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# Soil water balance in an unsaturated pyroclastic slope for evaluation of soil hydraulic behaviour and boundary conditions

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SUMMARY

Flowslides in granular soils pose a major threat to life and the environment. Their initiation in unsaturated soils is regulated by rainfall infiltration which reduces the matric suction and hence shear strength. Analysis of such phenomena is of strategic importance especially when it aims to mitigate landslide risk by means of early warning systems (EWSs). In this framework, physically-based models need to reproduce the hydro-mechanical behaviour of the slopes through numerical analyses, whose main uncertainty concerns the hydraulic conditions at the boundaries of the studied domain and hydraulic conductivity functions of unsaturated soils. Hence consummate knowledge of both these factors is absolutely necessary for efficient predictions. In this paper hydraulic boundary conditions and hydraulic conductivity functions are investigated at the scale of the slope through an application of soil water balance based on in-situ monitoring at the test site of Monteforte Irpino (southern Italy). Meteorological data, matric suction and soil water content measurements were collected over four years at the test site. The soil water balance was analysed on a seasonal time scale with regard to the whole pyroclastic cover resting on the steep limestone substratum. Infiltration and runoff are estimated, interaction between the soil cover and the substratum is investigated, and the hydraulic conductivity functions operative at the site scale are defined.

## 1. Introduction

Flowslides in granular soils undoubtedly constitute a major threat to human life, man-made structures and the environment in general. In unsaturated soils, rainfall is the most usual triggering cause, due to rainwater infiltrating into the superficial soil, which causes a decrease in matric suction and consequently in shear strength. However, many other factors determine slope hydraulic behaviour, namely stratigraphy, morphology, soil hydraulic properties and vegetation. The literature contains descriptions of many cases of landslides induced by rainfall, typically concerning residual slopes in tropical areas (Gasmo et al., 1999; Rahardjo et al., 2005), unsaturated slopes in China (Zhan et al., 2007; Zhang et al., 2000), pyroclastic unsaturated slopes (Cascini and Sorbino, 2002; Damiano et al., 2012; Rianna et al., 2014a; Pirone et al., 2011, 2015a) and alpine moraine slopes (Springman et al., 2003).

Early warning systems (EWSs) based on an accurate analysis of the groundwater response to meteorological factors, are widely used as measures for rapid landslide risk mitigation (Pagano et al., 2010; Eichenberger et al., 2013; Rianna et al., 2014b; Pirone et al., 2015a). EWSs can be set up by using physically-based models to reproduce the hydro-mechanical slope behaviour through numerical analyses. Although sophisticated numerical tools are available, the weakness in forecasting rainfall-induced landslides is due to uncertainties about hydraulic soil characterisation at the site scale (Chirico et al., 2007) and the hydraulic boundary conditions. Indeed, the presence of topographic irregularities, cracks on the soil surface, vegetation, and strong variation in hydraulic conductivity along the vertical soil profile make hydraulic slope behaviour uncertain. Full understanding of the soil-atmosphere interaction and the interplay between the soil cover and the fractured limestone bedrock is indispensable in order to rationally define the boundary conditions.

Hence full understanding of slope failure conditions as a response to rainfall infiltration is very complex and difficult to achieve without experimentation ad hoc at the local scale. Some examples of in situ monitoring of water regimes in unsaturated slopes are reported in the literature (Springman et al., 2013; Cascini and Sorbino, 2002; Smethurst et al., 2006), albeit carried out on a wide range of soils and hence with non-comparable findings. In situ monitoring allows hydraulic slope behaviour to be

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## Nomenclature

| | |
|---|---|
| $a_{vg^{-1}}$ | empirical parameter of the Van Genuchten soil water retention model (approximately equal to the inverse of the air entry pressure) |
| $d_{ij}$ | thickness of layer $i$ along the vertical $j$ |
| $e_a$ | water vapour pressure in the air filling the fracture network in the limestone bedrock |
| $e_s$ | saturation pressure of the water vapour corresponding to an assigned temperature $T$ |
| $et_o$ | reference evapotranspiration flux |
| $et_c$ | crop evapotranspiration flux |
| $f_{ew}$ | fraction of soil surface from which most evaporation occurs |
| $\mathbf{i}$ | hydraulic head gradients |
| $i^v$ | vertical component of hydraulic head gradients |
| $i^n$ | normal component of hydraulic head gradients |
| $k_{cb}$ | basal crop coefficient |
| $k_s$ | water stress coefficient |
| $k_e$ | soil evaporation coefficient |
| $k_{ij}$ | hydraulic conductivity of layer $i$ along the vertical $j$ |
| $k_{sat}$ | saturated hydraulic conductivity |
| $\ell$ | empirical parameter of the Mualem–Van Genuchten soil water conductivity model |
| $n$ | number of data |
| $n_{vg}$ | empirical parameter of the Van Genuchten soil water retention model |
| $n_L$ | number of soil layers |
| $n_v$ | number of instrumented vertical profiles |
| $q_e$ | daily evaporation flux from the soil bottom |
| $q_i$ | mean values of components normal to the slope surface of the instantaneous water flux |
| $p$ | evapotranspiration depletion factor |
| $s$ | matric suction |
| $t$ | time |
| $ET_0$ | cumulative reference evapotranspiration |
| $ET_c$ | cumulative crop evapotranspiration |
| $G_s$ | specific gravity |
| $H$ | height above see level |
| $I$ | *interception* by vegetation |
| $L$ | length |
| $P$ | rainfall |
| PDA | Personal Digital Assistant |
| $Q_i$ | total amount of water flowing in the direction normal to the slope surface across the top of the $i$th soil layer in the cover |
| $Q_{bi}$ | total amount of water flowing in the direction normal to the slope surface across the bottom of the $i$th soil layer in the cover |
| $Q_{fl}$ | total amount of water flowing in the direction normal to the slope surface across the fractured limestone bedrock |
| $R_{off}$ | runoff |
| SWB | Soil Water Balance |
| $T$ | temperature |
| TDR | Time domain reflectometry |
| $Z_e$ | depth of the surface soil layer subjected to evaporation from the FAO manual |
| $Z_r$ | rooting depth of vegetation |
| $S_i$ | mean soil water storage in the $i$th layer |
| $\Delta S_i$ | variation of mean soil water storage in the $i$th layer |
| $\alpha$ | slope angle |
| $\beta$ | mean angle of the hydraulic head gradient vector to the vertical |
| $\gamma_d$ | soil dry unit weight |
| $\theta$ | volumetric water content |
| $\theta_{fc}$ | volumetric water content at field capacity |
| $\theta_{sat}$ | volumetric water content at saturation |
| $\theta_r$ | volumetric residual water content |
| $\theta_{wp}$ | volumetric water content at wilting point |
| $\sigma$ | standard deviation of the logarithm to base 10 of soil water permeability data |
| $\bar{\mu}$ | arithmetic mean of original soil water permeability data |
| $\Phi$ | soil porosity |

captured at regional scale. However, data processing and assessment of the complete soil water balance may provide guidelines to investigate any monitored slope.

In the present paper, through the example of a test site, guidelines are provided for the assessment of Soil Water Balance (SWB) in unsaturated pyroclastic slopes; the SWB is used to accomplish (i) appropriate modelling of the upper and lower hydraulic boundaries, namely, the infiltration at the ground surface and interaction between the unstable cover and the bedrock, and (ii) identification of the hydraulic conductivity functions operating on site. These features were investigated by processing data from the test site at Monteforte Irpino (Pirone et al., 2015a) where meteorological data, matric suction and volumetric soil water content measurements were collected for about four years. In particular, by applying the SWB to the pyroclastic cover, a practical and novel method to detect a hydraulic conductivity function by processing in situ data is provided. To be precise, the saturated hydraulic conductivity and the hydraulic conductivity function obtained in the laboratory (Nicotera et al., 2010) are compared with the unsaturated hydraulic conductivity values derived from in situ measurements to show that laboratory testing results are not always representative of the effective hydraulic conductivity (see for instance Fenton and Griffiths, 2008) operating at the site scale. Finally by means of the SWB (iii) some insight into the hydraulic behaviour of pumiceous layers (a volcanic gravel) were obtained. Although pumiceous layers are very common in the stratigraphic profile of the pyroclastic slopes in southern Italy, their hydraulic behaviour has not yet been investigated in depth mainly due to the difficulty recovering undisturbed soil samples. Thus interpretation of the monitoring results via the SWB provided some useful information.

## 2. The test site: geological and stratigraphic features

The Campania region in southern Italy is one of the most landslide-prone areas in the country, especially as regards flowslides and debris flows, which involve loose pyroclastic soils mantling calcareous massifs in the central area of the region (Fig. 1a). Indeed, a number of catastrophic flowslides have occurred in southern Italy, especially in the last twenty years: the 1997 Pozzano and Nocera Inferiore flowslides (5 fatalities), the 1998 debris flows which hit four towns at the toe of Mt. Pizzo d'Alvano (160 fatalities) and the town of San Felice a Cancello, the 1999 Cervinara flowslide (5 fatalities), the 2005 Nocera Inferiore flowslide (3 fatalities) and finally the 2006 Ischia flowslides (3 fatalities) (Fig. 1a).

The test site at Monteforte Irpino (40°54′13.11″N, 14°40′24.21″E), about 40 km East of Naples, was selected as being representative of other pyroclastic slopes in Campania subjected to rapid landslides (e.g. Pizzo D'Alvano, Monti di Avella and Monte Partenio) (Cascini and Sorbino, 2002; Damiano et al., 2012). In the test site area, the slope is quite regular and has an average