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The role of the lowermost boundary conditions in the hydrological response of shallow sloping covers

Abstract In many areas of the world, slopes covered by shallow unsaturated non-plastic soil layers experience rainfall-induced landslides causing heavy damage and casualties every year. Landslide occurrence depends on the amount of water infiltrated and stored. Among the contributing factors are the hydraulic conditions at the lowermost boundary, a feature that is often disregarded. The paper focuses on this topic, presenting the results of some laboratory and numerical experiments on ash-pumice interfaces. A strategy is then proposed for selecting the lowermost boundary condition, and some studies are carried out to compare the results obtained with the proposed solution and other more popular ones.

Keywords Lower boundary conditions · Unsaturated soil · Capillary barriers · Layered soils · Infiltration

Foreword

Investigations on the mechanical response of slopes subjected to weather variables are assuming a prominent place in landslide hazard studies. In particular, these are focusing on the key factors governing slope safety conditions and are allowing an increasingly aware use of physically based predictive tools.

It is precisely within this scenario that Rahardjo et al. (2013) discussed the importance of a correct definition of the hydraulic conditions acting at the ground surface (the uppermost boundary). In unsaturated soils, these consist of an incoming or outcoming water flux, with the former reducing and the latter increasing soil suction and consequently slope safety conditions. In recent years, the topic has been widely addressed in numerous studies and from different scientific points of view worldwide, as illustrated by Stokes et al. (2013); among these, there are many key works with a sharp geotechnical approach (Blight 1997; Rahardjo et al. 2013; Smethurst et al. 2012, 2015). Moreover, two issues of the Italian Geotechnical Journal (Picarelli and Cotecchia 2012, 2014) have recently been devoted to the question of the slope-atmosphere interaction.

In contrast, the hydraulic conditions at the lowermost boundary, which often marks a sharp change in hydraulic soil properties, have so far received little consideration. Indeed, it represents a problematic topic especially in the case of shallow layers of relatively pervious soils. This is a typical situation in many geomorphological contexts, such as colluvial or residual soils, loess and pyroclastic materials.

In this regard, a specific example is represented by unsaturated pyroclastic soils covering a wide hilly and mountainous area around Naples (Southern Italy). They consist of relatively thin alternating layers of volcanic ash and coarser pumice. The hydrological behaviour of these sloping covers is often analysed by focusing on the response of the top soil (generally consisting of ash or of an ashy colluvium) and taking the interface with the lower pumice layer as the lowermost boundary. Often, scant importance is given to any influence of the hydraulic conditions acting on this boundary on the solution to the problem.

The goal of this paper is to address the importance of this condition on the hydrological and mechanical response of shallow unsaturated pyroclastic deposits and to establish a correct approach to problem modelling. The paper begins with an overview of the recent literature ("Recent contributions on the subject" section), providing some information about hydraulic behaviour at the ash-pumice interface based on experimental data on two well-documented materials ("Hydraulic impedance at the interface between pyroclastic soils with a different grain size" section). Then, it describes an infiltration column apparatus aiming to shed light on the hydraulic interaction mechanisms at the ash-pumice interface ("Results of column infiltration tests on layered pyroclastic soils" section). Lastly, these mechanisms are adopted in order to solve a boundary value problem; finally, the data obtained are compared to those yielded by a couple of case studies using more usual boundary conditions ("The influence of the lowermost hydraulic boundary condition in numerical analyses" section).

Recent contributions on the subject

The hydraulic phenomena that take place at the interface between unsaturated soils with different grain size have been widely investigated in the past with special reference to earth systems built to contain polluted waters and thus requiring impervious boundaries. It has been found that under well-defined unsaturated conditions, coarse-grained materials placed in contact with fine-grained soils behave as "capillary barriers" to the flux. In fact, such capillary barriers have been adopted widely as covers of landfill and mining waste in order to reduce water infiltration and to protect waste materials. However, the system is effective only if the amount of infiltrated water is less than the water loss due to the combined effect of evaporation, transpiration and lateral diversion.

Capillary barriers can also be used to improve slope stability conditions by limiting the amount of water influx by means of an unsaturated coarser layer lain over the sloping soils requiring protection (Rahardjo et al. 2012). The barrier effect can be relevant as long as the matric suction at the coarser-finer soil interface remains at a higher value than the water-entry value of the coarse-grained soil. Appropriate material selection plays a crucial role (Rahardjo et al. 2007).

However, an inverse effect takes place if the position of the two layers is reversed. In fact, in natural unsaturated layered deposits, the capillary barrier resulting from the presence of a finer layer resting over a coarser unsaturated one can favour water accumulation within the uppermost one (Khire et al. 2000), thus worsening rather than improving the slope stability conditions (Porro 2001).

Investigations carried out after the catastrophic rainfall-induced Sarno landslide events (Cascini et al. 2005) and further similar events that occurred in the same area in the subsequent years (Olivares and Picarelli 2003; Pagano et al. 2010) stimulated in-depth research projects into the hydrological and mechanical processes which lead to these phenomena, a topic that had been

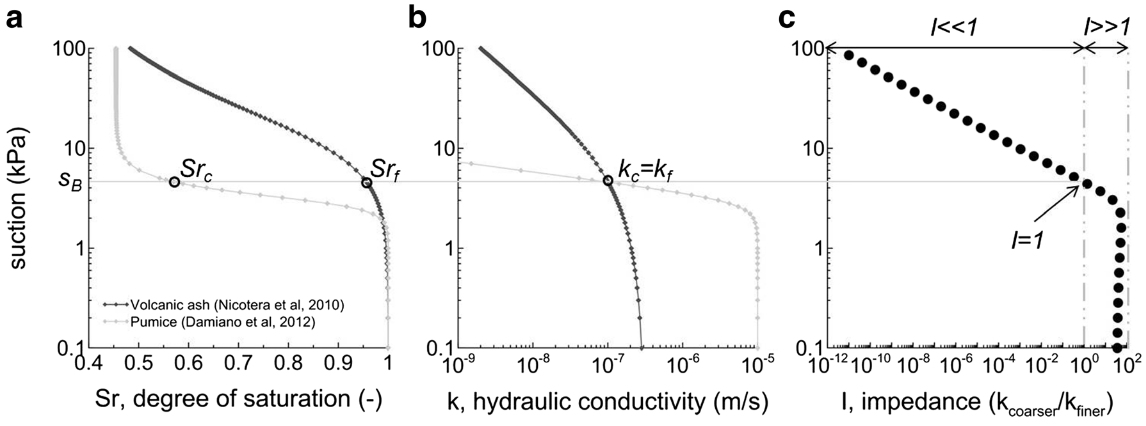

Fig. 1 SWRC (**a**) and permeability function (**b**) of two typical pyroclastic soils in the Campania region. **c** Resulting hydraulic impedance ratio

neglected until then. The research provided useful databases concerning the geotechnical properties of unsaturated pyroclastic soils (Nicotera et al. 2010; Picarelli et al. 2007; Sorbino and Nicotera 2013) and their hydraulic and mechanical responses to precipitations. In particular, the role of infiltration on suction profiles and its relationship with failure mechanisms have been the subject of a number of papers (Olivares and Damiano 2007; Pagano et al. 2008, 2010; Picarelli et al. 2008; Pirone et al. 2015a, b; Rianna et al. 2014a, b). Furthermore, some geological surveys have shown that slope failure may occur within thin pumice layers or at the ash-pumice interface, leading to the conclusion that it may have been a consequence of pumice saturation. However, some recent experiments have provided a different interpretation.

Olivares and Tommasi (2008) report the results of infiltration tests conducted on a 20-cm-thick model slope consisting of an ash layer incorporating a 4-cm-thick pumice seam. Both materials were reconstituted unsaturated at a porosity close to the field value of 75 and 72 % respectively. The tests highlight the strong influence of the interbedded pumice on the advance of the wet front leading to a rapid suction decrease in the uppermost ash layer and to a delayed decrease in the soils placed below the pumice seam. Further data obtained through other well-instrumented experiments have been published by Damiano et al. (2015).

Interesting data on the same subject have been provided by Mancarella and Simeone (2012) and Mancarella et al. (2012) through experiments carried out with an infiltration column and by 2D seepage studies. They point out the twofold hydraulic response of coarse-grained pumice layers lower-bounding ash covers: while essentially no-drainage conditions establish as far as the saturation degree of pumices remains less than one, free drainage does take place after full saturation. Based on such considerations, Mancarella et al. (2012) reinterpreted the Sarno events hypothesising that the saturation of the uppermost ash layers favoured by the presence of unsaturated pumice present at their base could have been the cause of the slope failure.

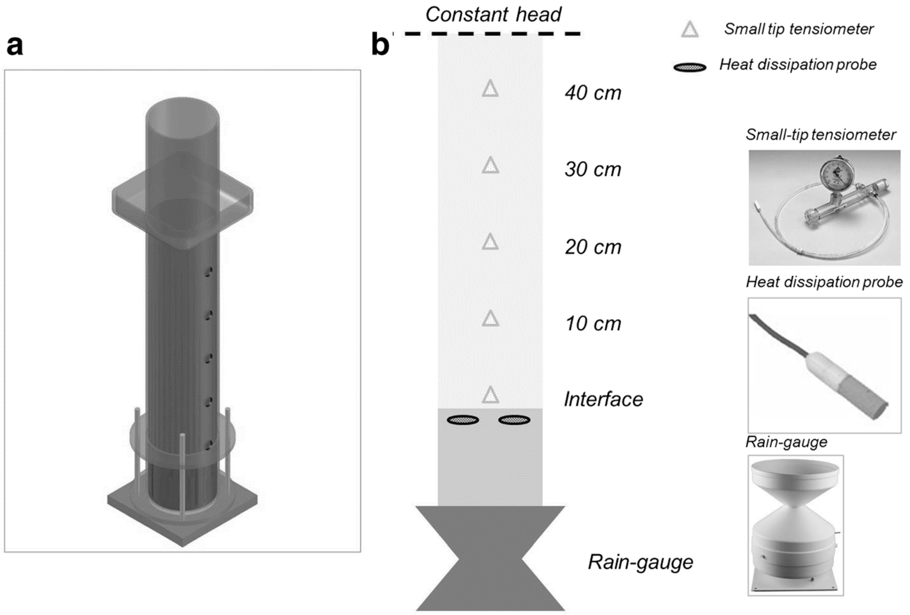

Fig. 2 The infiltration column (**a**) and a schematic representation of the equipment with adopted sensors (**b**)

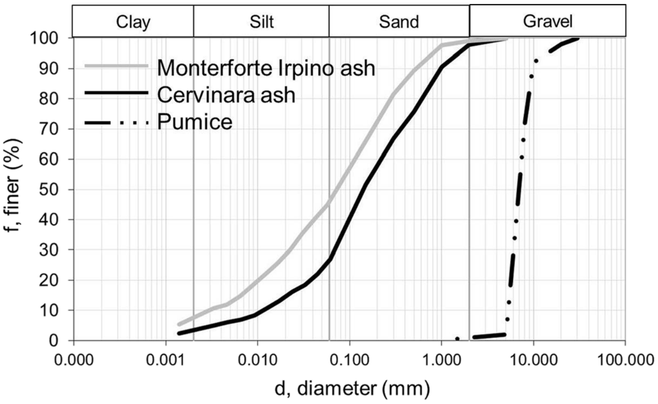

Fig. 3 Grain size distribution of adopted materials

The same subject is touched by Rianna et al. (2014a, b) who conducted a series of experiments with an instrumented lysimeter, filled with ash lower-bounded by a geotextile sheet. The lysimeter was then exposed to the atmosphere. The authors interpreted the soil conditions (water storage and suction profile) present throughout the layer in the different seasons, taking account of the continuous switching from conditions of no drainage to free drainage governed by the degree of soil saturation at the base of the ash column.

Finally, based on data obtained in an extensive monitoring of the instrumented Monteforte pyroclastic slope and considering a not fully different stratigraphic condition, Pirone et al. (2015b) remark that water crosses the lower boundary (ash-bedrock interface) only from January to May, while in the other periods of the year it moves essentially parallel to the top of the bedrock. The authors assume that the water flux through the ash-bedrock interface is liquid, if fractures are filled of soil, and in form of vapour if they are empty.

Hydraulic impedance at the interface between pyroclastic soils with a different grain size

The experiences summarised in "Recent contributions on the subject" section suggest that the abrupt change in grain size at the interface between two typical pyroclastic soils such as volcanic ash and pumice results in hydraulic impedance ratio, $I = k_{\mathrm{coarse}}/k_{\mathrm{finer}}$, leading to unexpected hydraulic patterns.

For a preliminary investigation of this topic, two well-characterized pyroclastic soils in the Campania region, i.e. an ash (Nicotera et al. 2010) and a pumice (Damiano et al. 2012), were selected and their hydraulic properties used to obtain I as a function of suction. Figure 1 plots the soil water retention curve (SWRC) and the permeability function (PF) of both materials as reported by cited authors; the figure includes the resulting hydraulic impedance ratio for any suction value, s, of the two materials. As expected, for s close to 0 (< 2 kPa), the hydraulic conductivity of the pumice is much higher than that of the finer ash ($I > 1$). However, when suction exceeds 2 kPa, I reduces rapidly reaching 1 for $s = 4$ kPa, decreasing to 10^{-4} at 10 kPa and dropping below 10^{-10} at 100 kPa. It is worth noting that a few tens of kPa are enough to make the hydraulic conductivity of the coarser material several orders of magnitude less than the one of the finer one (see Fig. 1a).

This can have a strong influence on the hydraulic behaviour of a layered geotechnical system consisting of ash overlying pumice and subject to a top-down wetting process. According to Stormont and Anderson (1999), the coarse layer should behave as a barrier to water flux as far as its water content remains fairly below the saturation value. This capillary barrier effect should persist as far as suction at the interface remains above a threshold value (s_B), called "breakthrough suction", that marks the rupture of the hydraulic barrier and the ingress of water in the coarser layer. Stormont and Anderson (1999) identify the breakthrough suction as the value at which the hydraulic conductivities of the two materials match ($I = 1$): it should roughly correspond to the air entry value of the finer soil. The process so described is reversible, in the sense that the capillary barrier is restored if the degree of saturation at the interface decreases (due to phenomena such as evapotranspiration and/or deep drainage) leading suction above to the so-called "barrier restoration suction" (s_R).

Results of column infiltration tests on layered pyroclastic soils

Targeted experiments with an infiltration column were carried out in the laboratory, in order to investigate the hydraulic response of a layered sequence of ash and pumice subject to top-down infiltration under one-dimensional flow conditions. The main goal was an in-depth characterization of the processes depicted in the previous paragraph with special reference to the hydraulic conditions present at the ash-pumice interface. Such a knowledge would be highly beneficial in defining the hydraulic conditions to impose at the ash bottom when conducting numerical analyses aimed at reproducing rainwater infiltration effects.

The experimental apparatus

The infiltration column consists of two superimposed Plexiglas cylinders with a diameter of 14 cm (Fig. 2). The uppermost cylinder (h = 50 cm) was filled with volcanic ash, the lowermost one (h = 13 cm) with pumice. A coarse-meshed steel wire net was positioned between the two cylinders. The lowermost one was placed on a perforated Plexiglas disc, which allows a free drainage.

Table 1 Main physical properties of adopted soils

	d_{10} (mm)	U (–)	γ_s (g/cm^3)	n (%)
Monteforte Irpino ash	0.002	50	2.656	71
Cervinara ash	0.01	20	2.636	70
Pumices	5	1.4	1.950	75

The monitoring system (Fig. 2b) makes it possible to record the following:

1. The progressive deepening of the wetting front in the uppermost ash column that was equipped with a sequence of five small-tip tensiometer sensors (Soilmoisture Equipment LTD, Fredlund and Rahardjo 1993) installed at intervals of 10 cm; the lowermost device was placed very close to the ash-pumice interface.
2. The time at which the wet front crosses the interface: this was captured by means of two heat dissipation probes (Campbell Scientific 2006; Reder et al. 2014) placed in the pumice layer, precisely at the interface with ash.
3. The amount of water discharged from the column that was recorded through a rain gauge located at the base of the cylinder

All instruments (small-tip tensiometers, heat dissipation probes and rain gauge) were connected to a CR1000 data logger. The data were recorded at 1-min intervals.

Water was supplied at the top of the infiltration column through a dispenser. Since the flow rate was higher than the absorption capacity of the sample (potential infiltration), the excess water was continuously removed in order to keep constant the pressure head at the top of the column.

A camera placed just in front of the lowermost pumice layer served to record the progress of the wetting front in order to show the breakthrough time. This was then compared to the breakthrough time obtained by analysing the data from the heat dissipation probes.

The materials tested

The experiments were conducted on two different ashes investigated in previous studies; the pumice soil was an almost monogranular material taken from the experimental site of Monteforte Irpino [30].

Figure 3 shows the grain size distribution of these soils. The grey curve represents the no. 6 layer of the Monteforte Irpino sequence described by Nicotera et al. (2010). The grain size distribution and other intrinsic properties of this soil are very similar to those of the materials involved in the Nocera Inferiore flowslide of 4 March 2005 (Pagano et al. 2010). The black curve represents soil B of the Cervinara sequence, described by Damiano et al. (2012), involved in the Cervinara flowslide of 16 December 1999 (Olivares and Picarelli 2003).

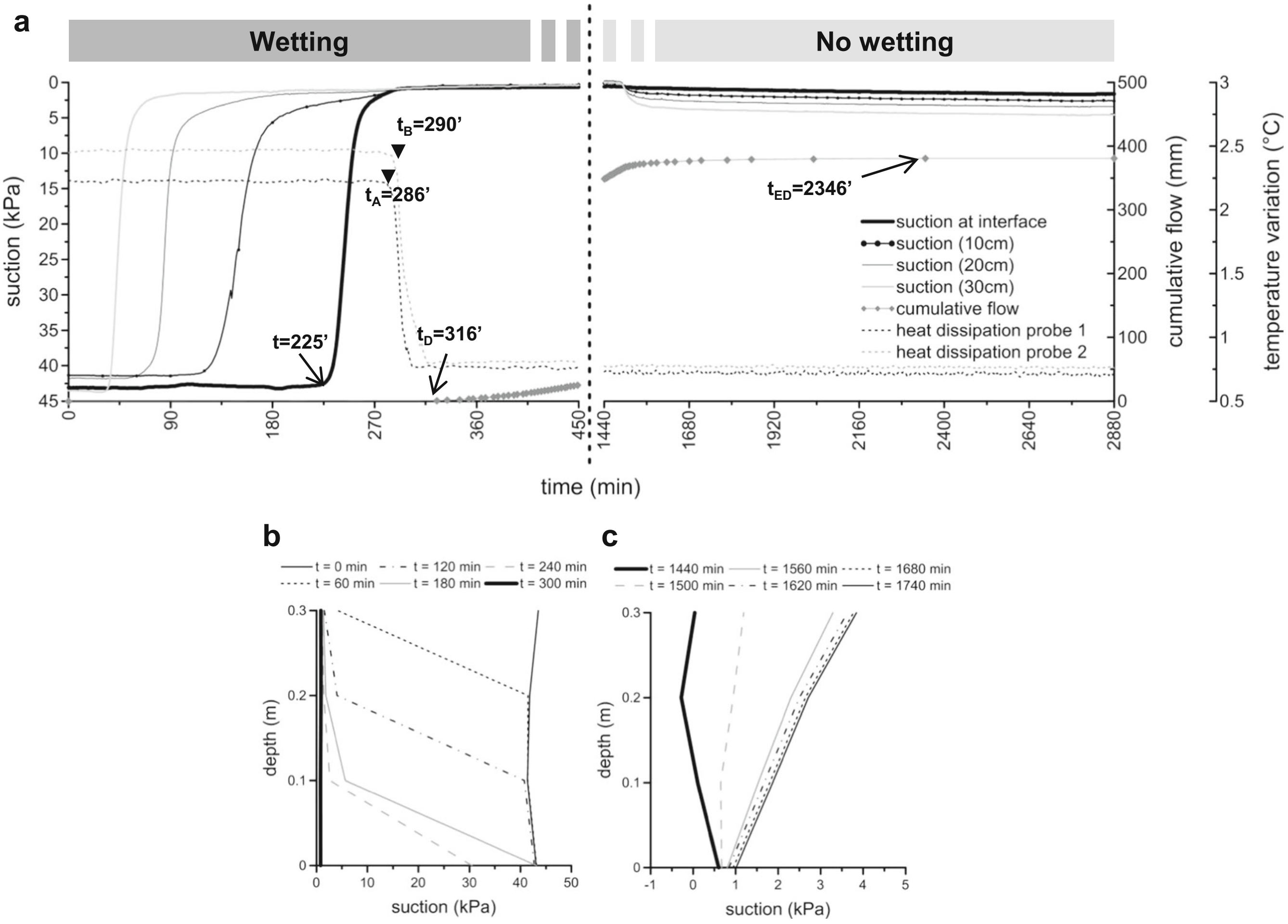

Fig. 4 Main results of experiment no. 1: **a** evolution of suction at different depths, cumulative flow through pumice and temperature variation within pumice; suction profiles **b** during wetting and **c** during drying

Table 1 summarizes the average field values of some physical properties. High porosity is a peculiar feature of these air-fall materials (Picarelli et al. 2007) that are unsaturated even in the wettest periods of the year. This assures the stability of slopes, but exceptional precipitations can lead to strong decreases in suction and associated contribution in soil strength (apparent cohesion).

The soils were installed in the infiltration column using the pluvial deposition method to assure an imposed ash porosity (*n* = 70–71 %) very close to the field values. The porosity of the pumice (*n* = 75 %) was slightly higher.

The adopted test procedure consisted of soil wetting over a time interval of 24 h, followed by a drying time of 24 h. In all experiments, the same initial suction was adopted, corresponding to the average value typically observed on site at the onset of autumn (40–45 kPa), which is also the beginning of the rainy season.

Experimental results

Experiment no. 1: Monteforte Irpino ash upon pumice

In experiment no. 1, the uppermost part of the column was filled with Monteforte Irpino ash. The main results of the experiment are shown in Fig. 4.

Figure 4a shows the suction evolution at any instrumented depth during the wetting stage. As water reaches a tensiometer depth, suction (initially comprising between 40 and 45 kPa) rapidly starts to decrease: in an extremely short time (tens of minutes), it can drop to around 10 % of its initial value; then, the process slows down even though it remains quite fast. The progressive deepening of the wetting front is clearly shown in Fig. 4b, which provides a spatial description of the phenomenon.

The heat dissipation probes obviously do not record any significant effect as far as the wet front does not reach the pumice top. The deepest tensiometer starts recording some suction decrease 225′ after the start of the test, but a temperature decrease is recorded by probes only later, when suction is approaching zero (t_A = 286′ for the probe 1, and t_B = 290′ for the probe 2). Falls in temperature indicate that the wet front has flown across the interface and is penetrating within the pumice. The suction values measured at the deepest tensiometer at times t_A and t_B are 1.4 and 1.2 kPa respectively. As a further confirmation of such results, cumulative flow is recorded only after the wet front has penetrated the pumice layer reaching its bottom. This occurs 26–30 min after the suction breakthrough and 316 min (t_D) after the beginning of the test (Fig. 4a).

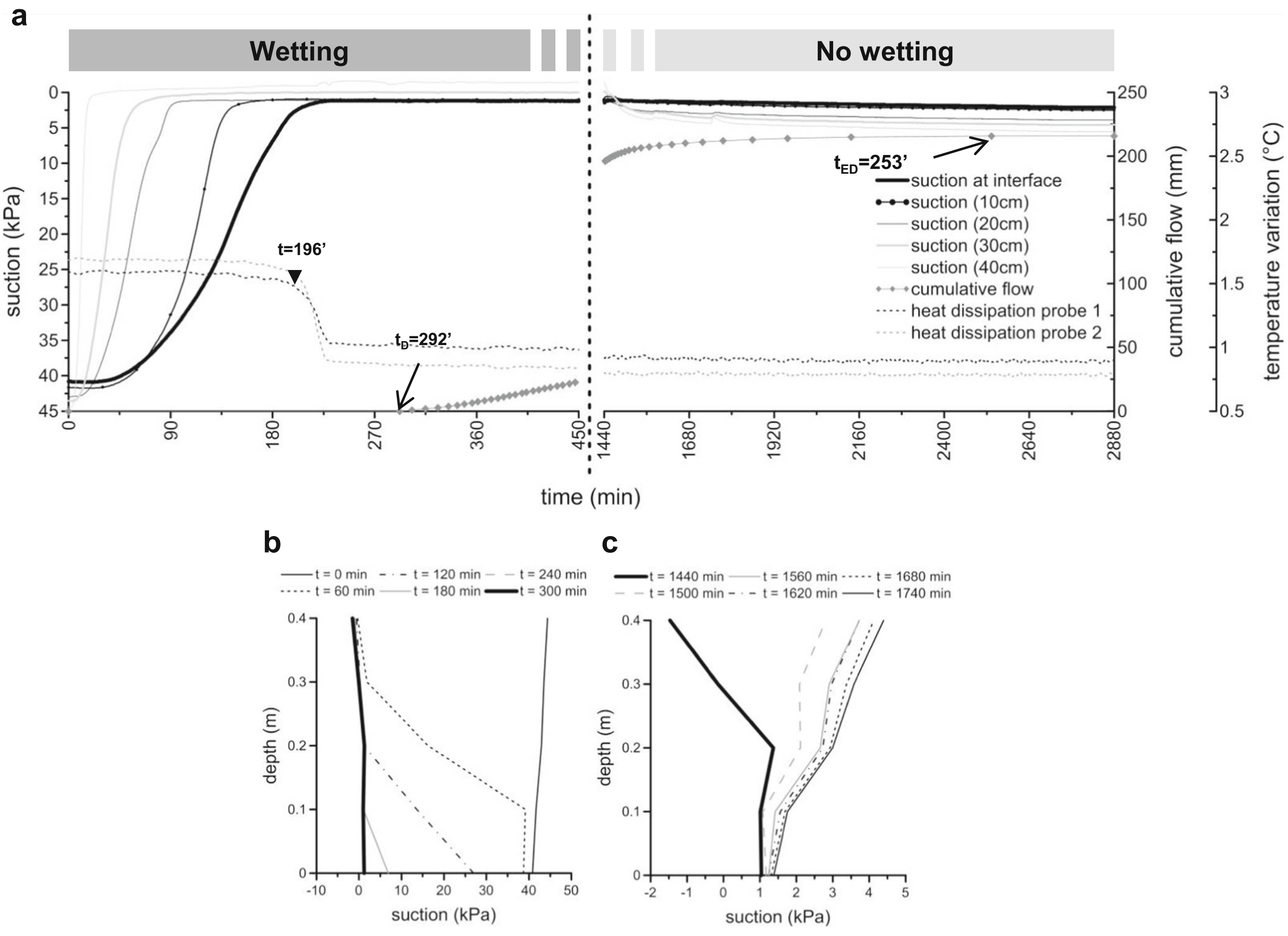

Fig. 5 Main results of experiment no. 2: **a** evolution of suction at different depths, cumulative flow through pumice and temperature variation within pumice; suction profiles **b** during wetting and **c** during drying

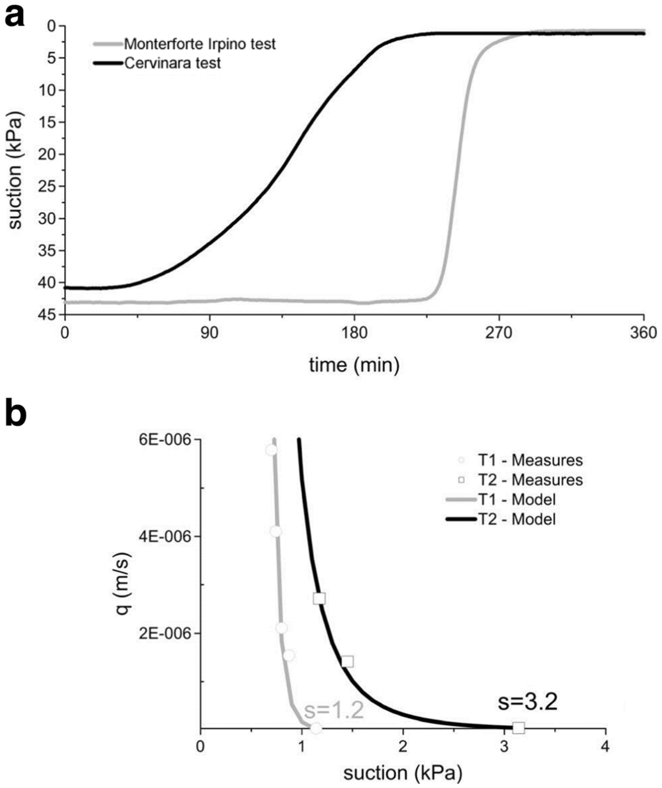

Fig. 6 Suction change at the base of the two ash layers as a function of time (**a**) and water flow rate as a function of suction (**b**)

In the first phase of the following drying stage that starts 1440′ after the beginning of the test, some water drainage is still ongoing at the pumice bottom coming to a complete stop at $t_{ED} = 2346'$ (Fig. 4a).

The suction profiles recorded during this stage (Fig. 4c) display an initial rotation around the point corresponding to the lowermost sensor due to the suction decrease recorded by the shallowest ones, then a translation, due to drying that involves also the deepest part of the column. The suction value at which the boundary condition at the ash-pumice interface switches to impervious again thus restoring the capillary barrier may be conventionally associated with the time when the bottom drainage stops ($s_R = 1.45$ kPa).

Experiment no 2: Cervinara ash upon pumices

Figure 5 shows the results of experiment no 2. In this experiment, the wetting front advances more quickly than in the previous one (Fig. 5a), reaching the pumice layer earlier (196 min). This is probably due to the coarser grain size of the Cervinara ash (Fig. 3). In addition, the suction decrease through the column is more gradual than in the previous experiment (Fig. 5a). The breakthrough occurs 196′ after the beginning of the test, when suction is 3.2 kPa, a higher value than in experiment no. 1. The wetting front reaches the pumice bottom at minute 292′ (Fig. 5a). The water discharge stops at minute 2533′.

The suction profiles recorded during the two wetting and drying phases (Fig. 5b, c) are very similar to those observed in the

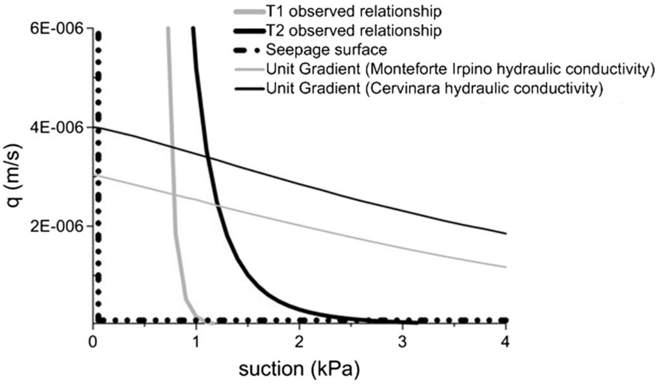

Fig. 7 Boundary conditions usually adopted for the lowermost boundary compared with the experimental relationships found in the present research

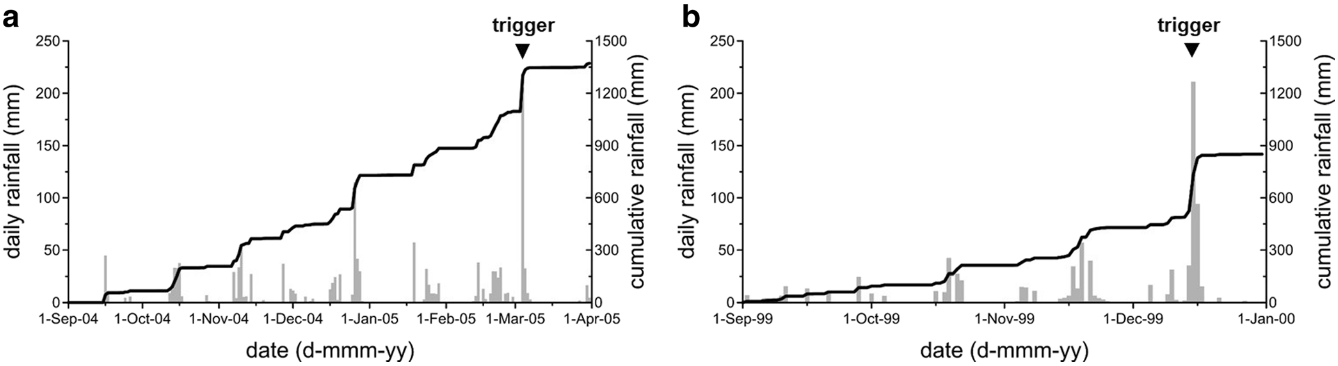

Fig. 8 Rainfall sequence for Nocera Inferiore (**a**) and Cervinara flowslides (**b**)

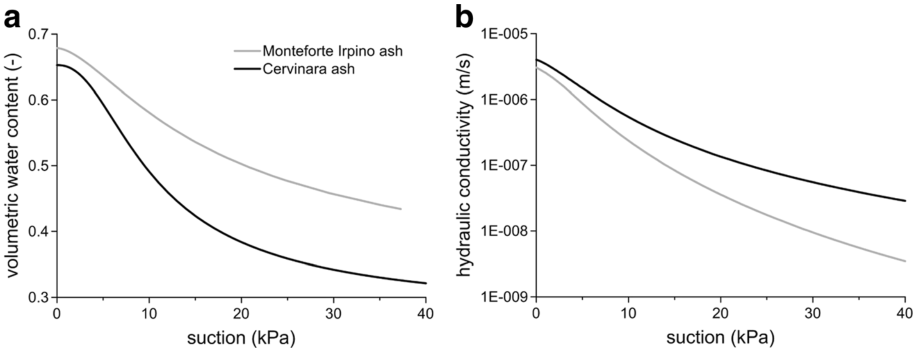

Fig. 9 **a** Soil volumetric water content and **b** hydraulic conductivity of Monteforte Irpino and Cervinara volcanic ash

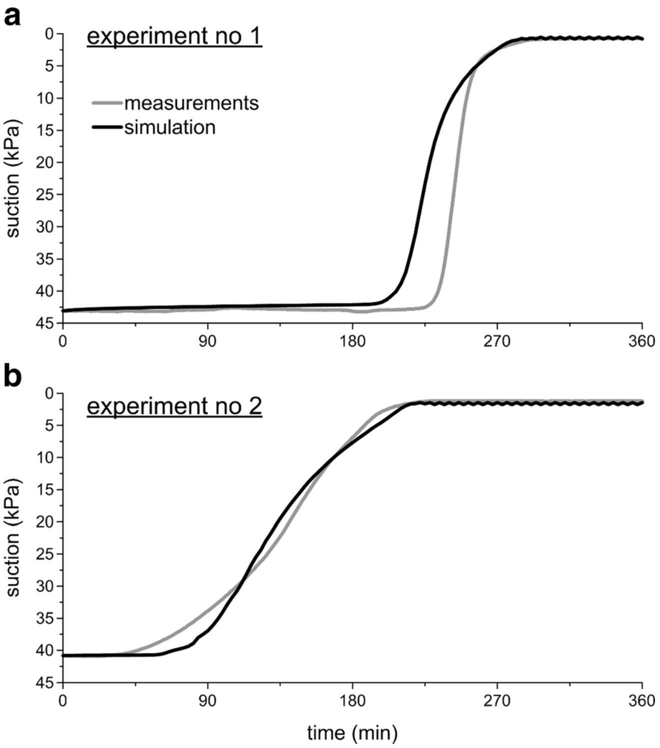

Fig. 10 Measured and simulated suction trends at the pumice-ash interface for experiment no. 1 (**a**) and no. 2 (**b**)

previous case. The capillary barrier is restored when suction rises to a value $s_R = 1.95$ kPa.

Some remarks

The experimental results outline some differences between the response of the two materials, possibly related to their different grain size and pore distribution. In terms of the hydraulic mechanisms which establish at the ash-pumice interface (which is the main topic of this paper), while the Monteforte Irpino ash displays a sudden suction decrease as water reaches the interface thus dropping from about 40 kPa to about 1 kPa in 60 min, the Cervinara ash shows a more gradual decrease that takes about 180 min (Fig. 6a).

Further elements are provided in Fig. 6b, which shows the drainage flow, measured by the rain gauge, against suction recorded at the interface. The figure has been plotted by shifting back the time when the first water flow is measured at the pumice base to the instant when the wetting front moves through the interface. As shown, the change from a condition of "impervious interface" ("hydraulic barrier") to that of a "draining" interface is quite different in the two cases, being somewhat abrupt in the case of the Monteforte Irpino ash and smoother in that of the Cervinara ash. Therefore, while a breakthrough suction can quite easily be defined in the first case, a precise value (in any case higher) cannot be clearly defined for the second one. The textural features of the soil, and in particular the pore distribution, certainly play a fundamental role even though a quantitative relationship does not exist.

In any case, the data obtained do not hide the importance of the hydraulic mechanisms which occur at the interface between essentially granular unsaturated coarser and finer soils, governing the boundary conditions and thus the overall hydrological response of the system.

The influence of the lowermost hydraulic boundary condition in numerical analyses

Comparison between the observed interface response and the response provided by usual numerical approaches

Experimental data as those shown in Fig. 6b provide useful water flow (q)-suction (s) relationships which could be adopted in numerical analyses. Figure 7 compares the observed relationships (T1 and T2 for the two examined cases) to those given by the most usual assumed lowermost boundary conditions.

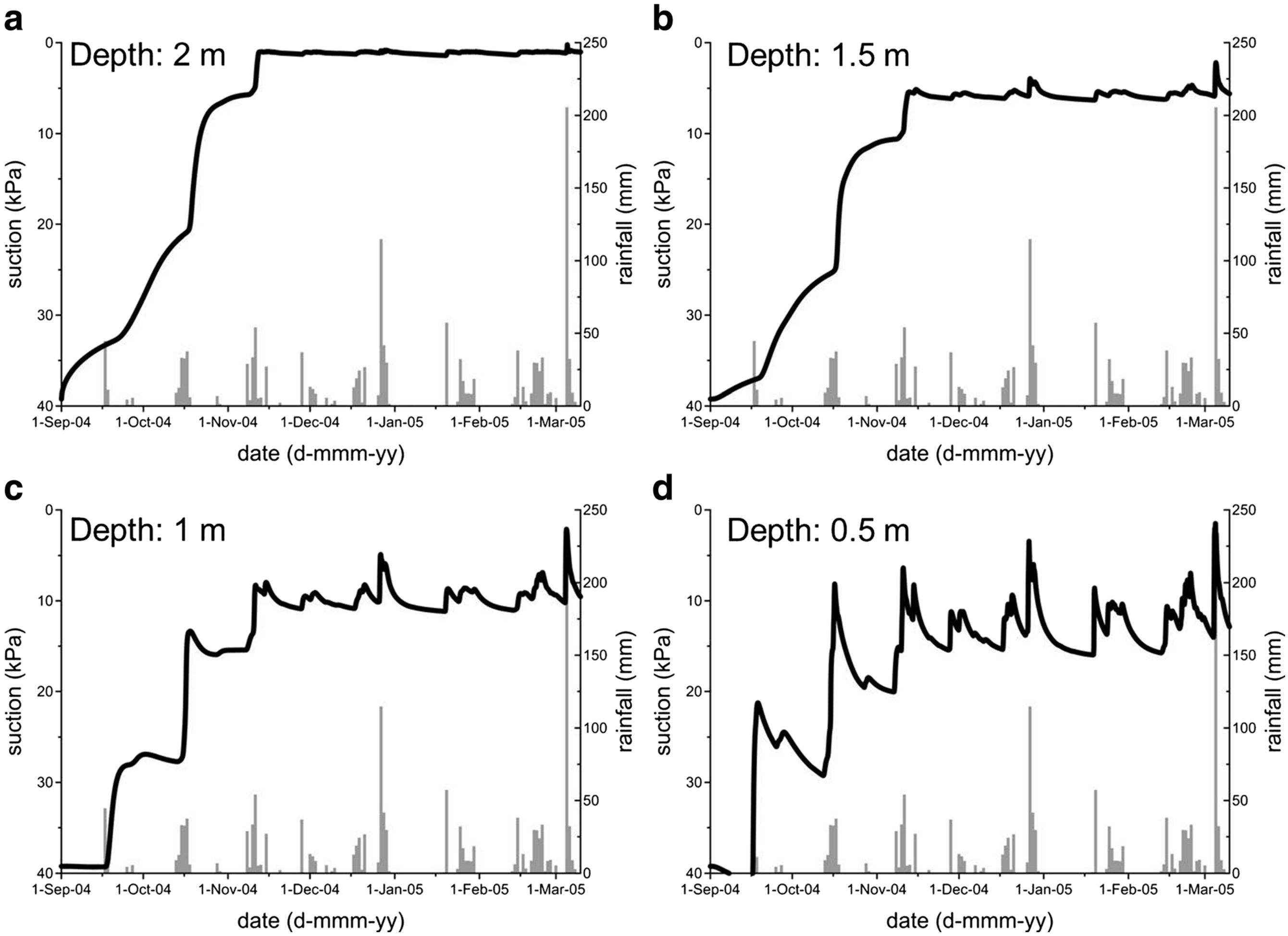

Fig. 11 Simulated suction trends for the Nocera Inferiore case by adopting hydraulic soil properties permeability and the $q(s)$ relationship derived from laboratory experiment no. 1

The traditional condition adopted in the analysis, here called "unit gradient", means imposing a flow rate through the interface equal to the soil's hydraulic conductivity, which in turn depends on the current suction value. This relationship is shown in Fig. 7 for both ashes over the suction range 0–4 kPa; it has been obtained by means of a back analysis, solving Richards' equation (Richards 1931) of the results of the column infiltration tests (see "Results of column infiltration tests on layered pyroclastic soils" section). As it can be clearly argued from the figure, the unit gradient assumption leads to very different values for impedance ratio *I* compared with those obtained from the experiments and for quite a wide range of *s* values.

Another approach usually adopted in numerical analyses consists in the assumption of a unique "infinite layer" neglecting the presence of the interface. At the depth where it is located, this condition obviously coincides with that of the unit gradient in the case of null/negligible pressure gradient.

Finally, in many cases the lowermost boundary is simulated using a "seepage surface" characterised by zero impedance for negative pore water pressure (unsaturated conditions) and by infinite impedance (free drainage) for positive pore water pressure (saturated conditions) (Fig. 7). In numerical analyses, the seepage surface is simulated by assuming a null water flow rate insofar as a negative pore water pressure is computed at the interface and a null pore water pressure when this exceeds zero. This latter condition then holds until the water flow is directed outward, but switches again to null water flow as the water flow direction tends to invert. Figure 7 shows that the $q(s)$ trend corresponding to a seepage surface is more similar to the experimental trends measured, especially in the case of Monteforte Irpino ash (experiment no. 1).

An application to case histories

As discussed above, the lowermost boundary conditions can significantly affect the results of numerical analyses in terms of pore water regime and consequent slope stability conditions.

In order to quantify the differences, some analyses were carried out adopting the properties of the soils tested in the laboratory. Rather than conducting the work in the abstract, the analyses were focused on the case histories of the Nocera Inferiore (4 March 2005) and Cervinara flowslides (16 December 1999), respectively described by Pagano et al. (2010) and by Olivares and Picarelli (2003). The first landslide took place in 39° sloping soils having a grain size very similar to the Monteforte Irpino ash used in experiment no. 1; the second one occurred on a 40° layered slope. The hourly resolution of the rainfall histories which led to the two landslide events is reported in Fig. 8.

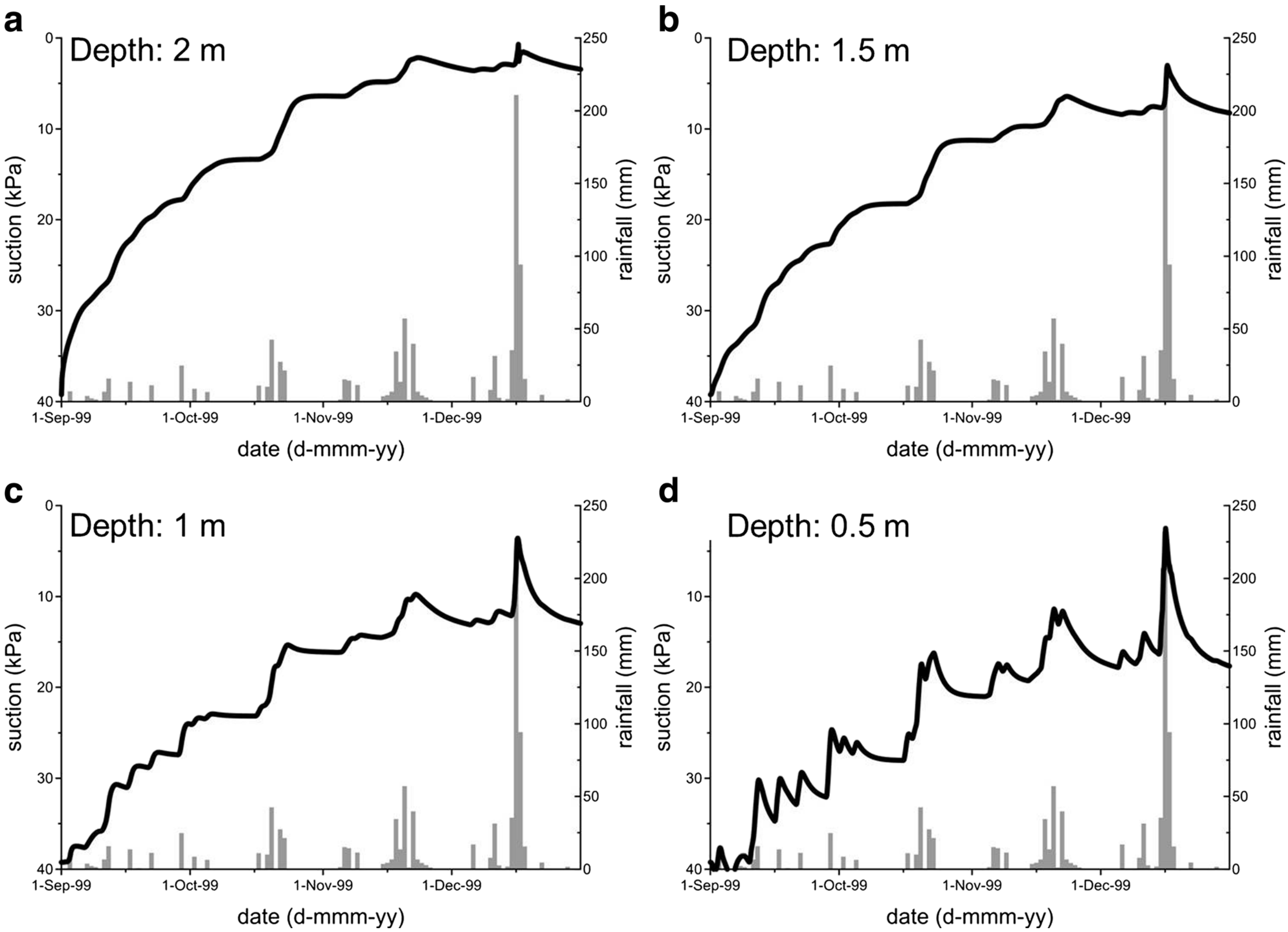

Fig. 12 Simulated suction trends for the Cervinara case by adopting hydraulic soil properties permeability and the $q(s)$ relationship derived from laboratory experiment no. 2

The SWRCs of the soils to use in the analysis (Fig. 9a) were obtained from data reported in the literature. Specifically, for the Monteforte Irpino ash (experiment no. 1), the adopted SWRC was reported by Pagano et al. (2010), while the SWRC of the Cervinara ash (experiment no. 2) was retrieved by suction and water content measurements on undisturbed samples (Damiano et al. 2012). In both cases, the curves were interpreted through the van Genuchten model (1980). Conversely, the PFs (Fig. 9b) were quantified through the best fitting of the experiment results at the interface (Fig. 10).

The infiltration analysis was carried out by integrating the Richards' equation under 1D flow conditions (isothermal analysis) over a domain 2 m thick. To this aim, the SEEP/W (2007) FEM code was used (GEO-SLOPE 2009). In both cases, 2 m is more or less the depth of the failure surface in the ash layer overlying pumices. In the two cases, the input of the analysis was the hourly rainfall history recorded from the beginning of the hydrological year (1 September). A uniform initial suction profile of 40 kPa was set throughout the entire investigated domain. This value is consistent with the results of measurements carried out at the end of summer in instrumented sites mantled by pyroclastic soils, including Monteforte Irpino and Cervinara (Pirone et al. 2012).

Figures 11 and 12 show the suction evolution predicted at four depths in the two cases, Nocera and Cervinara respectively, by adopting the $q(s)$ relationships measured at the interface. Since these results are obtained for actually observed boundary conditions, they are considered in the following as reliable references for comparison of the slope response yielded by further boundary conditions.

In the Nocera Inferiore case (Fig. 11), suction shows continuous fluctuations as a function of the precipitation regime, with quicker and higher changes at the shallowest depths. On average, it decreases with time, with the flattest trend at the greatest depth. The lowest value is predicted precisely for the date of the landslide (4 March, dropping to almost zero at all depths).

In the Cervinara case (Fig. 12), the different $q(s)$ relationship and hydraulic properties yield rather different suction trends, characterized by fluctuations at all depths, including the deepest point. Also in this case, the lowest suction values are predicted precisely for the date of the landslide.

A comparison with the results obtainable through the other boundary conditions (Fig. 7) is shown in Figs. 13 and 14, where only the reference experimental $q(s)$ relationships (T1 or T2) are given for comparison. It may be observed that the use of the unit gradient and the infinite layer leads to very similar results mostly at the shallowest depths, confirming that these two

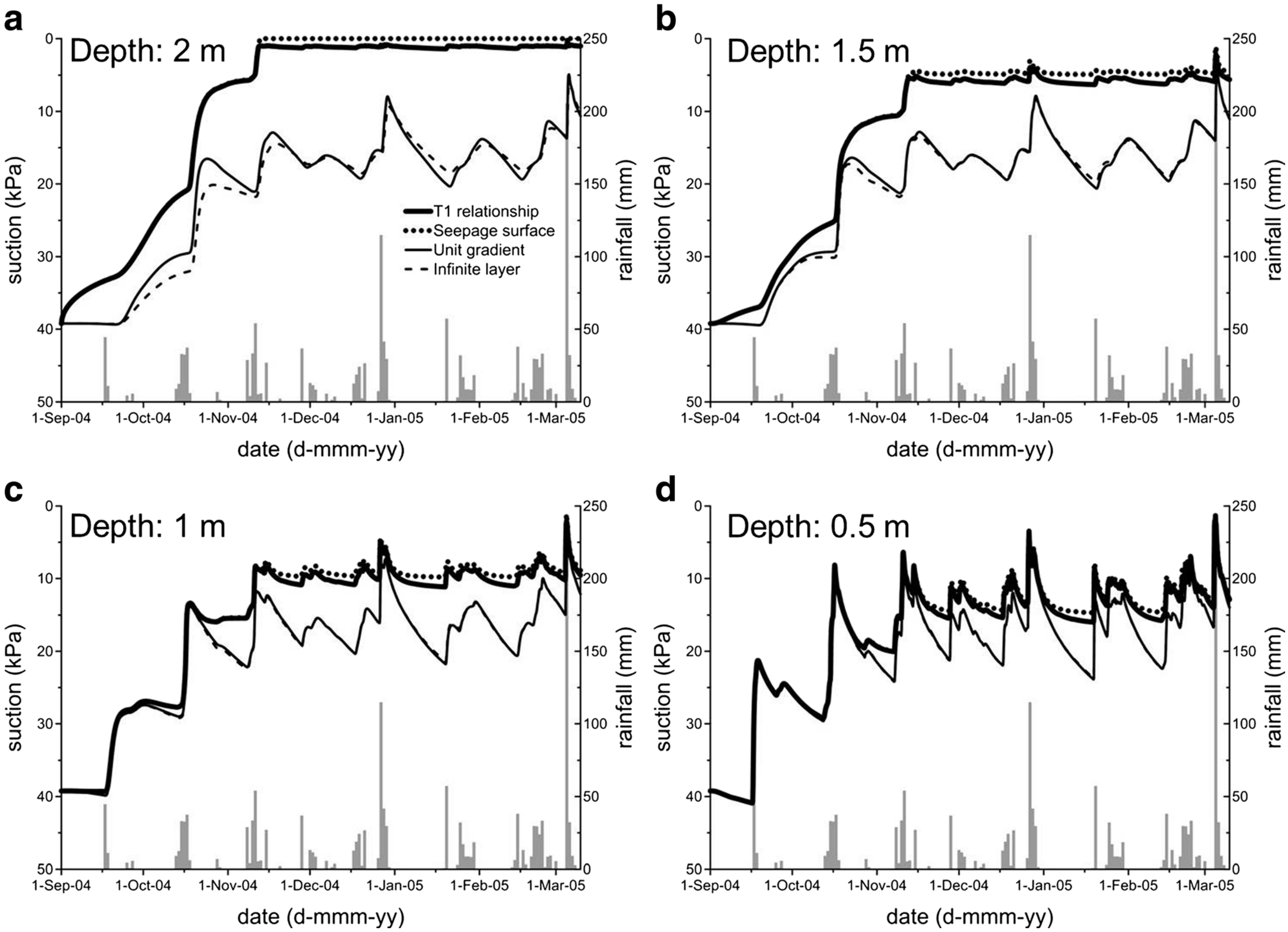

Fig. 13 Simulated suction trends for the Nocera Inferiore case for different lowermost boundary conditions

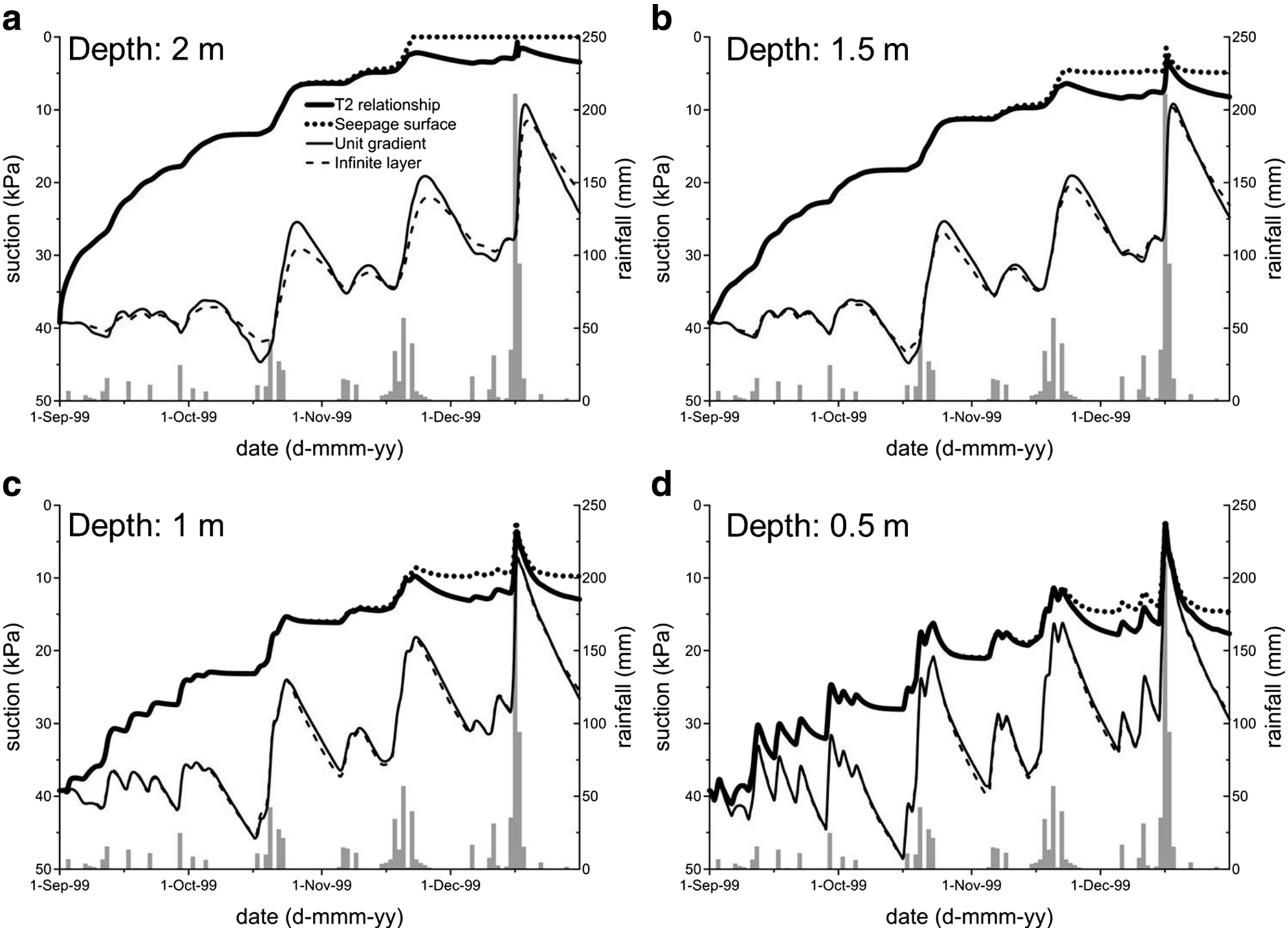

Fig. 14 Simulated suction trends for the Cervinara case for different lowermost boundary conditions

assumptions are practically equivalent in the cases in hand. However, the results are considerably different from those obtained using the measured *q*(*s*) relationships. The differences increase with the depth from the ground surface. In contrast, the seepage surface condition yields results comparable with those obtained in the *q*(*s*) hypothesis at all depths, especially the Nocera Inferiore case.

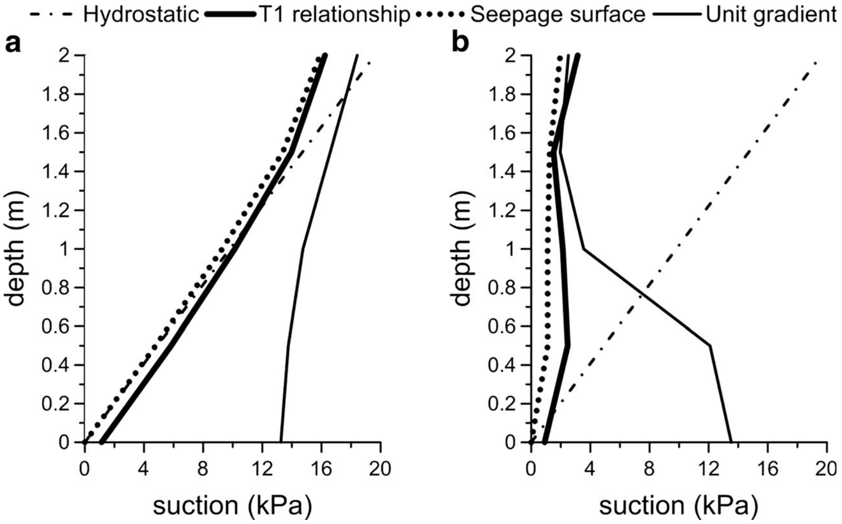

Fig. 15 Suction isochrones at Nocera Inferiore on 4 March 2005 before (**a**) and at the triggering time (**b**)

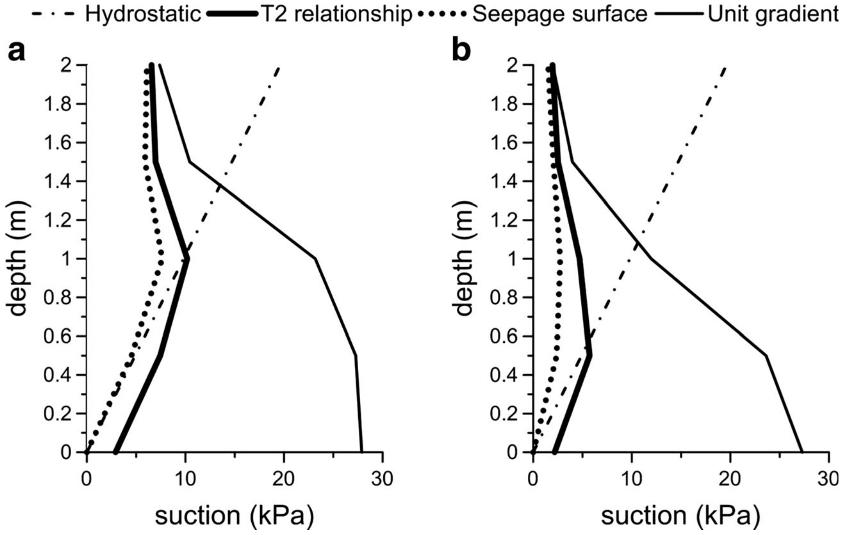

Fig. 16 Suction isochrones at Cervinara on 16 December 1999 before (**a**) and at the triggering time (**b**)

Focusing even more on the differences emerging from the analyses, it is worth noting that, using the experimental $q(s)$ relationships, as soon as the wetting front reaches the bottom layer, suction quickly decreases since the interface acts as an impervious boundary favouring water accumulation. However, as suction vanishes, the hydraulic barrier is overcome and suction remains at a constant zero value. The downward drainage in fact prevents any pore pressure increase in the positive range. Moreover, with any stop in rainfall, a hydrostatic suction profile tends to take place, with the minimum value at the bottom. Similar results are obtained when using the seepage surface as a boundary condition. In contrast, for the unit gradient and infinite layer conditions, a continuous water flow passes through the lowermost boundary leading to a reduction in the degree of saturation (and increase in suction). Hence, the dry phases after the wet front reaches the ash-pumice interface are those with the greatest differences among the selected boundary conditions.

In the first case (Nocera Inferiore), the wet front reaches the bottom of the ash layer in mid-November. After that, evident differences between the experimental and the usual boundary conditions (unit gradient and infinite layer) can be observed, not only at the bottom (Fig. 13a) but also half a metre above (Fig. 13b). At shallower depths, the differences between the computed trends are less marked and tend to disappear.

For the same case, Fig. 15 shows suction profiles computed some time before (Fig. 15a) and at the triggering time (Fig. 15b). These show that the differences in suction within the deepest metre, obtained through the selected boundary conditions, are a few kilopascals. Obviously, this could have a great influence on slope stability conditions.

In the Cervinara case, the wet front reaches the lowermost boundary at the end of November. Differences between the results computed in the two hypotheses are more evident than in the first case due to the higher hydraulic conductivity of the soil. For the unit gradient and infinite layer conditions, a desaturation process clearly takes place during the periods of no rain. Suction profiles just before and at the triggering time (Fig. 16) show that the differences in suction obtained with the different approaches are quite marked throughout the entire domain.

Summary and conclusions

The influence of the lowermost hydraulic boundary condition on the stability of slopes subject to precipitations is generally disregarded since much greater attention is paid to the role of the uppermost boundary condition. This could lead to significant errors, mostly in the case of shallow covers overlying unsaturated coarser soils, which are often subjected to severe landslide events. This is a usual stratigraphic condition in pyroclastic soils consisting of alternating ash and coarser pumice layers which act as capillary barriers.

The hydraulic conditions at the ash-pumice interface were thoroughly investigated in a laboratory at the Federico II University of Naples through some 1D infiltration experiments on well-instrumented unsaturated soil columns. The experiments confirmed the capillary barrier effect, showing that the threshold breakthrough suction is slightly higher than 0 kPa and its value depends on the grain size of the soils above and below the interface.

The role of the hydraulic boundary condition created by an ash-pumice interface was then investigated through some numerical analyses focused on landslides that have occurred in recent years. The results obtained using the experimental relationships were compared with those provided by the most usual lowermost boundary conditions adopted in numerical analyses. It is evident that some of these could be wrong on the unsafe side and that the best compromise can be obtained using the so-called seepage surface.

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