Engineering Geology 174 (2014) 22–35

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Rainfall patterns triggering shallow flowslides in pyroclastic soils

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ARTICLE INFO

Article history:
Received 24 July 2013
Received in revised form 22 February 2014
Accepted 8 March 2014
Available online 18 March 2014

Keywords:
Rainfall-induced landslides
Soil–atmosphere interaction
Soil suction
Unsaturated soils
Physical model
Pyroclastic soil

ABSTRACT

In the context of landslide-prone pyroclastic soils this paper investigates the physical significance of antecedent rainfalls in relation to the major rainfall event and the influence exerted by evaporation. The work is based on results from tests using a physical model, developed to characterise the hydraulic response of a pyroclastic soil volume subjected to actual meteorological conditions. Rainfall, evaporation, water storage, soil suction and soil volumetric water content were continuously monitored over a meteorological window exceeding two years. Interpretation of the experimental results provides three characteristic values of water storage which are used to explain the physical significance of antecedent and triggering precipitations and shed light on the aspects of major rainfall events triggering landslides.

1. Introduction

The issue of rainfall histories and their particular characteristics resulting in landslides has been extensively debated by the scientific community in recent years, especially with a view to drawing up early warning predictive models implemented at various scales to manage risks associated with rainfall-induced landslides. Some of these empirically- or physically-based models consider landslide initiation only as a consequence of the major rainfall event, quantified with cumulative rainfall over hours or days preceding slope failure. This is the case of Intensity–Duration (ID) based approaches in relation to the main rainfall event, widely followed after the original method proposed by Caine (1980) (e.g., Giannecchini et al., 2012; Lee et al., 2013). Other models also recognize the fundamental role of antecedent rainfalls, quantified as cumulative rain over weeks or months preceding slope failure (e.g., Johnson and Sitar, 1990; Sirangelo and Versace, 1996; D'Orsi et al., 1997; Glade et al., 2000; Rahardjo et al., 2001; Pagano et al., 2008a; Brunetti et al., 2009; Baum and Godt, 2010; Pagano et al., 2010).

Within silty pyroclastic deposits covering steep slopes in Campania (southern Italy) sliding phenomena appear to be related to suction drops induced throughout the pyroclastic cover by a major event lasting several hours preceded by a long-lasting wet period of some months (e.g., Pagano et al., 2008a,b; Greco et al., 2010; Pagano et al., 2010; Damiano et al., 2012; Sorbino and Nicotera, 2013). High porosity exceeding 70%, and near-saturated conditions throughout the cover are considered major factors in predisposing the slope to instability and, at the same time, increasing the susceptibility of the sliding mass to static liquefaction, responsible in these soils for rapid post-failure behaviour (Olivares and Picarelli, 2003).

Table 1 reports the four rainfall histories resulting in flowslides within a limited area in the Nocera Inferiore district (southern Italy) extracted from a database from 1950 up to the present day. They are summarised in terms of cumulative values over progressively longer periods preceding slope failure, all ending at the landslide triggering moment. Common features are cumulative rainfall exceeding 500 mm in the previous few months and 100 mm in the previous one–two days. Within the same database only three additional cases are at all similar to those resulting in landslides and several other cases prove exceptional either in single events or in long-run cumulative rainfall. Such observations show that a synergy between significant antecedent rainfalls and a major event is required to induce instability (see Table 1).

The most recent case of those listed in Table 1 (4 March 2005) entailed failure of a silty pyroclastic cover 2 m thick, at an inclination of 40°, with a porosity slightly higher than 70%. For this case the high velocity of the sliding mass during the down-slope run-out resulted in a strong impact with a house, causing its destruction and three deaths within it.

Monitoring of hourly precipitations very close to the landslide site allowed the hydrological state of the cover to be derived numerically from evolution of rain falling over six months preceding triggering by solving Richards' equation in 1-D flow conditions (Pagano et al., 2010). Results yielded by this analysis indicated that, over six months, rainfall induced suction vanishing several times at one or more depths.

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http://dx.doi.org/10.1016/j.enggeo.2014.03.004
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Table 1
Rainfall histories triggering flowslides in the Nocera Inferiore district, represented as cumulative rainfall over days (first column) antecedent to the triggering time.

Number of days antecedent to triggering	08/12/1960	06/03/1972	10/01/1997	04/03/2005
	Rainfall heights cumulated over antecedent days (mm)			
1	87.1	77.0	110.0	143
2	128.3	115.0	119.0	143
3	128.3	115.0	120.0	143
4	128.3	115.0	120.0	143
5	128.3	115.0	121.2	148.4
6	128.3	115.0	138.2	148.8
7	128.3	115.0	138.2	158
10	140.5	187.0	141.4	201
15	161.7	215.0	194.0	292.4
20	237.9	225.8	211.8	353.4
30	371.1	315.2	251.8	354.8
40	416.8	404.8	298.2	446.8
50	421.3	490.0	456.4	510.8
60	501.5	490.0	547.2	511.8
70	538.6	605.0	547.6	708.8
80	661.0	605.0	547.6	794
90	661.0	605.0	627.6	805.4
100	668.7	829.0	777.8	875.8
110	668.7	1002.2	802.8	878.6
120	668.7	1073.6	974.0	1037.4
130	668.7	1073.6	993.2	1045.6
140	683.7	1073.6	996.4	1089.6

The triggering time emerged, however, as the only time when the occurrence of suction vanishing occurred at all depths (Figure 1). This state condition was considered of great influence for the occurring instability, as it correlates with almost full saturation throughout the cover and, consequently, the highest probability of occurrence of extensive liquefaction phenomena. The same results also indicated that antecedent rainfalls and the major event induced different patterns of suction evolution. Antecedent rainfalls (945 mm of rain fell over 4.5 months) led to smooth and overall significant suction reductions, down to zero at the cover base and a few kPa at higher points. The major event (143 mm of rain fell over 16 h) led to an abrupt suction drop to zero at all depths. Analyses carried out by eliminating or reducing the antecedent rainfalls showed (Pagano et al., 2010) that the major event would not alone have induced sufficient suction drops to trigger the landslide.

The present paper attempts to identify the specific peculiarities of rainfall histories resulting in rapid flowslides of slopes with a cover of silty pyroclastic soils. To attain the objective, the various hydrological effects induced by antecedent rainfalls and major events are experimentally investigated. Such effects are explored to provide a physical meaning for this traditional synthesis of rainfall history into two cumulative values, often adopted for early warning purposes.

The work interprets the hydrological behaviour experienced by a silty pyroclastic layer subject to actual atmospheric conditions within a physical model, forcing one-dimensional flow conditions. The physical model therefore accounts for evaporation phenomena (Rianna et al.,

Table 2
List of devices installed to monitor the physical model.

Physical variable	Device	Position
Atmospheric variable		
Precipitation	Pluviometer ARG 100 Environmental Measurement LTD	Near the tank, at 2 m elev. from the floor
Temperature-relative humidity	T-RH probe CS215 Campbell Scientific	Near the tank, at 2 m elev. from the floor
Wind	Anemometer WSS Environmental Measurement LTD	Near the tank, at 2 m elev. from the floor
Air pressure	Barometer CS 100 Setra	Inside the datalogger system
Incoming solar radiation	Pyranometer LI-COR 200SL	Near the tank, at 2 m elev. from the floor
Net radiation	Radiometer NR-Lite Kipp&Zonen	At 1 m elev. above the layer surface
Soil variable		
Bulk weight changes	Load cells Vishay Huntleigh 3510 C6	Sustaining the tank at three point of its lowermost surface
Soil heat flux	Heat flux plate HFP01SC Hukseflux	Within the layer at depth of 5 cm
Temperature	Termisthore 107 Campbell Scientific Ltd	Within the layer at depths: 5, 15, 30, 50, 70 cm
Volumetric water content	TDR CS 605 with 30 cm needles	Within the layer at depths: 15, 30, 50, 70 cm
Matric suction	Jet fill Soil Moisture LTD	Within the layer at depths: 15, 30, 50, 70 cm