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ORIGINAL PAPER

Analysis of rainfall infiltration effects on the stability of pyroclastic soil veneer affected by vertical drying shrinkage fractures

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Abstract The paper presents a preliminary, simplified evaluation of the effects of rainfall infiltration on the stability of slopes in layered pyroclastic soils affected by shrinkage vertical fractures. The analysis has been developed with a special reference to a stratigraphic sequence obtained by an in situ survey at Pizzo d'Alvano (Southern Italy). The analysis of rainfall infiltration is performed using an original dual-permeability model. Results show how fractures strongly condition infiltration depending on rainfall intensity. Prolonged low-intensity rainfall may lead to a higher saturation of the surface soil layer than short, intense rainfall when water may flow quickly through fractures into the underlying more permeable soil layers. Calculated distributions of pore pressure are used for the slope stability analysis using the infinite slope approach. Variations of the safety factor as a consequence of infiltration show that prolonged rainfall can induce a more relevant decrease in the safety factor than intense precipitations.

Keywords Dual-permeability model · Infiltration · Layered soils · Pyroclastic soils · Rainfall-induced landslides

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Introduction

The stability of steep slopes in fine-grained soils is generally related to soil suction. Rainfall infiltration induces variations of pressure heads and a decrease in soil suction and consequently a decrease in shear strength and an increase in soil weight, causing slope failure (Fredlung and Rahardjo 1993; Wieczorek 1996; Iverson 2000). If a fine-grained soil overlies a substratum of more permeable soils or rocks, such as pyroclastics deposit over pumices, silt upon fractured bedrock, or silt over sand or gravel, the large contrast between their soil hydraulic properties generates a capillary barrier for deep infiltration (Mancarella et al. 2012) that may condition the infiltration process. The capillary barrier can produce the accumulation of infiltrated water in the less permeable surface soil, resulting in a decrease in the soil suction and a loss of stability.

An interesting example of slopes where a fine-textured soil overlies a more permeable one is in Pizzo d'Alvano (Campania, Southern Italy) where a lot of landslides (debris flows and debris avalanches) were triggered by prolonged rainfalls in May 1998 (Del Prete et al. 1998; Crosta and Dal Negro 2003; Guadagno et al. 2003, 2005; Revellino et al. 2004; Cascini et al. 2008). Landslides were triggered by the sliding of superficial pyroclastic debris from the covering mantle and were subsequently channelized as debris flows (Fiorillo et al. 2001; Crosta and Dal Negro 2003; Revellino et al. 2004). For these landslides, Crosta and Dal Negro (2003), Fiorillo and Wilson (2004), and Mancarella and Simeone (2012) reported that these extreme instability phenomena took place after a period of several days of not intense, but quite continuous rainfall, which cannot be characterized by a really relevant return time, to be considered hydrologically exceptional, but which were surely singular. Landslides happened in May, at the beginning of the warm season, so that fine-textured soils were easily affected by sub-vertical shrinkage cracks, which may have further conditioned the infiltration process. Fractures constitute preferential flow paths for rainfall water and may favor infiltration toward deeper permeable layers, especially for high-intensity rainfall.

This paper presents and discusses the results, with respect to slope stability, obtained by analyzing infiltration phenomena into a fractured pyroclastic soil layer overlying pumiceous layers for different rainfall scenarios. Stratigraphy, slope inclination, and hydraulic and geotechnical soil properties have been obtained by an in situ survey at Pizzo d'Alvano (Campania, Italy) (Mancarella et al. 2012) and by laboratory tests (Mancarella and Simeone 2012). In these hill slopes, fine shrinkage fractures may affect the fine-textured pyroclastic surface soil overlying a more permeable layer during the warm season.

Infiltration processes in a fractured pyroclastic soil layer overlying a more permeable pumiceous layer have been analyzed by considering a horizontal soil surface and different rainfall scenarios, and by evaluating water content and pressure head distributions at the end of each of them. The analysis has been performed by means of a dual-permeability model (Galeandro and Simeone 2010, 2012; Galeandro et al. 2011, 2013b). The results obtained by means of this analysis have been extended for a sloping soil surface, in order to evaluate the effects of infiltration processes on slope stability (Galeandro et al. 2013a). Evaluations of slope stability have been developed according to the infinite slope analysis (Skempton and De Lory 1957; Doglioni et al. 2013a). Even though the model so far simulates only infiltration into horizontal layers, the results have been used to perform stability evaluations of sloping covers. Although this approximation is not formally correct, the main purpose of this work is to show how the fractures may affect rainfall infiltration and slope stability conditions. It is thus our opinion that this analysis can be considered as an acceptable first-level approximation of a qualitative evaluation of the influence of rainfall scenarios on slope stability of the modeled situations.

Methods

Infiltration processes in a horizontally stratified and vertically fractured soil layer of a fine-grained pyroclastic soil overlying a more permeable pumiceous layer have been modeled for different rainfall scenarios by a finite elements dual-permeability model (Galeandro et al. 2011, 2013b). The water flow infiltration in the soil matrix is described using the two-dimensional Richards equation, while soil hydraulic properties are described using the van Genuchten (1980) and Mualem (1976) relationships. When the rainfall intensity exceeds the infiltration capacity of the matrix, a certain amount of water is not able to infiltrate into the matrix and starts flowing into fractures. Infiltration flow in fractures is modeled using the continuity equation. The flow rate in the fractures is obtained, at different depths, as the difference between the fracture inflow rate and the amount of water laterally adsorbed by the matrix, which depends on the amount of water available in the fractures and on the saturated hydraulic conductivity of the soil matrix (Fig. 1a).

Matrix swelling is evaluated assuming a linear relationship between the matrix volumetric water content and the soil volume, so that the fractures completely close when complete saturation is reached in the matrix. The model additionally implements a capillary barrier below the surficial fractured soil. Water accumulates in cracks up to a maximum capillary height that depends the width of a crack opening and capillary tension, while in the matrix, it is stored above the interface between layers until the critical pressure head is reached. As output, the model provides the distribution of pressure heads in the soil matrix during the considered meteorological event, the variation of crack openings, and the time required to break the capillary barrier.

Distributions of the degree of saturation and pressure heads were then used in the stability analysis of a hill slope with the above-described stratigraphic sequence. The adoption of these results for the stability evaluations of steep hill slopes is not formally correct, since the infiltration model works, so far, only for horizontal soil layers. However, the main purpose of this work was to underline the potential influence of the fractures and the capillary barrier on the infiltration process and on the slope stability. Depending on different rainfall scenarios, this approximation was considered to be acceptable as a first-level qualitative evaluation of the problem.

Evaluations of the hill slope stability have been performed according to the infinite slope model (Fig. 1b). An incipient failure of infinite slopes is described using an equation that balances the downslope component of gravitational driving stress against the resisting stress due to basal Coulomb friction (mediated by the pore water pressure). Failure occurs at a depth z if at that depth (Iverson 2000):

$$\mathrm{FS} = \frac{\tan\phi'}{\tan\beta} - \frac{h(z,t)\gamma_w \tan\phi'}{\gamma z \sin\beta\cos\beta} + \frac{c'}{\gamma z \sin\beta\cos\beta} = 1 \tag{1}$$

where z is the depth, at which the factor of safety is evaluated, c' is the cohesion (kPa), ϕ' is the friction angle, γ is the soil unit weight (kN/m^3), γ_w is the unit weight of groundwater (kN/m^3), β is the inclination of the slope and $h(z, t)$ is the average pressure head (cm) at depth z and time t, evaluated by the infiltration model.

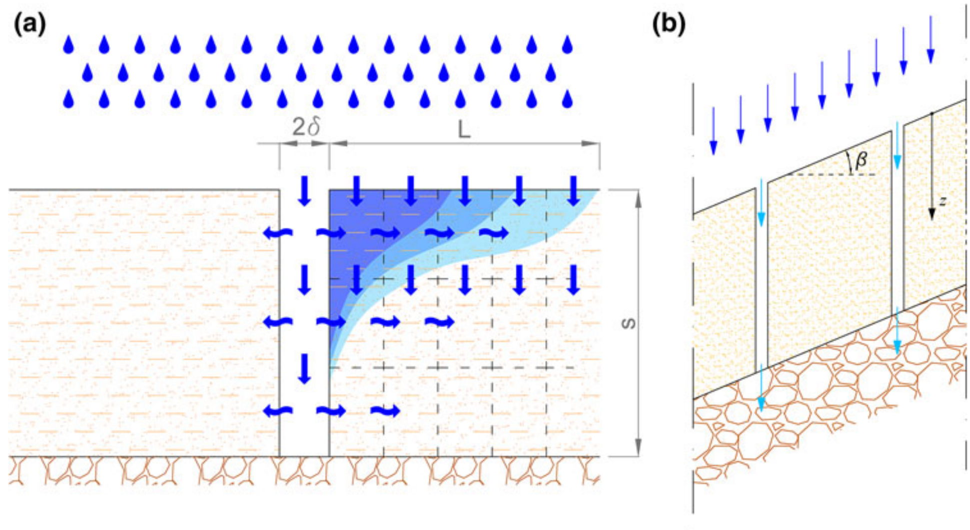

Fig. 1 **a** Schematic representation of the model (after Galeandro et al. 2013b) and **b** schematic representation of the hill slope

The unit weight γ (kN/m^3) for pyroclastic soils may change significantly as a function of the water content, affecting the evaluation of the slope stability. The value used for the slope stability analysis has been calculated as a function of the average degree of saturation S reached at a particular depth, the specific gravity G_s, and the void ratio e, which is assumed to be constant in the entire surface fine-textured soil layer:

$$\gamma(S) = \frac{(G_s + Se)\gamma_w}{1 + e} \tag{2}$$

The case study

The proposed infiltration model is applied here to the soil stratigraphy described by Mancarella and Simeone (2012), based on the in situ surveys in the area of Pizzo d'Alvano (Campania, Italy, Fig. 2a). It is a pyroclastic veneer consisting of alternating ashy and pumiceous layers (Fig. 2b), with very different grain size distributions and permeabilities. Geotechnical and hydraulic properties of this pyroclastic soil outcropping in that area were extensively studied by several authors by both in situ and laboratory measurements (Esposito and Guadagno 1998; Basile et al. 2003; Crosta and Dal Negro 2003; Olivares and Picarelli 2003; Cascini and Sorbino 2003; Bilotta et al. 2005; Mancarella and Simeone 2012; Esposito et al. 2013 and others).

The hydraulic properties of both soils have been selected based on in situ permeability measurements and laboratory hydraulic conductivity tests on pyroclastic soil columns, carried out by Mancarella and Simeone (2012) and Mancarella et al. (2012). The saturated hydraulic conductivity K_{sat} of the upper layer is equal to 10^{-4} cm/s, the van Genuchten parameters α and n for the pyroclastic fine soil are equal to 1 m^{-1} and 1.8, respectively, and the residual and saturated water contents are equal to 0.1 cm^{3}cm^{-3} and 0.4 cm^{3}cm^{-3}, respectively. The water-entry pressure head of the pumiceous layer can be assumed to be approximately equal to the water-entry pressure head of a gravel and equal to 2 cm (Stormont and Morris 1998), due to the similarity between their grain sizes (a grain size of about 1 cm) and saturated hydraulic conductivities (10^{-2} to 10^{-1} cm/s).

The analysis of the infiltration process has been performed only for the surface soil layer of fine-grained pyroclastic with a thickness of 40 cm, overlying a coarser pumiceous layer. The upper layer is characterized by a regular system of fractures spaced 80 cm apart in both horizontal directions with a fracture thickness of 2 cm. Table 1 summarizes hydraulic properties and geometric properties of the soil system. The upper layer has been spatially discretized into soil elements of small dimensions (2 cm $\times$ 2 cm). Simulations have been performed using a time step of 10 s. The infiltration process has been analyzed for a meteorological event characterized by a total rainfall height of 70 mm, with two different rainfall scenarios: a low-intensity rain of 5 mm/h (event A) and a quite intense rainfall of 50 mm/h (event B). The analysis has been performed assuming two different values of an initial degree of saturation of the surface soil layer: 25 % in scenario IS_1 and 40 % in scenario IS_2 (Table 3).

For the slope stability analysis, according to Mancarella et al. (2012), the slope inclination has been assumed to be equal to 45° and the thickness of the surface fine-textured soil layer to 40 cm (Fig. 1b). The parameters of the shear strength have been chosen according to previous geotechnical studies (Bilotta et al. 2005): the cohesion c' and the friction angle ϕ' are set equal to 2 kPa and 37°, respectively (Table 2). The unit soil weight γ(kN/m^3) has been evaluated according to the indication of Esposito and

Fig. 2 **a** Location of the study area and **b** schematic stratigraphy, indicating thicknesses (m) and saturated hydraulic conductivities K_{sat} of each soil layer (after Mancarella and Simeone 2012, modified)

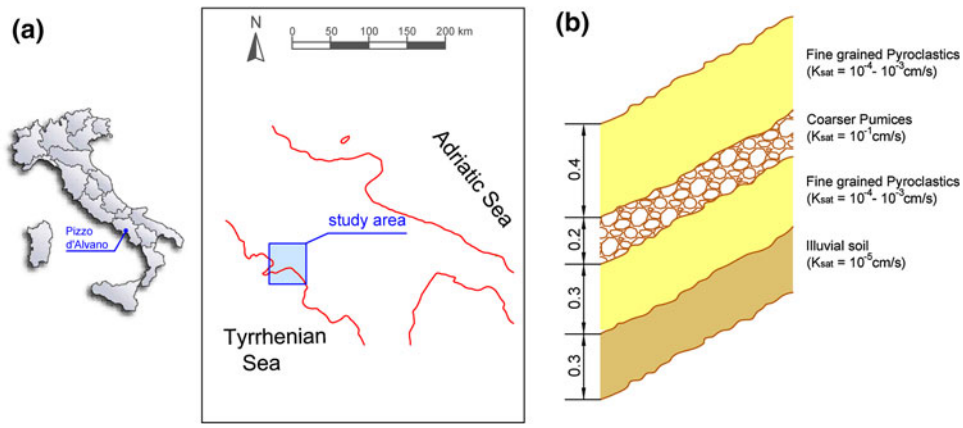

Table 1 Hydraulic properties of the fine-textured soils and geometric features of the system

Hydraulic properties (pyroclastic soil)	
Residual water content θ_r (m^3m^{-3})	0.1
Saturated water content θ_s (m^3m^{-3})	0.4
Saturated hydraulic conductivity K_{sat} (cm/s)	10^{-4}
α (van Genuchten 1980) (cm^{-1})	0.01
n (van Genuchten 1980)	1.8
Geometry	
Spacing L (cm)	80
Half opening δ (cm)	1
Thickness S (cm)	40

Table 2 Geotechnical, physical, and geometric properties

Geotechnical, physical, and geometric properties	
c' (kPa)	2
ϕ' (degrees)	37
β (degrees)	45
γ (kN/m^3)	7.5

Guadagno (1998). A specific gravity G_s of 2.62 g/m^3 and a unit dry weight γ_d of 7.5 kN/m^3, corresponding to a void ratio e of 2.45, have been used for the entire surface soil layer. Figure 3 shows the initial safety factor versus depth evaluated using Eq. 1. The initial safety factor is in both cases (two initial saturations) much higher than 1, indicating that the stability of the hill slope is clearly guaranteed for both considered initial degrees of saturation (Table 3).

Results and discussion

Rainfall infiltration analysis

The results of the analysis performed for the two rainfall scenarios (A and B) for the two initial degrees of saturation (IS_1 and IS_2) are shown in Fig. 4. With regards to the low-intensity rainfall scenario A (5 mm/h for 14 h) and both considered initial degrees of saturation, water flows relatively slowly into the fractures, reaching a maximum depth of only 16 cm (Fig. 4a, b). In both cases, the surface soil layer is quite close to full saturation and the fracture is almost completely closed at the end of the rain event. In case A_1 (Fig. 4a), water flows into the matrix and reaches the bottom of the soil layer, resulting in an increase in the degree of saturation from its initial value of 25–57 %. The volumetric water content increases from its initial vale of 0.175–0.27 cm^3cm^{-3}. Similarly, in case A_2 (Fig. 4b), the saturation degree at the interface between the surface soil layer and the underlying layer reaches a value of 70 % at the end of the rainfall event. The water content increases from the initial value of 0.22–0.31 cm^3cm^{-3}.

In the rainfall scenario B (50 mm/h for 1.4 h) and for both considered initial degrees of saturation, water reaches the bottom of the fractures quite quickly (after only 2 min), allowing accumulation of water in the fractures until the breakdown of the capillarity barrier. Lateral infiltration of water involves only few centimetres of the soil close to the fracture walls (Fig. 4c, d), as a consequence of vertical fracture flow. Even when water reaches the bottom of the upper soil layer, only a very few centimetres of the topsoil are really affected by significant changes in water content (6 cm in case B_1, Fig. 4c, and 8 cm in case B_2, Fig. 4d). Apart from the first few centimetres of the soil near the fracture interface (which is saturated due to lateral adsorption), the rest of the soil matrix does not show significant changes in the water content: from 0.175–0.177 cm^3cm^{-3} in case B_1 and from 0.22–0.23 cm^3cm^{-3} in case B_2.

In order to emphasize the effects of the rainfall intensity and duration on the saturation of the pyroclastic cover, the average saturation degree of the first 20 cm of the soil matrix has been evaluated for each evaluated scenario. The average degree of saturation of the first 20 cm of the soil reaches the value of 95.5 % in case A_1 and 99.8 % in case A_2, while for the rainfall scenario B, the degree of

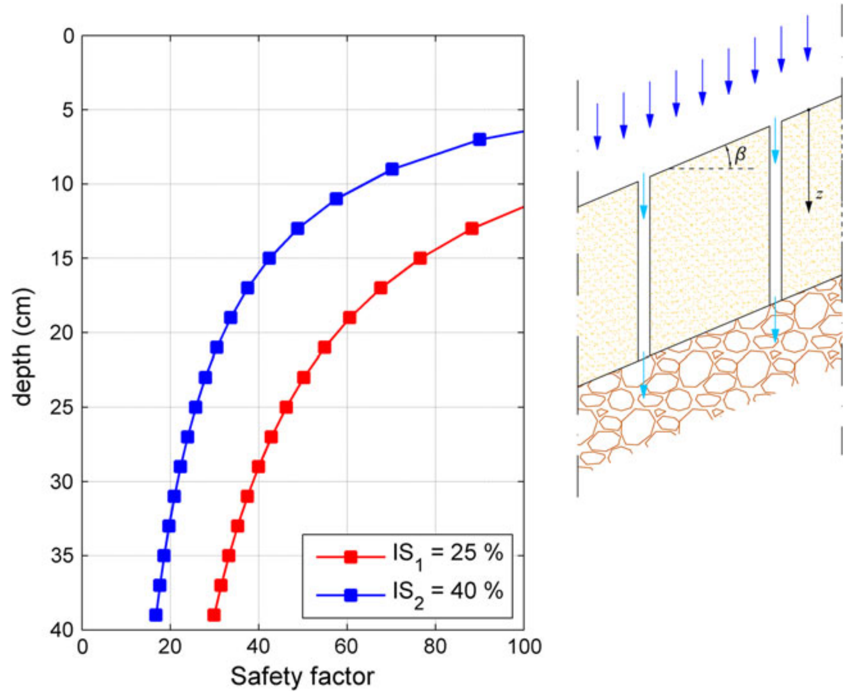

Fig. 3 An initial safety factor for both considered initial conditions (IS_1 and IS_2)

Table 3 Summary of the analyzed combinations

Cases	Rainfall intensity *i* (mm/h)	Duration *T* (h)	Initial saturation degree *IS* (%)
A_1	5	14	25
B_1	50	1.4	
A_2	5	14	40
B_2	50	1.4	

saturation is much lower, equal to 38 % in case B_1 and to 53 % in case B_2.

The fractures (cracks) start closing due to swelling of the soil matrix at the soil surface, and their closure propagates toward the bottom, essentially depending on lateral water adsorption from the fractures into the soil matrix. It is noteworthy that for the low-intensity but prolonged rain, the swelling induces the complete closure of cracks about 10 h after the beginning of the rainfall (corresponding to a rainfall height of 50 mm) in case A_1 (Fig. 5a) and after about 7.3 h (corresponding to a rainfall height of about 37 mm) in case A_2, preventing more water flowing into the fractures.

In scenario B with intense precipitation, the swelling is quite irregular and does not induce the complete closure of cracks. The soil initially swells at the surface, inducing cracks to narrow, while deeper parts of the soil are not yet reached by infiltrating water. In case B_1 (Fig. 5b), the swelling process causes a crack closure of 73 % of the initial half-width value, while in case B_2, the crack closure is more significant and equal to 80 % of the initial half-width value.

With regard to the capillary barrier phenomenon, for low-intensity rainfall (rainfall scenario A), the capillary barrier remains active in the matrix and fractures during all rainfall events, since the pressure head at the interface between the pyroclastic cover and the pumiceous layer does not reach the critical breaking value (2 cm) and water flow does not reach the bottom of the fractures. For the intense rainfall event (event B), it is possible to observe a really fast breakthrough of the barrier in the fractures, since water flow reaches the bottom immediately. The maximum capillary height is reached in both cases after 120 s (a corresponding rainfall height of 1.67 mm) after the beginning of the rainfall.

Implication on slope stability

At the beginning of the rainfall events and for both considered initial saturation degrees, the initial safety factors at all depths of the potentially unstable soil layer are significantly higher than 10 (Fig. 3), as a consequence of high suction values. Rainfall infiltration induces a decrease in the soil suction and consequently also in the safety factor.

Spatial and temporal distributions of water contents and soil suctions obtained by the rainfall infiltration analysis have been used for the evaluation of safety factor variations induced by rainfall infiltration. In each simulation, the safety factors at different depths have been evaluated considering water content, saturation degree, and soil suction distributions in the pyroclastic soil layer at times when a rainfall height reached 10-mm increments (i.e., 10, 20, 30, 40 mm, etc.). Results are presented in Fig. 6.

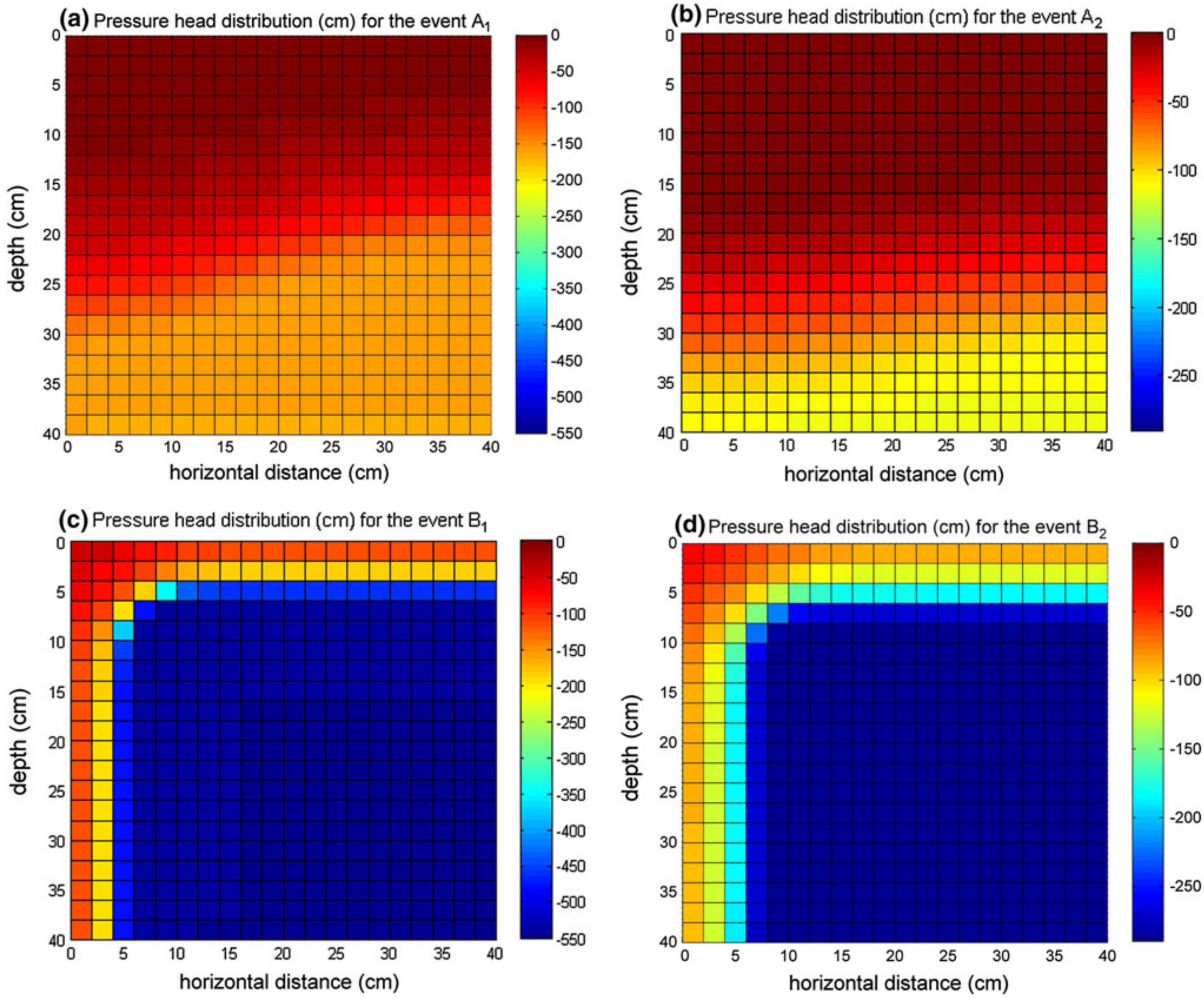

Fig. 4 Pressure head distributions for rainfall scenarios: **a** A_1 (rainfall A and initial condition IS_1). **b** A_2 (rainfall A and initial condition IS_2). **c** B_1 (rainfall B and initial condition IS_1) and **d** B_2 (rainfall B and initial condition IS_2)

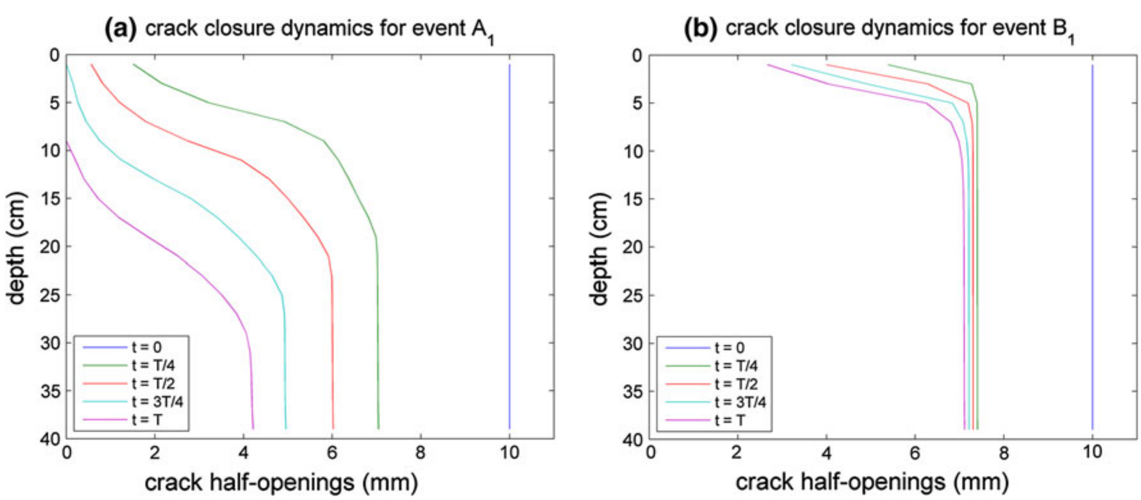

Fig. 5 Crack closure dynamics for rainfall scenarios: **a** A_1 (rainfall A and initial condition IS_1) and **b** B_1 (rainfall B and initial condition IS_1)

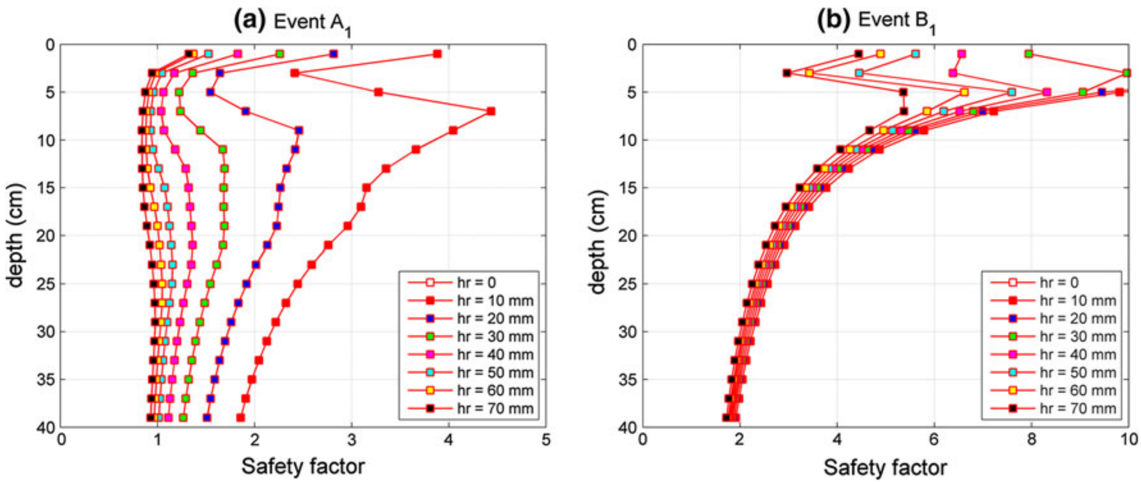

Fig. 6 Safety factor variations during the rainfall for rainfall scenarios: **a** A_1 (rainfall A and initial condition IS_1) and **b** B_1 (rainfall B and initial condition IS_1)

In case A_1 ($r = 5$ mm/h, $T = 14$ h, $IS_1 = 25$ %), after 2 h from the beginning of the rainfall (corresponding to a rainfall height of 10 mm), the factor of safety is <5 at all depths, with a minimum value of 2 at the bottom of the fine-grained pyroclastic layer (Fig. 6a). Subsequently, the further decrease in the safety factor is more gradual and follows the S-shaped trend shown in Fig. 6a. The safety factor reaches the failure condition (FS = 1) at a depth of about 7 cm after little more than 8 h (corresponding to a rainfall height of 40 mm), while at the bottom of the soil profile, the safety factor reaches the unit value after 10 h (corresponding to a rainfall height equal to 50 mm). It is noteworthy that the upper part of the cover reaches the failure condition before the rest of the profile. In case A_2 ($r = 5$ mm/h, $T = 14$ h, $IS_2 = 40$ %), as consequence of the higher initial water content, slope failure occurs more quickly, after about 6 h from the rain initiation (corresponding to a rainfall height of 30 mm), and simultaneously at a depth of about 7 cm and at the interface between the pyroclastic cover and the pumice.

In both B_1 ($r = 50$ mm/h, $T = 1.4$ h, $IS_1 = 25$ %, Fig. 6b) and B_2 ($r = 50$ mm/h, $T = 1.4$ h, $IS_2 = 40$ %) cases, it is possible to observe an initial relevant decrease in the safety factors, especially during the first 12 min (corresponding to a rainfall height of 10 mm). However, the decrease in the safety factor affects only the surface layer (about 10 cm), while only small variations can be observed in the deeper parts of the pyroclastic cover, with the factor of safety is always being higher than 1. This is due to the almost immediate breakthrough of the capillary barrier in the fractures, which allows rainfall water to flow downward into the pumiceous layer. The amount of water which is absorbed by the matrix is not high. Absorbed water is stored in the first few centimeters of the soil matrix close to the soil surface and to the fracture walls. There is a noticeable decrease in suction only in these parts of the soil matrix, while in the rest of the matrix, the pressure heads do not change significantly. Consequently, the average suction at a certain depth is still quite high, and the corresponding decrease in the shear strength is not sufficient to trigger the slope failure. On the other hand, in rainfall scenarios A, almost all rainfall water enters the soil matrix by vertical infiltration, resulting in almost full saturation of the soil matrix, which produces a significant decrease in suction and triggers the slope's failure.

Results are in good agreement with the failure mechanisms observed by many authors for the analyzed slope. According to Crosta and Dal Negro (2003), Fiorillo and Wilson (2004), Mancarella et al. (2012), and Mancarella and Simeone (2012), instability phenomena affecting Pizzo d'Alvano slopes took place after a period of several days of not intense, but quite continuous rainfall, which cannot be considered hydrologically exceptional. Fiorillo and Wilson (2004) observed that the total amount of rainfall was significantly less than during other major precipitation events recorded during wet periods which did not trigger slides. While rainfall was not remarkable with respect to its statistical return time, it produced severe consequences. The constancy and temporal extent are the most remarkable characteristics of the May 1998 precipitation. Rainfall lasted from April 28 to May 6 with very few and short interruptions.

In summary, results show how prolonged low-intensity rainfalls could easily lead to the saturation of the surface soil layers and could trigger instability phenomena. Such types of rainfall are more dangerous with respect to slope failure in surface fine-grained soil covers than intense and short precipitations. The schematic representation of these phenomena is shown in Fig. 7.

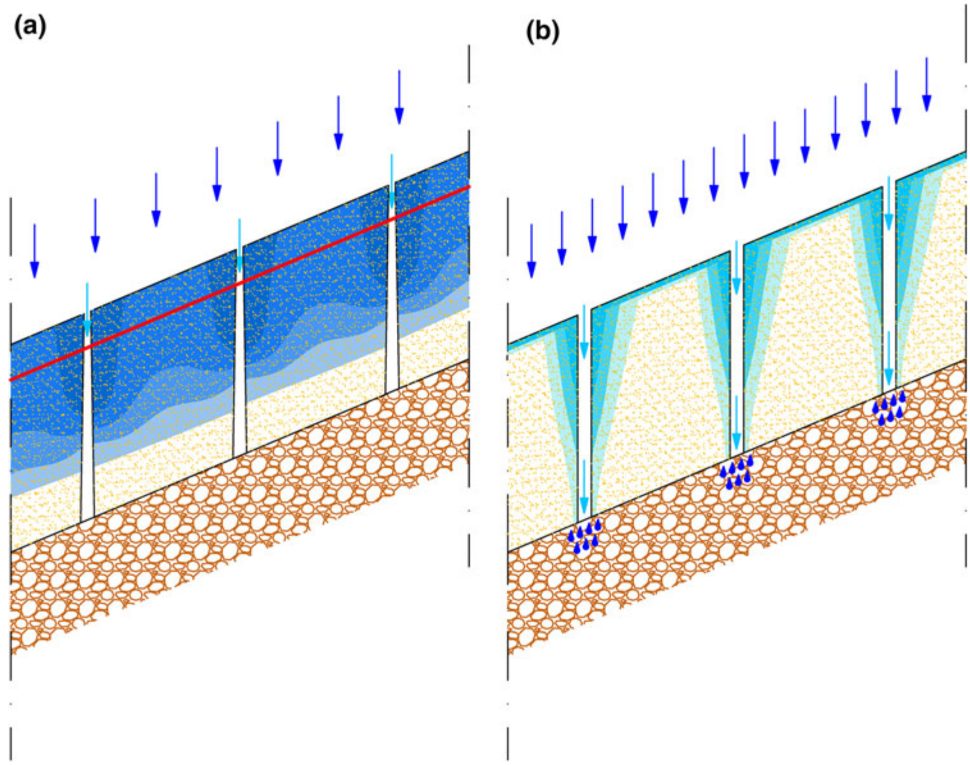

Fig. 7 Schematic representation of infiltration scenarios at the end of (**a**) a low-intensity and prolonged rain and (**b**) an intense and short precipitation. The *red line* indicates the potential failure plane

Conclusion

The analysis of the effects of the presence of vertical cracks due to drying and shrinkage phenomena on the evaluation of the hill slope stability of layered pyroclastic deposits for different rainfall scenarios has been presented. The analysis has been performed with special reference to a stratigraphic sequence obtained by an in situ survey at Pizzo d'Alvano (Campania, Southern Italy). The analysis of the infiltration process in the fractured soil overlying a coarse soil has been performed using a specifically developed dual-permeability model, which simulates infiltration into the surface soil in the presence of fractures and a capillary barrier below this layer. The results obtained for a horizontal soil surface have been used to evaluate the stability of a sloping soil.

The results show that for a low-intensity rainfall event, fracture flow is limited only to the top of the soil surface layer, while for an intense precipitation event, water reaches the bottom of the fractures quite quickly and flows quite easily downward in the underlying more permeable layer. Distributions of the soil suction obtained from the infiltration analysis have allowed us to evaluate the hill slope stability. The results show that the hill slope failure is more likely for long, low-intensity rainfall than for short, intense precipitation. In the latter case, water is drained quickly by the fractures downward toward the capillary barrier, which is quickly broken, allowing water to flow downward in the pumiceous layer.

Results are consistent with the failure mechanisms observed at Pizzo d'Alvano as a consequence of the events in May 1998. Extreme instability phenomena took place after a time period of several days of low-intensity, but quite continuous rainfall, during which the total amount of rainfall was significantly less than during other major precipitation events recorded during wet periods which did not trigger landslides. Thus, our results show how prolonged low-intensity rainfall could easily result in the high saturation of the top surface soil layers and could trigger instability phenomena in these surface layers. Such rainfall events are potentially more dangerous for surface fine-grained soil covers than intense and short precipitation.

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