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Evaluation of the hydraulic hysteresis of unsaturated pyroclastic soils by in situ measurements

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Abstract

The triggering mechanism of debris flows and mudflows involving unsaturated soils has been extensively covered in the literature. It is associated with heavy rainfalls occurring during wet periods, when the pore water pressure regime is critical for landsliding. Having said this, full understanding of slope failure conditions needs a fair analysis of groundwater flow and, therefore, a proper hydraulic soil characterization as fundamental basis of the analysis. At this regard, laboratory characterization could be not sufficient: the soil water retention curve (SWRC) is hysteretic and the paths followed in situ, in terms of water content and matric suction, depend on the preceding hydraulic history. This aspect has to be accurately taken into account for analysis and prediction. In order to explore the hydraulic hysteretic behaviour of pyroclastic soils, in this paper pairs of water content and matric suction measurements registered at the same depth in an instrumented unsaturated pyroclastic slope are compared to a number of retention curves obtained in the laboratory.

Keywords: debris flow, hydraulic hysteresis, pyroclastic slope, soil water retention curve, slope stability

1. Introduction

Full understanding and analysis of triggering mechanism of debris flows and mudflows in unsaturated slopes requires a proper hydraulic soil characterization. Paths followed in situ, in terms of matric suction and water content, influence the soil hydraulic conductivity and, as a consequence, pore water pressures into the subsoil[1,2,3]. Therefore, the choice to adopt the *main wetting curve* or a *scanning curve* to model the soil domain during rainfall infiltration is crucial to carry out a numerical analysis of groundwater flow in unsaturated slope and, thus, to obtain reliable results.

In this paper suction and soil water content measurements collected over three years at the pilot site of Monteforte Irpino (Southern Italy) are shown to derive hydraulic paths actually followed in situ during rainfall infiltration[4,5].

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Couple of suction and water content measurements taken in the top soil (at 25 and 45 cm from the ground surface) respectively by tensiometers and TDR probes located at the same depth, are presented. Moreover main drying path and wetting-drying cycles have been derived in the laboratory on undisturbed samples taken from the top soil of the pilot site. Results are compared with paths detected in situ and differences are discussed.

Nomenclature

h	pressure head	β_{SC1}	parameter of model interpolating suction and water content data over dry period
n	empirical parameter (van Genuchten model)	β_{SC2}	parameter of model interpolating suction and water content data over wet period
n	soil porosity	γ	unit weight
s_{sc}	matric suction at transition between dry and wet period	γ_d	dry unit weight
S_e	effective saturation	γ_s	specific unit weight
α^{-1}	empirical parameter (van Genuchten model)	θ_r	volumetric residual water content
β_{MD}	slope of the main dry retention curve in the range 5-80kPa	θ_s	volumetric water content at saturation

2. Test site

In 2005 a pilot site was set up in the municipality of Monteforte Irpino in Southern Italy to investigate debris flow initiation in unsaturated pyroclastic slope. The stratigraphic profile detected on site is constituted of a pyroclastic cover (4.0-4.5 m thick), resting on fractured limestone. In particular a series of cineritic layers alternated with pumices belonged to different eruptions have been recognized. The monitoring system installed on site provides suction and water content measurements in the pyroclastic cover and meteorological data (rainfall, wind speed and direction, net radiation, air humidity, air temperature). For more details about the pilot site, readers can refer to Papa et al.[6], Pirone and Urciuoli[7].

2.1. Soil physical and hydraulic properties

Investigation on the hydraulic hysteresis by results of laboratory tests and field-measurements has been carried out only for the top soil layers of the pilot site. Starting from the ground surface, the first and second layer, both thick 40 cm, are called in the following soil 1 and soil 2 respectively. The topsoil consists of humified ash including roots and organic matter. Both the layers (soils 1 and 2) are very loose and unsaturated in natural conditions. They have quite similar grain-size distributions and are identified as a silty sand[5,6]. The main soil properties are reported in Table 1 (see[4,6,8]). Main drying paths were already available from previous experimentations carried out in laboratory by evaporation tests performed in ku-pF apparatus (ku: unsaturated permeability; pF: $\log_{10} h$) on undisturbed samples collected at different depths (see[4,6]). The results were interpreted by Mualem-van Genuchten model[9,10] by means of inverse procedure implemented in the Hydrus 1D code.

Table 1. Main soil physical properties

	γ_s (kN/m³)	γ_d (kN/m³)	γ (kN/m³)	n
Soil 1	26	8	12	0.69
Soil 2	27	8	12	0.70

Thus, the Soil Retention Curve can be expressed through the eq. (1):

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[1 + |\alpha h|^n\right]^{\frac{1}{n}-1} \tag{1}$$

where θ_s is the saturated soil water content, θ_r is the value at residual condition, α and n are model parameters, h is the pressure head. The main drying curves for samples taken at 25 (soil 1) and 45 cm (soil 2) from the ground surface are plotted in Figure 1. The air entry values are between 8 and 9 kPa and the mean model parameters are reported in Table 2. The curves modelled by using the van-Genuchten model and the mean parameters are shown in Figure 1.

Table 2. Main drying curve: mean model parameters

	θ_s	θ_r	$\alpha^{-1}\,(kPa^{-1})$	n
Soil 1	0.565	0.135	8.08	1.716
Soil 2	0.617	0.143	8.72	1.602

3. In situ monitoring: suction and water content

Within the investigated pilot site, the monitored area is about 230 m^2. Within this area, 20 verticals were instrumented along three different longitudinal sections, located at the vertexes of a fairly regular rectangular grid formed by 14 square meshes 4 m x 4 m[5,8]. Ninetyfour tensiometers and fourty TDR probes were installed only within the cineritic layers, because both the instruments are ineffective in measuring in pumice. Suction measurements are available from 2006, water contents from 2008; readings were regularly carried out three times a month. In Figure 2 the mean values of suction and water content calculated from all the measurements collected at 25 cm (soil 1) and 45 cm (soil 2) are reported. The data trend is seasonally, being it controlled by the hydraulic condition at the upper boundary, hence by the ground-atmosphere interaction[8]. In Figure 1 the couple of suction and water content collected at the same depth are overlapped to the main drying curves obtained in the laboratory for the same soils[6]. It's important to highlight that the procedure of obtaining paths in terms of water content (from TDRs) and matric suction (from tensiometers) is open to criticism.

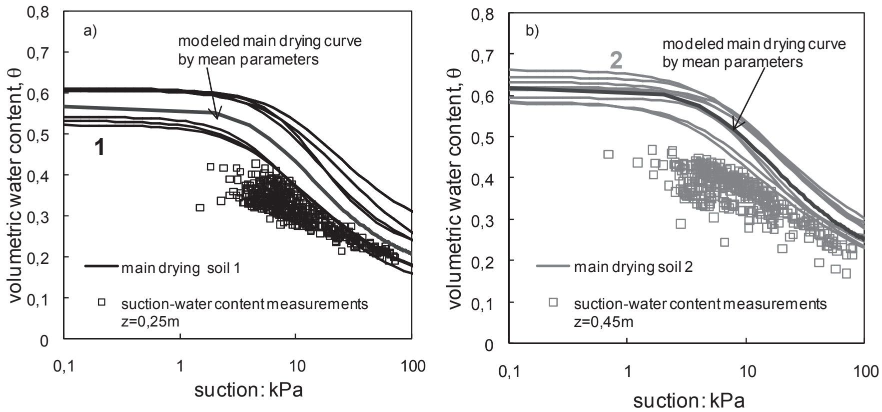

Fig. 1. Soil retention curve in main drying, carried out in laboratory tests, curve modelled by mean parameters and suction-water content measured in situ: soil 1(a); soil 2 (b)(modified from Papa et al.[6])

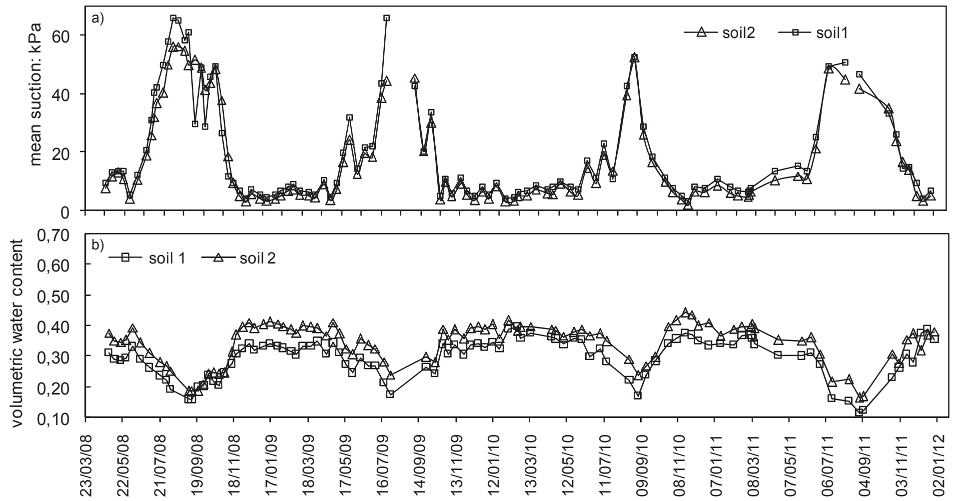

Fig. 2. Monitoring data: mean suction (a) and mean volumetric water content (b) in soil 1 and soil2 (modified from Papa et al.[6])

In fact (i) the ground conditions and hydrological pathways around the two instruments are not exactly the same; (ii) measurements of matric suction and volumetric water content involve different ‘samples of soil’ which are distributed differently around the sensor/cap; (iii) the two instruments respond at different time scales. By observing the Figure 1, the data collected in situ always lie below the main drying curves; the maximum value of volumetric water content is equal to 0.46 for suction of 2 kPa. Suction measured in situ is always lower than the residual one measured in the lab, in fact suction higher than 80 kPa cannot be measured because of tensiometer desaturation.

3.1. Drying and wetting path

The coupled measurements of matric suction and water content collected along one vertical profile in soil 1 and 2 over the years from 2008 to 2011 are reported in Figures 3a, b, c and 4a, b, c respectively. The data are subdivided into different arrays on a yearly basis, to distinguish each path. In addition the dates corresponding to numbered points shown by Figures 3 a, b, c and 4 a, b, c are specified in Table 3.

In situ data identify a narrow and open hysteresis loop, whose maximum suction value changes year by year. Regardless of the year in question, the path registered in situ over drier periods, from May to October, detects a series of scanning curves without exhibiting a significant hysteresis. These lines seem to be almost straight in the semi-logarithmic water retention plane. Indeed as first interpretation, all the measurements are interpolated by a logarithmic function with a coefficient of determination higher than 0.92. The mean slopes, β_{SC1}, of the logarithmic function interpolating the data over the drier periods are reported in Table 4 and in Figures 3a and 4a. These slopes result less than those calculated for the main dry retention curves, β_{MD}, in the range of suction from 5 to 80 kPa. In particular, the ratio β_{SC1}/β_{MD} is 0.5 for the soil layers 1 and 2. During the wet season, from November to April, the amplitude of suction and water content variations was smaller, thus, the corresponding paths are magnified in Figures 3a, b, c and 4 a, b, c in order to clearly identify each trail. In this period, measurements in both the soil layer 1 and 2 describe almost straight lines with no significant hysteresis; the suction value is always smaller than 5-6 kPa. When the value of the matric suction becomes smaller than the above threshold (s_{sc}) of 6 kPa, the straight lines interpolating data in the semi-logarithmic water retention plane has a significantly smaller slope, β_{SC2}, than that detected in dry period, β_{SC1} (see Table 4, Figures 3a and 4a). In conclusion, it seems that the paths traced by the measurements available in the semi-log water retention plane can be simply described by two straight lines. The mean values of s_{sc} separating the ranges of validity of the two different lines are about 5-6 kPa in soil layers 1 and 2; in any case s_{sc} is smaller than the air entry suction value (see Table 4, Figures 3a and 4a).

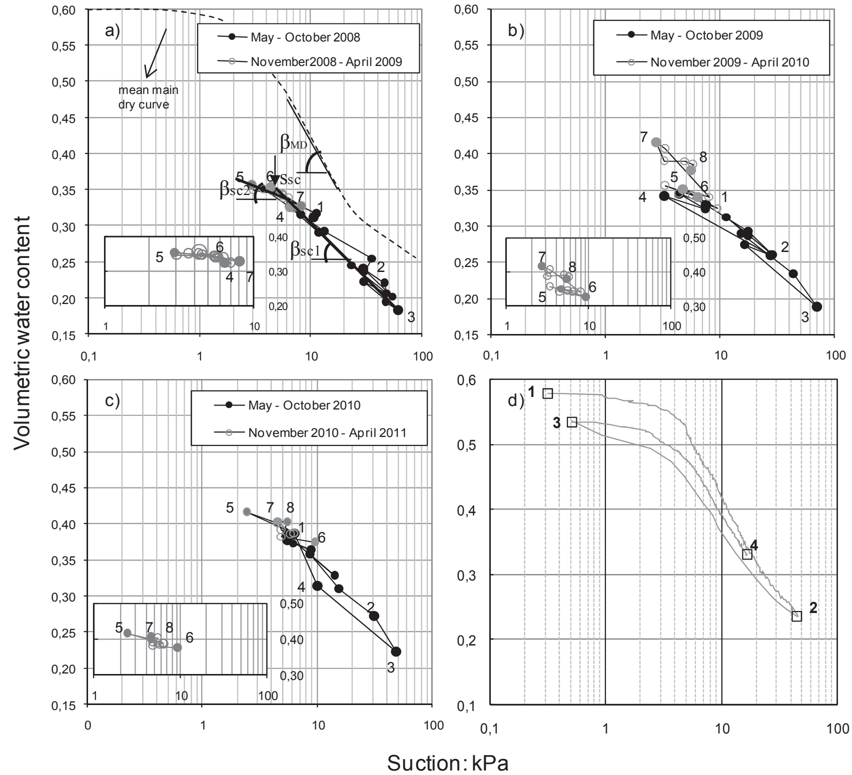

Fig. 3. Suction and water content measured in situ in a selected point of the soil 1 over the years: 2008-2009 (a), 2009-2010 (b), 2010-2011(c); drying and wetting cycles carried out in the laboratory on the undisturbed samples of soil 1 (d).

Table 3. Parameters of the logarithmic functions interpolating suction and water content measurements in the retention curve plane

			points	1	2	3	4	5	6	7	8	9	10
Soil 1	May 2008 April 2009	Fig. 3a	date	28/05	12/09	8/10	23/10	16/1	10/3	18/04	-	-	-
	May 2009 April 2010	Fig. 3b	date	9/05	30/05	30/07	24/10	31/12	12/1	21/02	25/04	-	-
	May 2010 April 2011	Fig. 3c	date	24/05	22/08	4/09	3/10	30/10	16/01	7/03	20/02	-	-
Soil 2	May 2008 April 2009	Fig. 3a	date	30/04	5/07	3/10	30/10	3/12	22/12	16/01	28/02	4/04	18/04
	May 2009 April 2010	Fig. 3b	date	29/04	20/05	30/07	24/10	11/11	27/01	7/03	-	-	-
	May 2010 February 2011	Fig. 3c	date	5/06	19/06	4/09	3/10	23/10	11/12	16/01	20/02	28/02	10/03

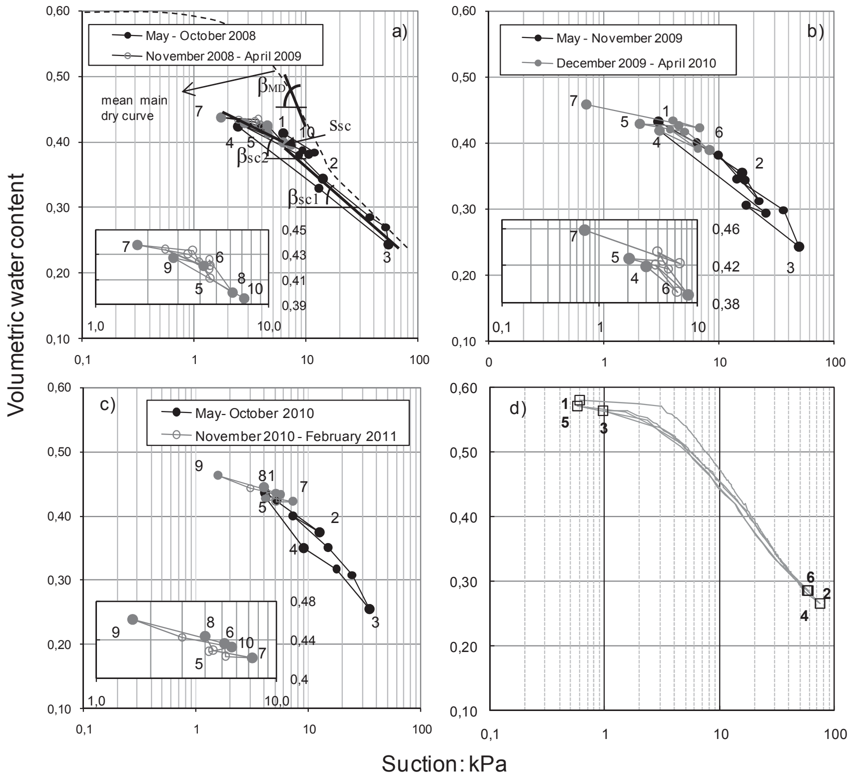

Fig. 4. Suction and water content measured in situ in a selected point of the soil 2 over the years: 2008-2009 (a), 2009-2010(b), 2010-2011(c); drying and wetting cycles carried out in the laboratory on the undisturbed sample of soil 2 (d).

Table 4. Parameters of the logarithmic functions interpolating suction and water content measurements in the retention curve plane

	β_{MD}	β_{SC1}	β_{SC2}	S_{sc} (kPa)
Soil 1	-0.10	- 0.053	-0.032	5.3
Soil 2	-0.10	-0.057	-0.032	5.6

3.2. Comparison between laboratory and field water retention curves

In Figures 3d and 4d, results of laboratory tests carried out on undisturbed samples of soil 1 and 2 are reported. Tests consist of the following phases: (i) main drying, path 1-2, obtained by imposing forced evaporation on an initially saturated soil core in ku-pF apparatus up to a suction value lower than 70 kPa; (ii) a wetting-drying cycle, path 2-3-4 (Fig. 3d) and from 2 to 6 (Fig. 4d), obtained by progressively wetting the same soil core (by sprinkling water from the top of soil core sealed on the other sides and by waiting for the suction equalization) and then drying it again. In this way it is attempted to reproduce in the laboratory the upper boundary condition occurring on site, i.e. the rainwater infiltration from the ground surface. In Table 5 experimental tests performed in the laboratory are summarized. These results point out that: (i) the hysteresis of the second cycle is lower than that of the first one; (ii) the suction corresponding to the knee on the wetting path is lower than that on the main drying curve (entry air suction).The observed paths in situ are in some sense qualitatively similar to the results of laboratory tests on soil 1 and 2 reported in Figures 3d and 4d. In fact, the hysteresis in the first drying/wetting cycle (i.e. path 1-2-3 in Fig. 3d) is significantly larger than that exhibited during the second wetting drying cycle (i.e. path 2-3-4 in Fig. 3d), which is similar to those recorded in situ. However, the range of water contents measured in situ (0.25-0.46) is rather small with respect to the range attained in the laboratory (0.20-0.60) in the same suction interval. The considerable difference between the water content measured close to the saturation (i.e. 3 kPa) along the laboratory wetting branch (i.e.θ = 0.48 see Fig. 3d) and on the path detected from field measurements (i.e. θ = 0.38 see Fig. 3c) is due to a larger amount of entrapped air in the second case. Although wetting both in the laboratory and in situ occurs from the top, due to water infiltrating, a higher fraction of air in situ has no possibility of escaping through the soil surface (as it is explained in the following).

As it is known in literature, the amount of air that remain trapped in the pores during the wetting process in the field depends on several variables, related to the porous medium features, such as pore distribution, and on the history of drying and wetting cycles[11,12]. Moreover, even if the tests in the laboratory were carried out on undisturbed samples, the instrument installation can provide the decrease of soil void ratio in situ and other kinds of disturbing phenomena. Then, generally in the comparison of the methods, the differences noted in the soil retention curve are accounted for: 1) the representativeness of the laboratory sample (sample size); 2) the space time resolution of field and laboratory measurements (measurements scale), which is manly related to probe technical characteristics; 3) the simplified assumptions of the applied theory to guess the data[11,13,14,15,16,17]. Moreover, even if the tests in the laboratory were carried out on the undisturbed samples, the instrument installation can provide the decrease of soil void ratio in situ and other kinds of disorders.

Finally, it is worth noting that, beyond the above similarity in quality, the scanning path described by in situ data differs quantitatively from that registered during laboratory tests. Hence the actual values of in situ water content and, in turn, of the unsaturated permeability, cannot be merely estimated on the basis of laboratory-determined water retention curves only. Moreover the minimum suction value collected in situ is about 2 kPa, therefore, the modelling of the retention curve from field measurements close to the saturation is still unknown. Indeed for high suction value the paths detected in situ seem to approach to the main drying curves that guess well the behaviour beyond 100 kPa.

Table 5. Phases of the laboratory tests

	porosity	*phase*	*final state*		*Points in Figs.3d and 4d*
			suction (kPa)	volumetric water content	
Soil 1	0.638	*saturation*	0.3	0.579	1
		main drying	44.7	0.236	1-2
		wetting	0.5	0.536	2-3
		drying	16.6	0.331	3-4
Soil 2	0.710	*saturation*	0.6	0.582	1
		main drying	74.4	0.266	1-2
		wetting	1.0	0.565	2-3
		drying	58.7	0.285	3-4
		wetting	0.6	0.572	4-5
		drying	58.1	0.285	5-6

4. Conclusions

The couple of suction-volumetric water content from in situ measurements always lay below the laboratory main drying curves[6], and detect a lots of drying-wetting cycles along the scanning curves, without exhibiting hysteresis (more or less). All the measurements are well interpolated by a logarithmic function with a two different slopes over dry and wet periods.

In this paper the paths from field measurements have been compared with results of laboratory. Some differences have been observed close to saturation: volumetric water content collected in situ are lower than that detected on the wetting branch of the cycle reproduced in the lab. Therefore, in the wetting phase, a higher fraction of air in situ has no possibility of escaping through the soil surface.

Hereafter the research in the next future will focus on these phenomena in order to comprehend the hydraulic behaviour of pyroclastic soils on wetting paths. At this aim the hydraulic hysteresis will be investigated on the undisturbed samples through laboratory tests by reproducing other cycles of drying and wetting. A possible formalization and quantification of the differences between laboratory results and field-measurements will be so as to achieve a mutually conversion of field and laboratory hydraulic properties. The research of a fair soil retention curve will be carried out and, in turn, a reliable hydraulic conductivity function will be searched, suitable to be used in slope stability analysis at prediction aim.

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