitoring, aimed at the reconstruction of physical models of initial landslides triggering debris flows and simulation of hydrological processes leading to slope instability. For this purpose, we carried out a numerical simulation based on a deterministic approach, accounting for a complete hydro-mechanical stability modelling of sample slopes [12; 13; 14; 15].

The modelling was set up taking into account topographic, stratigraphic, geotechnical and soil hydrological characterizations of ash-fall pyroclastic deposits, which were carried out for three representative source areas of debris flows, occurred in May 1998 in the Sarno Mountain Range (Figure 1). Moreover, the modeling was based also on field hydrological measurements collected since January 2011 by a soil hydrological monitoring station. The installation was set with a series of tensiometers and matric potential sensors (Watermark sensors) coupled with a rainfall and air temperature gauge station. Sensors were installed at different depths, according to the local stratigraphic setting [16], which was found to be formed by pedogenised pyroclastic soil horizons and alternated to unweathered pumiceous lapilli horizons. Time series of pressure head, measured for each soil horizon, were used to calibrate a hydrological numerical model of the pyroclastic soil mantle for 2011. This calibrated model was re-run for a 12 years period, beginning in 2000, given the availability of rainfall and air temperature monitoring data. Based on this simulated time series, a hydrological and stability modelling of sample slopes was carried out by a deterministic approach to identify Intensity-Duration (I-D) and cumulated Event rainfall-Duration (E-D) rainfall thresholds [17].

Main results can be summarized as it follows: (i) identification of an approach suitable to take into account of different hazard conditions, related to seasonality of hydrological processes acting into the ash-fall pyroclastic soil mantle; (ii) recognition of an important factor of uncertainty that potentially affects empirical rainfall thresholds; (iii) focusing the remarkable role of antecedent hydrological conditions as a not negligible predisposing factor to instability during short and heavy rainstorms.

2. The study area

Rainfall-induced debris flows represent one of the most important geohazard of the Campania region, which has shown its catastrophic nature in several deadly events and especially in the high-magnitude events occurred on the 25th and 26th October 1954 and on the 5th and 6th May 1998, causing the loss of 316 and 161 human lives, respectively. Mountain ranges that surround the Campanian Plain and the Somma-Vesuvius volcano represent a geological and geomorphological context which is very prone to rainfall-triggered landslides. In fact, they involve