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Rainfall-induced infiltration, runoff and failure in steep unsaturated shallow soil deposits

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ABSTRACT

In unsaturated shallow deposits, rainfall infiltration and runoff may cause either slope failure or erosion processes depending on the combination of rainfall intensity and duration. Consequently, different flow-like mass movements may occur, whose distinction is fully necessary for the management and mitigation of the posed risk. To provide a contribution to this topic, the paper proposes an engineering reference framework to evaluate the amount of both rainfall infiltrating the ground surface and runoff flowing as wash out and remarks are outlined as far as the time to runoff and the slope failure time. This framework is validated through a numerical parametric analysis based on seepage and slope stability analysis. The obtained results show that time to runoff, time to failure and runoff rates are strongly affected by soil water characteristic curves, soil initial conditions, rainfall intensity and slope angle. Furthermore, slope stability analyses show that time to failure can be either shorter or longer than time to runoff depending on soil mechanical parameters. Finally, it is outlined that the proposed framework provides more accurate estimates of time to runoff and runoff rates compared to simplified standard procedures.

1. Introduction

Rainfall infiltration process in unsaturated soils is a complex process heavily affecting the slope stability conditions (van Asch et al., 1999; Lacerda, 2004; Rahardjo et al., 2004), especially in the case of steep shallow soil deposits (i.e. slope angle larger than 30° and soil thickness of 1–2 m) (Godt et al., 2008). Due to rainfall, different types of slope instability phenomena (either slope failures or erosion-like phenomena) are triggered which cause, in turn, different flow-like mass movements (Hutchinson, 2004; Cuomo, 2006; Cascini et al., 2011a, in press) depending on slope morphology, soil water characteristic curves and shear strength of involved soils. Referring to the solid/water percentages of the propagating mass, these phenomena can be classified as: i) debris flows (Hungr et al., 2001), i.e. "a very rapid to extremely rapid flow of saturated non-plastic debris in a steep channel", or ii) hyperconcentrated flows (Costa, 1988; Coussot and Meunier, 1996), if a smaller amount of solids is transported, mainly due to sediment transport by overland flow (Kavvas and Govindaraju, 1992). Many worldwide case histories testify the huge consequences of these phenomena in terms of causalities and damages to property. However, the run-out distances and consequences associated to these flow-like mass movements are extremely different and it is important to discriminate among them in order to properly assess and mitigate the risk posed to life and property. In fact the above processes are characterized by different runoff discharges which, in turn, determine the solid concentration and the rheology of the propagating flows.

A proper estimation of the runoff discharge necessarily requires the assessment of the rainfall amount that infiltrates the ground surface. In literature, different methods are available which can be divided in two main groups: empirical and physically-based.

As for the first group, a well-known empirical method is the Curve Number (CN) method (USDA-SCS, 1972) that is based on a simple mass balance equation between the cumulated rainfall computed from the beginning of the rainfall storm, the runoff and the initial water "losses" before the runoff generation. In particular, this method computes the runoff height Q (mm) as a function of both the rainfall height P (mm) and a storage term S (mm) which is a function of a dimensionless index called "Curve Number" (CN); the latter depends on the soil type (hydrologic soil group), the land-use and the antecedent soil moisture conditions at the time of the rainfall. A modified version of the CN method also includes the effect of slope angle and it was firstly applied to East African soil conditions (Sprenger, 1978).

As far as the physically-based methods, it is worth mentioning the Green–Ampt (GA) method (Green and Ampt, 1911) that is a 1D vertical infiltration method based on the Darcy's law (1856). The method assumes the presence of a continuous thin sheet of water at the ground surface which causes a downward moving wetting front into a homogeneous soil with a uniform initial water content. Mein and Larson (1973) propose a modified version of the Green–Ampt method which includes a simple two-stage model for infiltration under a constant intensity rainfall into a homogeneous soil with a uniform initial water content: i) the first stage includes water infiltration before runoff starts; and ii) the second stage coincides with the process schematized by Green and Ampt (1911).

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Both classes of methods have important limitations. For instance, the CN method doesn't explicitly consider the unsaturated–saturated soil hydraulic properties while considering the effect of slope angle; on the other hand, the modified Green–Ampt method (Mein and Larson, 1973) allows considering measurable soil properties as the soil saturated hydraulic conductivity and the initial moisture content but it refers to a vertical 1D infiltration pattern that is not the general case for water infiltration in a slope. Therefore, different simplifications prevent both methods to properly simulate the infiltration and runoff processes.

The present paper aims to improve the understanding of the governing mechanisms of infiltration and runoff generation; moreover, an engineering reference framework is proposed to evaluate both the amount of rainfall infiltrating the ground surface and runoff flowing at the ground surface as wash out. A special attention is devoted to the temporal occurrence of both processes whose combination may cause the occurrence of different types of flow-like mass movements.

2. Mechanisms for rainfall infiltration and runoff generation

2.1. In-situ evidences

Direct in-situ observations of failures are rare except for few real-time monitored sites during the events (e.g. Marchi et al., 2002). More often the amount of rainfall capable to induce slope instability phenomena is individuated referring to time ranges heuristically selected through an expert judgment. In the literature, many contributions deal with the so-called "critical rainfall" which is usually lower bounded through threshold lines in log–log plots (Frattini et al., 2009). Examples are provided in Guzzetti et al. (2007) who also show the wide dispersion of the collected data and interpolating lines. Data dispersion is a weak point of this kind of approach especially for forecasting purposes and it is mainly related to: i) variable in-situ conditions, ii) different temporal resolutions of the data, and iii) different mechanisms governing the observed soil mass movements.

This last aspect is investigated in this paper with reference to relevant case histories of shallow landslides which are selected from different countries (i.e. Italy, United Kingdom, Japan, Taiwan, China, United States, Canada, Brazil and Thailand) in the period from 1950 to 2010 (Table 1). These events caused catastrophic consequences in terms of victims and damage and the scientific literature provide a comprehensive data set regarding the duration of the rainfall storms, the cumulative rainfalls and the maximum rainfall intensities. Fig. 1 shows the average rainfall intensities (1–53 mm/h), durations (5–104 h) and cumulated rainfall (37–586 mm) for the selected events: the data are somehow correlated by a straight line in a logarithmic plot and lie within the envelope curves proposed by Guzzetti et al. (2007). However, such a heuristic approach has important drawbacks as it provides limited chances to understand the governing mechanisms and forecast future events. This is mainly due to the lack of any direct reference to slope geometry and soil mechanical parameters that are completely disregarded. Furthermore, as most of steep slopes lie in unsaturated conditions, a suitable framework should take into account the unsaturated soil conditions as well as the possibility of different mass movements to occur depending on features of slope, rainfall and initial conditions.

On the other hand, detailed information is becoming more often available from monitoring of rainfall infiltration and runoff in well-instrumented sites. For instance, based on experimental data from India, Rao et al. (1998) perform a regression analysis which outlines as significant factors in determining the runoff: i) amount of precipitation, over a period of 30 min, ii) soil cover, iii) cumulated time since the beginning of the experiment and iv) amount of rain during the previous 2 days. In addition, Zhang et al. (2000) observe in Hubei Province (China) that the infiltration rate depends on the soil initial water content and the presence of stratigraphic discontinuities can influence the infiltration pattern.

Notwithstanding the promising results coming from in-situ observations, it's worth noting that the abovementioned experimental evidences may suffer of a partial control of some factors such as local stratigraphy peculiarities and soil strata heterogeneities; consequently, also the results of different approaches must be greatly taken into account.

Table 1
Critical rainfall for 35 selected case histories.

ID	Country	Location	Year	Duration (h)	Cumulative rainfall (mm)
1	USA	Seattle	1950	55	81.95
2	UK	Bristol	1952	24	228
3	Italy	Campania Region	1954	16	504
4	USA	Seattle	1956	104	101.92
5	China	Hong Kong	1966	24	525
6	Brazil	Rio de Janeiro	1967	48	586
7	UK	United Kingdom	1968	24	172
8	USA	Appalachians	1977	9	300
9	Canada	Vancouver	1979	24	300
10	Japan	Boso peninsula	1980	72	559
11	USA	California	1982	32	440
12	USA	Seattle	1983	28	36.96
13	USA	Appalachians	1985	24	240
14	USA	Seattle	1986	28	85.4
15	Japan	San-In district	1988	10	500
16	Japan	Boso peninsula	1989	24	350
17	USA	Seattle	1991	53	121.9
18	USA	Seattle	1996	45	109.8
19	USA	Seattle	1997	44	79.64
20	Italy	Campania Region	1998	48	248
21	Italy	Campania Region	1999	38	264
22	Thailand	Thailand	1999	24	290
23	Italy	Tuscany Region	2000	39	210
24	Italy	Tuscany Region	2000	39	210
25	Taiwan	Taiwan	2000	24	370
26	USA	Seattle	2001	37	55.87
27	USA	Seattle	2001	30	92.7
28	Thailand	Thailand	2001	24	100
29	Thailand	Thailand	2003	24	110
30	Japan	Minamata Hishicari	2003	8	337
31	Japan	Minamata Hogawachi	2003	5	265
32	Japan	Minamata Fukagawa	2003	5	265
33	Thailand	Thailand	2006	24	150
34	Japan	Hofu City	2009	20	241
35	Italy	Campania region	2010	19	120.8

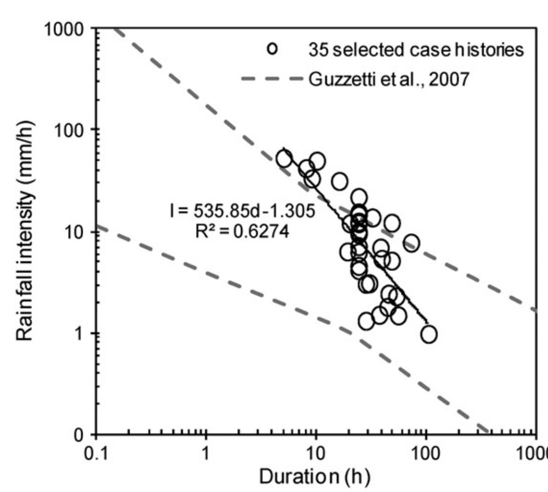

Fig. 1. Rainfall intensity–duration for 35 selected cases.