Laboratory rainfall-induced slope failure in a soil from the Colombian coffee region

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ABSTRACT

There are few studies on the processes involved in landslides in the soils of the Colombian coffee region in relation to the soil water content. In order to contribute to this knowledge, several experiments over a terrain model under simulated rainfall were conducted. Seven experiments on laboratory slope models, 1.8 m^2 base, 1.0 m height, and 32° slope, with soil bulk density and soil horizons arrangement similar to in situ conditions, were built. Samples of altered residual soil derived from granitic rocks were collected in the municipality of Ibagué – Colombia from the surface down to 1.6 m depth. In each laboratory model, eight suction tensiometers (0 to −85 kPa) were located, and measurement under simulated rainfall was done. The results indicated a relationship of mass movements with hydrological processes occurring in the slope, related to soil permeability, rainfall intensity and duration, and water table changes. The major portion of soil slope instability cases was related to a saturated condition of the slope toe.

KEYWORDS

suction; non-saturated soils; landslides; geotechnical engineering

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1. Introduction

Landslides are natural hazards causing major economic losses in the Andean region of Colombia (Mantilla et al. 2001). Applied research on soil and water conservation has been conducted for decades in CENICAFÉ, a research institution supported by the Colombian Coffee Growers Federation, oriented to prevent and mitigate the soil erosion and mass movement through cultural practices and ecological restoration (Gómez et al. 1975). Soil erosion and mass movement affect the coffee growing sustainability in the Andean slopes (Salazar-Gutiérrez and Hincapié-Gómez 2013). The maximum daily rain amounts of the Colombian Andean Region, where coffee is grown, are between 101 mm and 120 mm for a return period of 50 years (Jaramillo Robledo 2009). Landslide frequency is closely related with high precipitation associated with El Niño–Southern Oscillation (ENSO); the probability of landslides occurrence could be increased by rainfall associated with the climate change (Crozier 2010).

Mass movements are caused by several factors, including geological, geomorphologic and anthropogenic ones; the rainfall and soil water dynamic have strong potential to cause slope failure (Sidle and Bogaardb 2016). Shallow landslides in coffee farms of Colombia are associated with anthropogenic factors like the poor water management by farmers leading to excessive water seepage (Salazar-Gutiérrez and Hincapié-Gómez 2013). In tropical residual soils, landslides are related to the reduction of soil matric suction induced by rainfall (Fredlund et al. 1978; Miyazaki 1993) where the rapid increase in pore pressure from rain is a critical factor that triggers the failure of a slope (Miyasaki 1993).

To understand mass movements several researchers have used laboratory models, combining hydrological and geotechnical aspects with slope stability (Tohari et al. 2007; Lee et al. 2011; Wu et al. 2017). Bujang et al. (2006) evaluating under laboratory conditions the effect of slope inclination and soil cover on infiltration and soil matric potential, found that infiltration was higher in the lower part of the slope and the soil matric potential was lower during infiltration, which may have negative effects on the stability of the slope.

In order to explore the initiation process of slope failure, Tohari et al. (2007) conducted experiments on a group of laboratory models to induce slope failure by three different modes of increased levels of water (slow and fast from a tank head and simulated rain). Hydrological responses were recorded by soil moisture sensors. Such results showed that model slope failures were essentially initiated by the formation of an unstable area near the foot of the slope, above the water table, with a non-circular slip failure. In the slope toe, soil moisture values at the beginning of the fault were close to saturation; however, a large proportion of slope failures were conducted under saturated conditions.

Despite global advances in the study of landslides, rainfall and hydrologic soil conditions as a mass movement factors in the soils of the Colombian Coffee Region are yet poorly understood (Jaramillo-Robledo 2018). The objective of this research was to determine the soil water conditions with a potential to trigger mass wasting in the Colombian coffee region by mean of experimental physical models.

2. Materials and methods

2.1 Conditions of the site study

We conducted the investigation at the National Center for Coffee Research in Manizales, Colombia; the soil samples were taken at the coffee region of Ibagué, Colombia (4°28′36″N, 75°9′59″W, 1350 m altitude), this last site is located in the Central Cordillera of the Andes in the Magdalena River Basin, with slopes of up to 80%, annual precipitation of 2022 mm with a rainfall bimodal behavior (two rainy periods between March to June and September to November), mean annual temperature is 20.4 °C, relative humidity of 75% and solar brightness of 1664 h, characterized by humid tropical climate (Jaramillo-Robledo 2018), the predominant vegetation are forests of tropical rainy conditions, grasslands and perennial crops under agroforestry systems.

2.2 Soil

Three megagrams (3 Mg) of altered soil, from the surface down to 1.6 m depth, were collected in a coffee growing. The soil was derived from granite, which is part of Ibague batholith, belong to San Simón unit (Inceptisol) representative of Central Cordillera of Colombia (Beltran et al. 2006), it is susceptible to processes of erosion and mass movements, some physical and chemical properties for the soil are presented in Tab. 1.

The soil was characterized as low plasticity silt (ML), a bulk density between 1.28 and 1.54 kg m^{-3},

Tab. 1 Basic properties of soil samples from a coffee field in Ibagué, Colombia.

Soil depth	Sand	Clay	w_L	w_p	G_s	ρ_b	K	OM
(m)	%				(kg m^{-3})		(cm s^{-1})	%
0–0.35	52	21	45	30	2.63	1.28	1.0×10^{-4}	5.0
0.35–0.45	50	23	46	34	2.64	1.46	2.4×10^{-5}	1.8
0.45–1.60	58	20	46	28	2.66	1.54	3.4×10^{-7}	0.3

w_L: Liquid limit, w_p: Plasticity limit, G_s: Particle density; ρ_b: Bulk density, *k*: Permeability index, OM: Organic matter.

with a specific gravity of 2.66 kg m^{-3}. The soil horizon B provided an effective cohesion of 10 kPa and an effective angle of friction of 26°. Due to their low cohesion, differences in the soil permeability between horizons, the soil saturation value of 0.3 $cm^3\ cm^{-3}$, the limits of consistency and soil moisture characteristic curve parameters, could be inferred that this is a soil prone to hydric erosion and shallow mass movements (Tab. 1).

2.3 Methodology

Two laboratory physical slope models, 1.8 m^2 base, 1.0 m height, and 32° slope, with the bulk density and soil horizons arrangement similar to *in situ* conditions (Tab. 1) were prepared in a rectangular glass case. A schematic diagram of the experimental model is shown in Fig. 1. One side of the model was covered by an acrylic board, 20 mm thick, to observe. In each model, eight suction tensiometers (0 to −85 kPa) were located (S1 to S8) (Fig. 1). The saturation level was determined from the water retention curves following to Fredlund and Xing (1994).

2.4 Experiments

Seven experiments observations were conducted; slope failure in the experimental models was triggered by simulated rainfall (Fig. 1) and seepage from the top of the slope (Fig. 2).

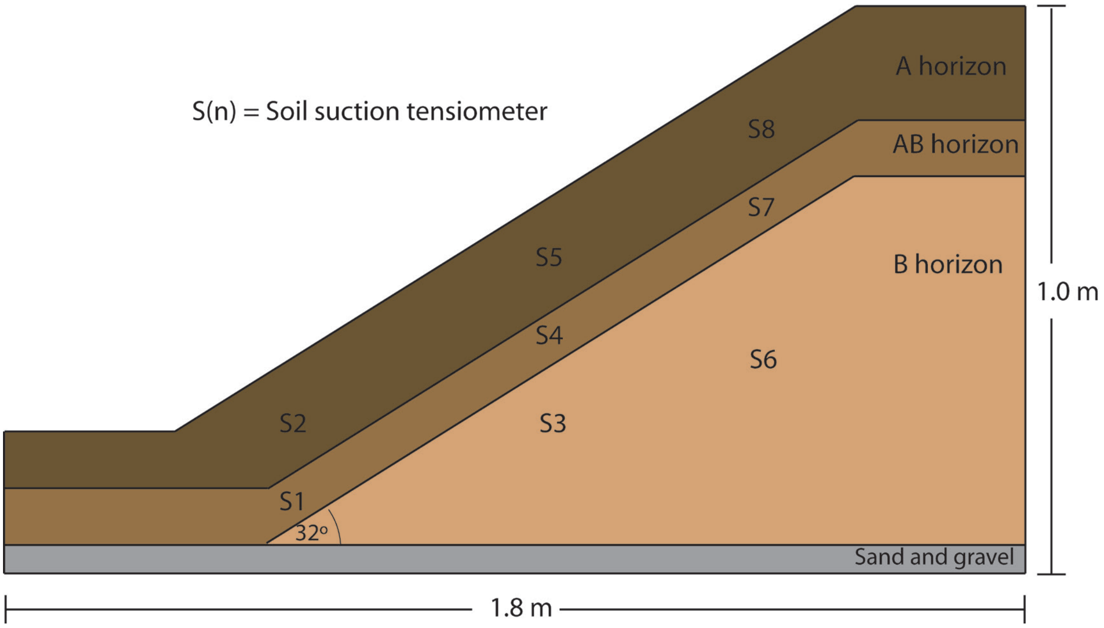

Fig. 1 Experimental model and location of soil suction tensiometers (S1 to S8).

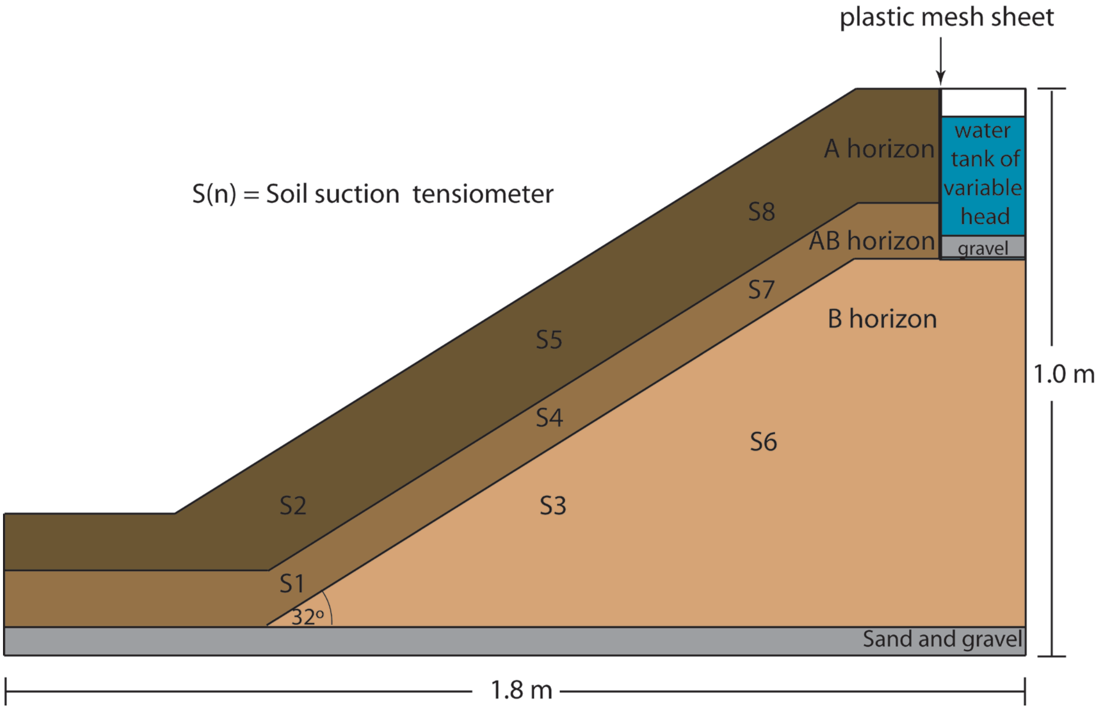

Fig. 2 Experimental model for seepage simulation at the top of the slope; soil suction tensiometers (S1 to S8).

I. In order to simulate maximum rains of the coffee zone of Colombia (Jaramillo-Robledo 2009), simulated rainfall using a simulator of nozzles type vee-jet 80100 was applied as follows:

- Experiment 1: 680 mm during 35 h (rainfall of 60 mm h^{-1} for 5 hours, followed by intermittent rainfall events of 60 mm h^{-1} until completing 35 hours).
- Experiment 2: 680 mm during 140 h (intermittent rainfall events of 60 mm h^{-1} for 140 hours).
- Experiment 3: 150 mm during 6 h (intermittent rainfall events of 60 mm h^{-1} for 6 hours from an initial soil suction of −300 hPa).

II. Soil water seepage, which frequently triggers landslides in coffee farms in Colombia (Salazar-Gutiérrez and Hincapié-Goméz 2013), was simulated as follows (Fig. 2):

- Experiment 4: Rising water level from 0.70 m to 0.75 m in 8 h.
- Experiment 5: Rising water level from 0.70 m to 0.75 m in 30 h followed by rising from 0.75 m to 0.90 m in 0.15 h.
- Experiment 6: Rising water level from 0.70 m to 0.90 m in 1.5 h.

III. A combination of water rise and simulated rainfall was evaluated.

- Experiment 7: Rising water level from 0.70 m to 0.90 m in 1.5 h followed by simulated rainfall of 100 mm h^{-1} during 1 h.

Due to the exploratory nature of the research, each experiment was conducted independently without an experimental design.

3. Results

In Experiment 1, when 680 mm rainfall in 35 h was simulated (Fig. 3), the slope toe (S2) was the first sector to become saturated (pore pressure equal to or greater than zero) and both shallow landslides and severe laminar erosion occurred, which may have a negative influence on the stability of the slope.

The rainfall of 680 mm in 180 h (Experiment 2), caused the saturation of the slope toe and the fastest saturation of the subsoil (Fig. 4). At the beginning of the rainfall, suction increased, followed by a fall below the initial value when the rain was over. Once rainfall stopped, the suction drop continued in both the toe and the subsoil slope but increased in the slope head section (Fig. 4).

When the rain simulation stopped, pore pressure increased in the subsoil (S6 and S3) and the slope toe

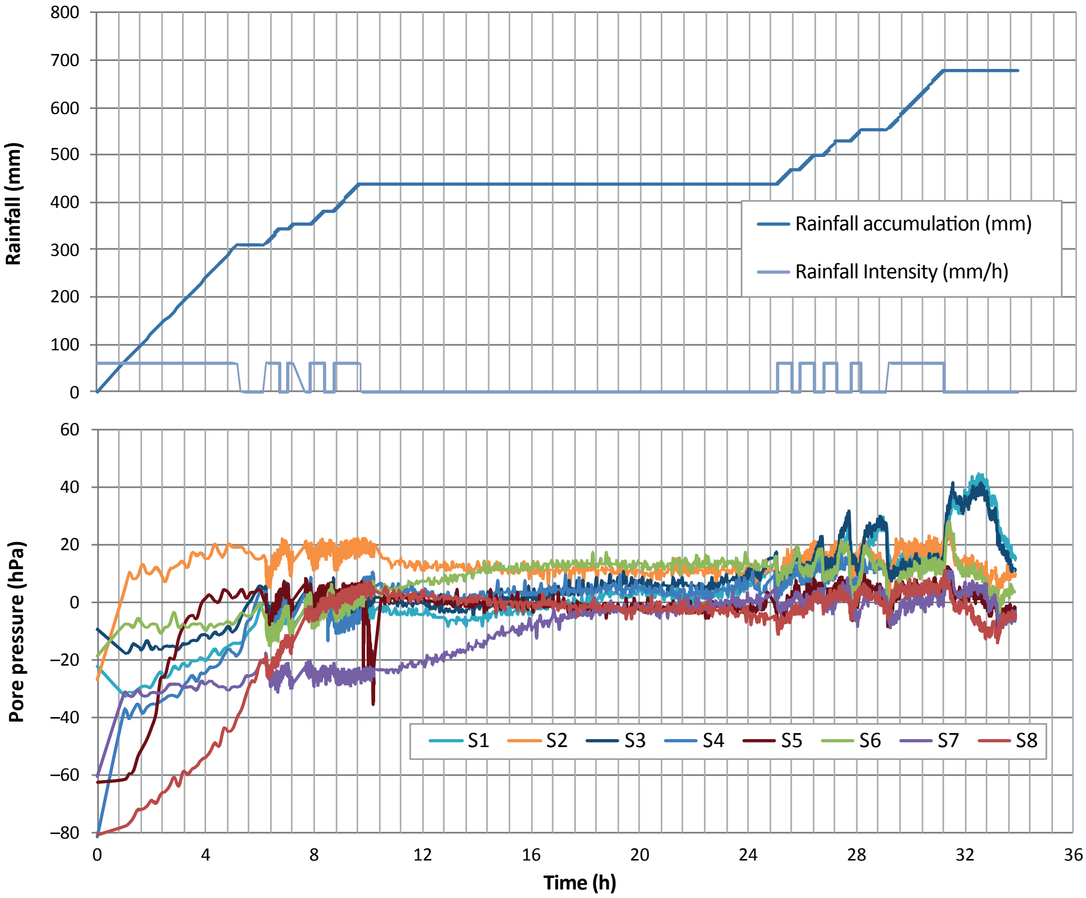

Fig. 3 Effect of simulated rainfall (680 mm during 35 h) on soil pore pressure of a model slope; soil suction tensiometers (S1 to S8).

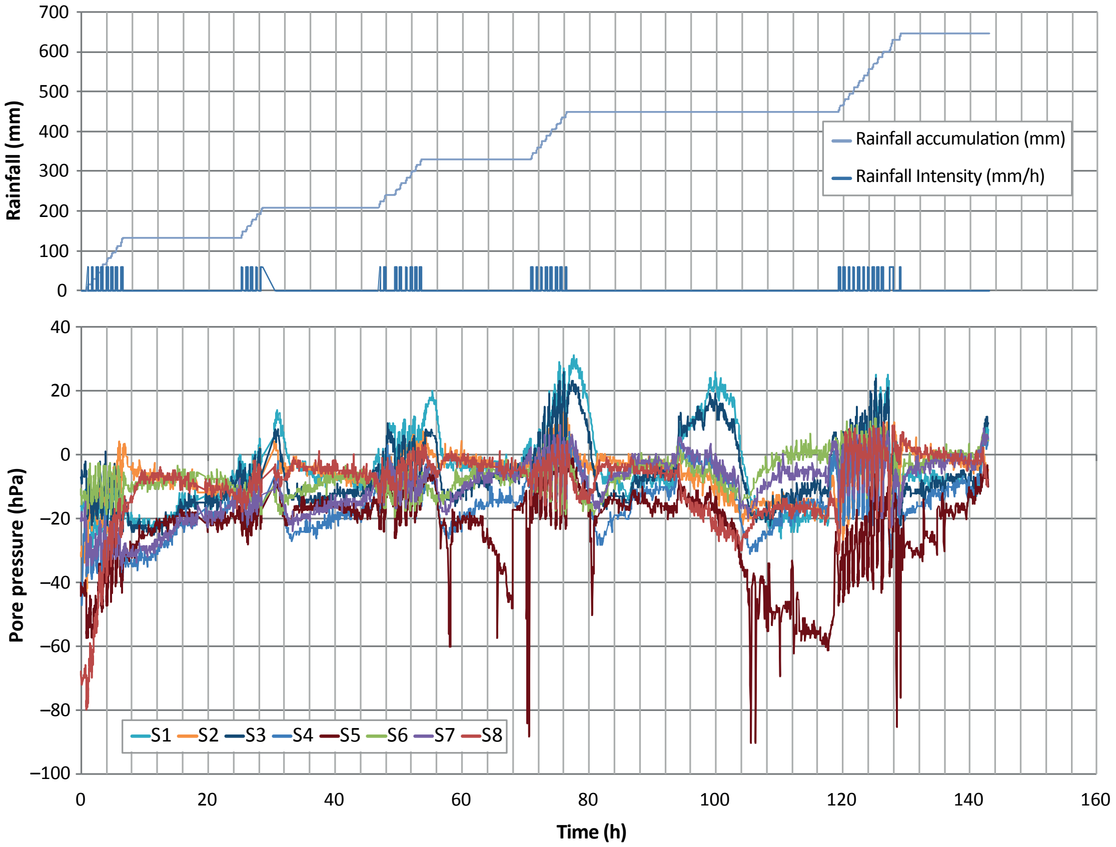

Fig. 4 Effect of simulated rainfall (680 mm during 140 h) on soil pore pressure of a model slope; soil suction tensiometers (S1 to S8).

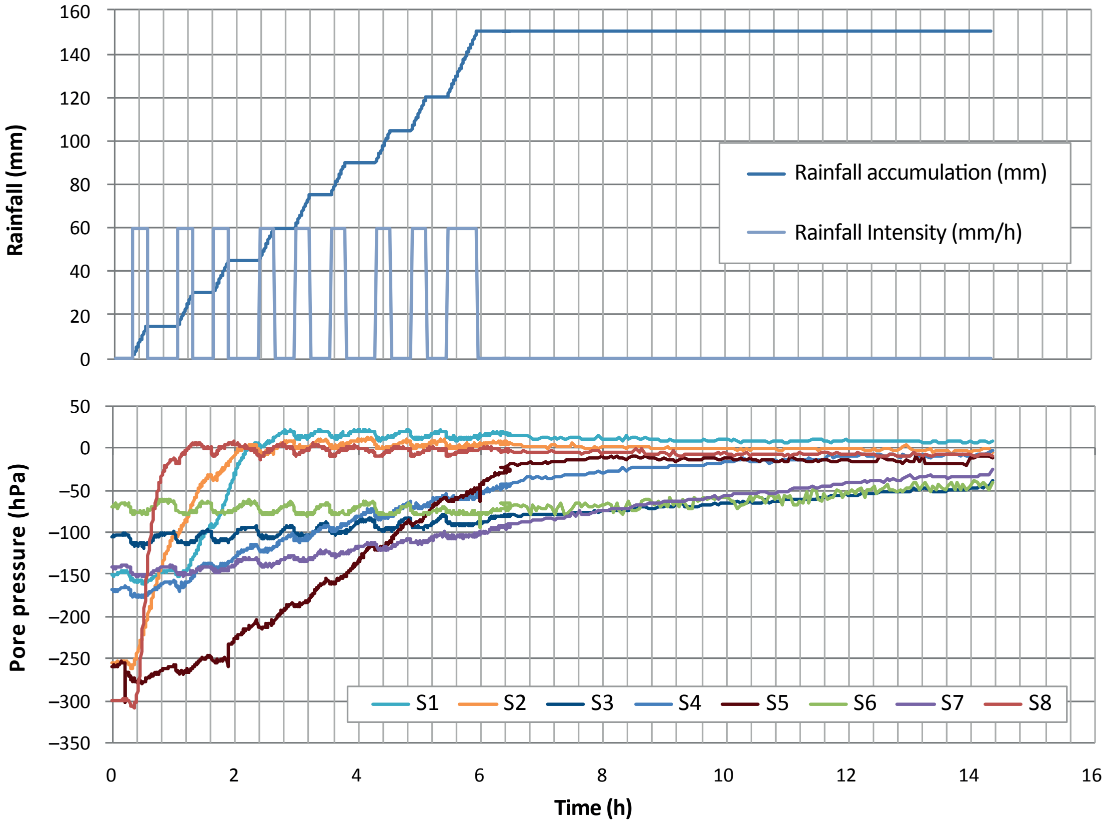

Fig. 5 Simulated rainfall under high soil suction values and the presence of soil cracks produced by drying-suction tensiometers (S1 to S8).

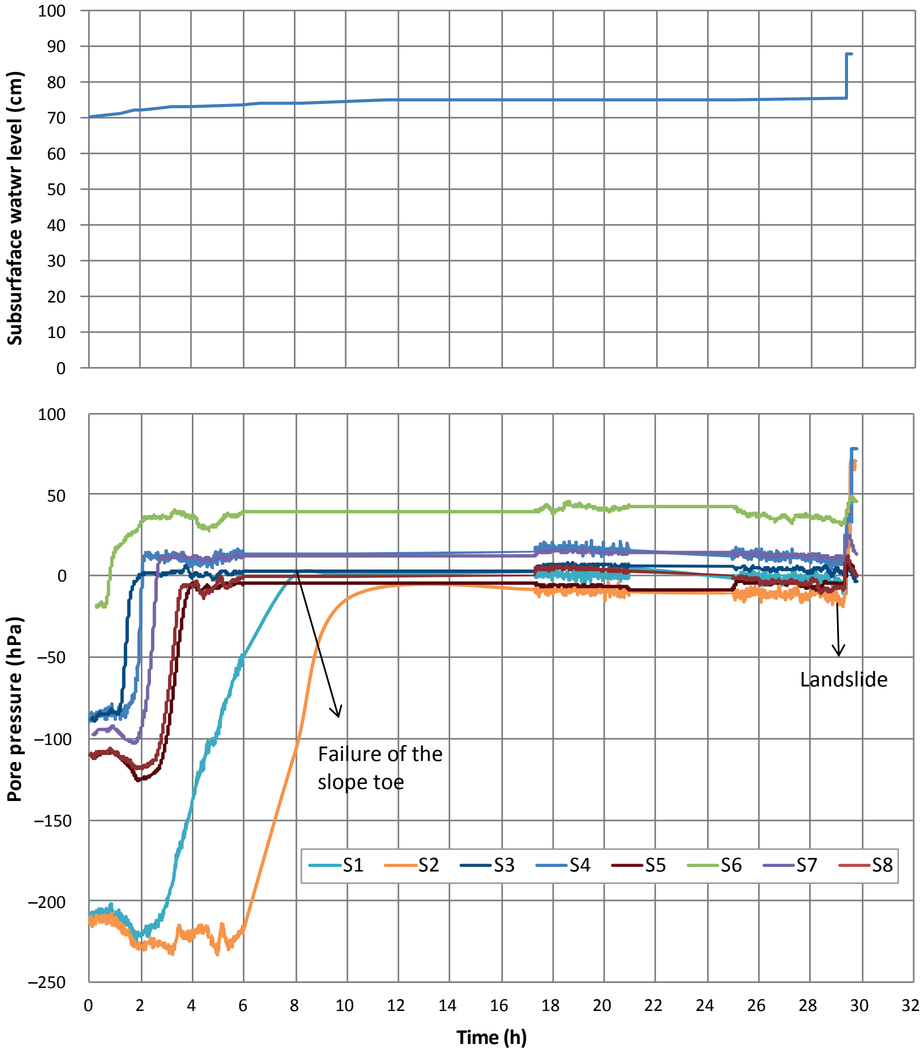

Fig. 6 Effect of the subsurface water level on the soil pore pressure in a laboratory model; soil suction tensiometers (S1 to S8).

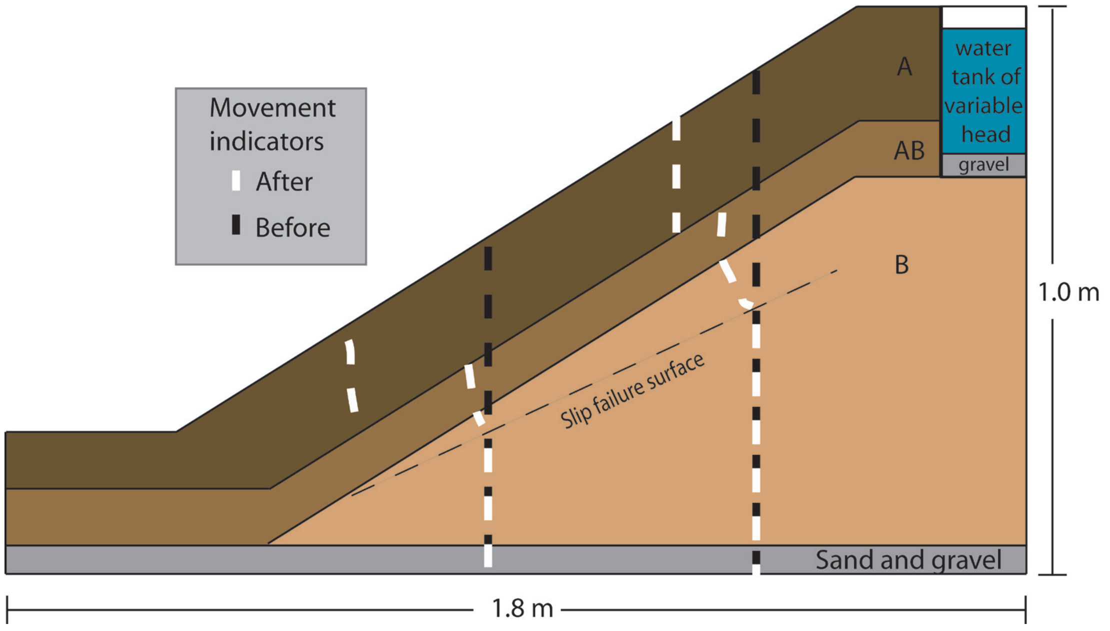

Fig. 7 Indicators of landslide induced by the effect of seepage on the experimental model and slip failure formation similar to that found by Ochiai et al. (2007). Before: Indicators of mass movement before seepage simulation. After: Indicators of mass movement after seepage simulation.

(S1) (Fig. 4), which could be due to drainage of the slope in both horizontal and vertical directions.

Accumulated rainfall of 140 mm in the first 6 hours only caused saturation in the slope foot (S2 and S3), which did not occur on the middle (S4 and S5) and upper part of the slope (S6, S7, and S8); nonetheless an accumulated rainfall of 400 mm after 70 hours allowed the saturation of the slope (Fig. 4).

In Experiment 3, a simulated rainfall of 150 mm during 15 h, when the rainfall started in high soil suction conditions (−300 hPa) with the presence of soil cracks produced by drying, the rainfall caused both the saturation of the toe (S2) and the superficial soil horizon (S8 and S5) (Fig. 5).

When seepage at the top of the slope was simulated (Experiments 4 to 6), the soil failure was generated by the loss of suction of the slope toe associated with the sub-surface flow in the head of the slope (Figs. 6 and 7).

Experiment 7 showed that once the slope becomes saturated a subsequent high-intensity rain event could trigger shallow landslides and mudflows, which in real scale could be catastrophic (Fig. 8).

4. Discussion

The results of this research are consistent with other scientific works. The soil properties (Tab. 1) might have negative implications for its stability and susceptibility to erosion because the pore spaces fill up with rainfall water and both the pore pressure and runoff increase (Acharya et al. 2009).

The fastest saturation of the slope toe (S2 – Fig. 3) was also found by Tohari et al. (2007) when tested non-cohesive soils derived from granite. According to Rahardjo et al. (2010) suction is not necessarily lost after an event of heavy rain, although in this study the initial condition of the B horizon (S3 and S4) was close to saturation, however the rate of this stage did not change significantly in relation to rainfall as the saturation degree of soil horizon A (S2, S5, and S8 in Fig. 3).

Air compression ahead of the wetting front in unsaturated soils (Fig. 4) leads to instability which occurs during the infiltration process (Wang et al. 1997). The transport of gases in the soil pores slows the flow of water in the soil and generates both slope deformation and stability loss (Hu et al. 2011).

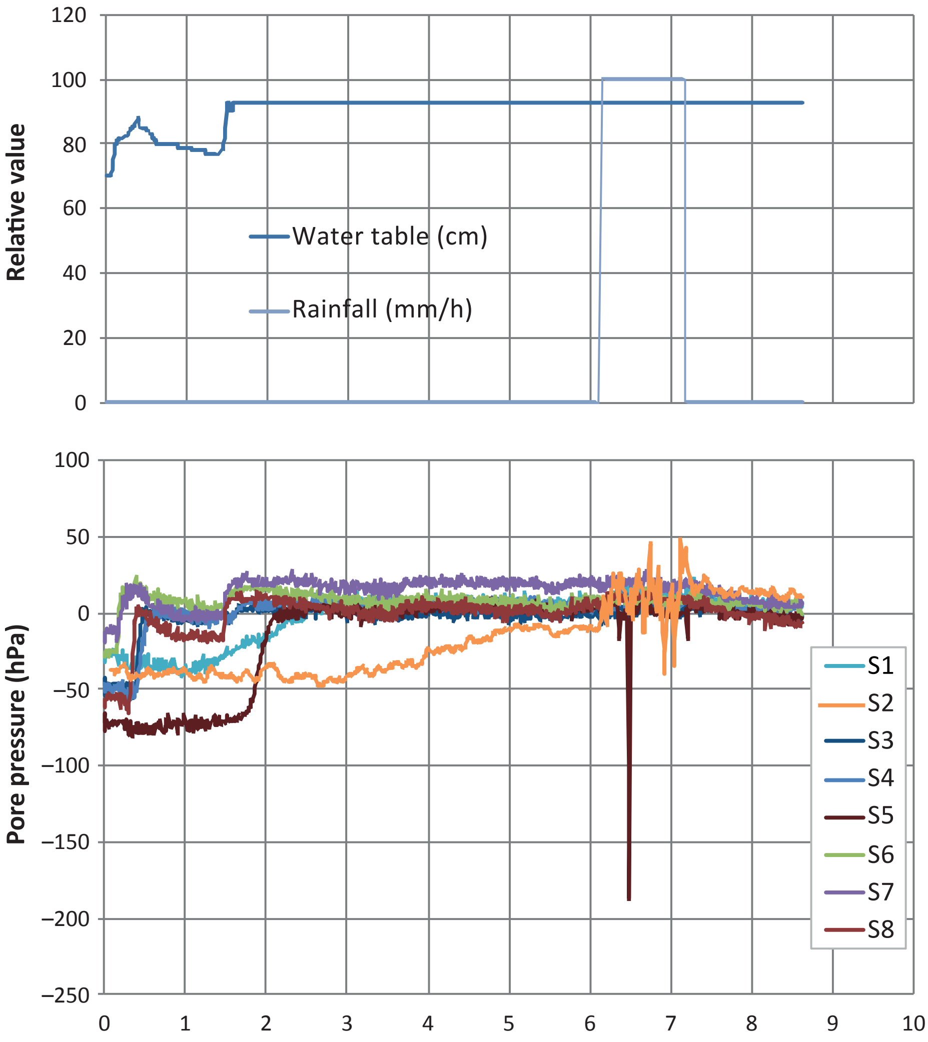

Fig. 8 Soil suction behavior under a combination of infiltration and simulated rainfall; suction tensiometers (S1 to S8).

Rahardjo et al. (2010) found similar results in their field experiments which may be interpreted as if when the simulated precipitation was over, the degree of saturation in the upper part of the slope decreased and in the lower part continued to increase. When the rain finished the infiltration and the decrease in soil suction continued (Fig. 4).

The initial slope state in terms of soil suction (Fig. 5) can also affect the rate of soil saturation, this has been found in several experimental models, where soils with fine particles subjected to drying, showed that infiltration is not governed by soil permeability as it is by the preferential flow through the soil discontinuities developed by soil drying (Lee et al. 2011).

A slip failure surface similar to that found by Ochiai et al. (2007) was formed (Fig. 7); the failure was associated with the permeability of the soil horizons and the changes in the soil water table (Figs. 6 and 7). Changes in soil matric potential can result in adverse variations in the soil shear strength as well as in the soil volume (Fredlund 2006).

Similar to our results (Figs. 6, 7 and 8), Jia et al. (2009) found a major problem of a large number of failures observed during the rapid fluctuation of the water level on the slopes. In this sense Germer and Braun (2011) found that the position of the water table and especially the abrupt change in pore pressure have a large influence on the stability conditions of a slope; for that reason, these authors suggest that pore pressure monitoring is an important tool of stability prediction.

Mortrasio and Valentino (2007), working with experimental models on soils derived from pyroclastic materials, found that the slope failure occurred just after reaching full saturation of the slope; similar conclusions were reached in our investigation (Figs. 6, 7 and 8). This type of flows has already caused disasters in the municipality of Ibagué – Colombia (Beltran et al. 2006).

The results have a limited scope due to the sampling site may not represent the general behavior of the soil derived from granitic rocks, due to its heterogeneity which is governed by soil formation factors. One of the major limitations of the experimental model is the problem of scale.

From the results obtained, we can consider some practical recommendations for the management of coffee crops. The soil and water management practices in coffee farming should prevent soil saturation by means of drainage systems and conservation tree planting in the toe of the slope. During long periods of drought in the coffee farming, it’s necessary to cover the soil with mulch to reduce the expansion crack formation which could have slope stabilization (Salazar-Gutiérrez and Hincapié-Goméz, 2013).

5. Conclusions

Experimental models can contribute to the knowledge of the behavior of the soil humidity and the failure of unsaturated soils triggering by rainfall or subsurface water flow. It helps to clarify the physical processes associated with the failure of the slopes.

Under study conditions, the results provide a link of mass movement to hydrological processes occurring in the slope which are related to the soil permeability, intensity, and duration of the rainfall and water table changes. The major portion of soil slope instability was related to a saturated condition of the slope toe.

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