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Two applications of soil water balance in unsaturated pyroclastic soils

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Abstract

Evaluation of the monthly soil water balance (SWB) provides a tool for understanding and predicting the effects of seasonal and long-term changes in soil water conditions within many geotechnical problems. In this paper, two applications of the SWB approach in the pyroclastic partially saturated soils are shown. Firstly, rainfall, evapotranspiration, water storage measured or estimated at the experimental site in Monteforte Irpino (in Southern Italy) are shown. Secondly, rainfall, infiltration, actual evapotranspiration and water storage measured by data provided by a physical model are shown. In the both cases, data are reported over two years (2010-2012). The physical model was constituted by a wooden tank filled with reconstituted silty pyroclastic soil taken from experimental site at Monteforte Irpino (AV) and it was exposed to the atmosphere at a site in Napoli. Comparison between soil hydraulic behaviours observed is discussed and the scale effects on the estimation of the SWB are analysed, treating with practical implications. From the results, it is clear that similar trends in SWB and the same value of suction over wet season (10 kPa) can be observed at both the scales in spite of differences in meteorological conditions and hydraulic properties of soils exposed to atmosphere.

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Keywords: in situ monitoring; lysimeter; partial saturation; pyroclastic soil; soil water balance

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1. Introduction

Evaluation of soil water balance (SWB) provides a tool for understanding and predicting the effects of seasonal and interannual changes in soil water conditions within many geotechnical problems. In this paper, two applications of the SWB approach in the pyroclastic partially saturated soils are shown: they are devoted to investigate the hydraulic boundary conditions at soil surface and hydraulic soil behavior of a shallow soil cover to set up a sound numerical model for landslide prediction occurring in this soil. Firstly, rainfall, evapotranspiration and water storage estimated within the top soil (0.80 m thick) at the experimental site in Monteforte Irpino (in Southern Italy) over two years (2010-2012) are shown. In particular all the variables involved in the SWB were measured (rainfall) or calculated by using meteorological data, suction and water content measurements collected at site in the soil ashy cover [1,2,3]. Secondly rainfall, infiltration, actual evapotranspiration and water storage measured or estimated by data provided by a physical model are reported over the same time interval considered at the test site. The physical model was constituted by a wooden tank filled with reconstituted silty pyroclastic soil taken from experimental site at Monteforte Irpino (AV) and it was exposed to the atmosphere at a site in Napoli [4,5]. Since the SWB is affected by the hydraulic properties of the top soil, it is useful to underline the soils used to fill the physical model, hereafter named ashy soil B, was sampled at the test site at the depth of 3.30 m and it is constituted by higher amount of fine-grained soil respect than the top soils (see Fig. 1d).

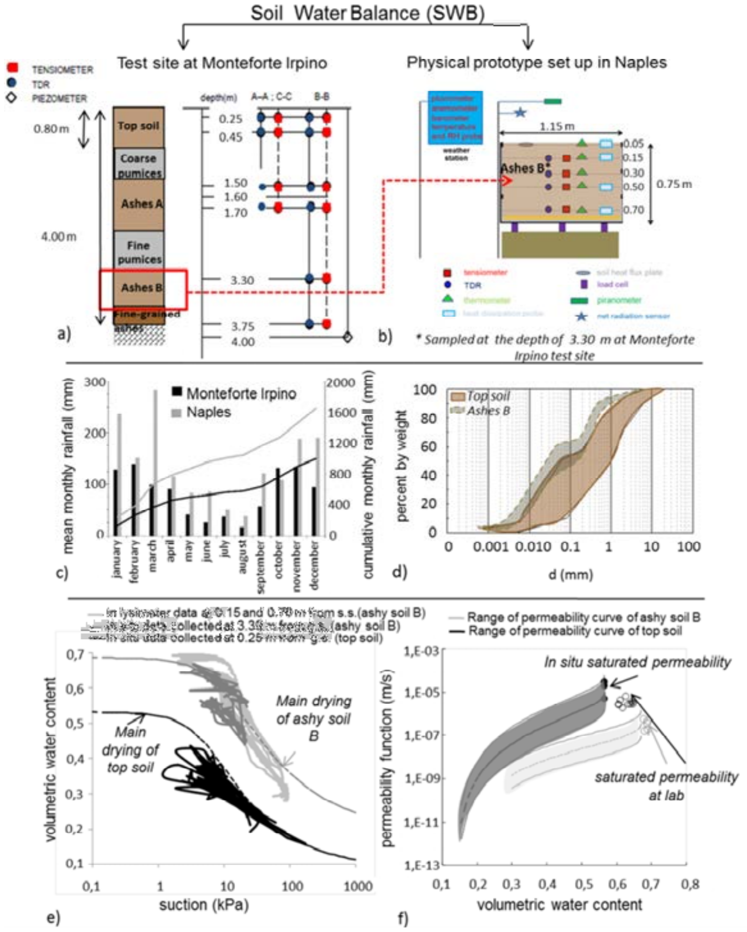

Fig. 1. (a) Simplified soil profile at test site with indication of instrumentation installed; (b) scheme of physical prototype and the instrumentation installed; (c) mean monthly and yearly rainfall at Naples and at Monteforte Irpino; (d) grain size distribution of top soil and ashy soil B recovered at test site; (e) data of suction and volumetric water content collected: in situ and in physical prototype; (f) range of permeability curves for top soil and ashy soil B determined at field, field saturated permeability of top soil, lab saturated permeability of top soil and of ashy soil B.

Nevertheless the hydraulic behavior of the soils recognized at the test site (both top soil and ashy soil B) is typical of pyroclastic soils belonged to Pizzo d'Alvano and Avella massif, macro-area F according to [6]. Comparison between soil hydraulic behavior observed at the test site and in the physical model is discussed and the scale effects on the estimation of the SWB are analyzed by taking into account the influence of different grain size distributions and hydraulic properties of the soils exposed to the atmosphere.

Nomenclature

AE	Actual evaporation	PE	Potential evaporation
AET	Actual evapotranspiration	PET	Potential evapotranspiration
D	Drainage	R	Runoff
P	Rainfall	Q_{TOP}	Water fluxes crossing the top soil

2. Test site

The test site at Monteforte Irpino, about 40 km East of Naples, was selected as being representative of other pyroclastic slopes in Campania subjected to rapid landslides (e.g. Pizzo D'Alvano, Monti di Avella and Monte Partenio). The stratigraphic profile consists of an unsaturated pyroclastic soil cover a few meters thick (3–5 m), deposited by a series of eruptions of Mt Somma–Vesuvius on top of the limestone bedrock (Fig. 1a). The test site was monitored from 2006 to 2012. The monitoring equipment consisted of: (i) 94 traditional vacuum tensiometers, i.e.: jet-fill tensiometers (SoilMoisture Equipment Corp.) and SMS (Soil Measurement system) tensiometer tubes (SDEC France); (ii) 40 TDR (Time Domain Reflectometry) probes with needles 15 cm long; (iii) 6 Casagrande piezometers; (iv) a weather station (Fig. 1a). However, the test site itself has been extensively described elsewhere; readers can refer to [1,2,3] for further detailed information about the instrumented area. About meteorological conditions of the area, mean daily and yearly rainfall have been obtained by averaging data over six years (Fig.1c), major amount of rainfall falls from October to April reaching also a total of 290 mm per month; the total amount over one year is about 1600 mm. Henceforth the properties of the top soil will be investigated since it affects the infiltration at the soil surface. The top soil is a silty sand, its porosity is 0.60 and its field hydraulic behavior displays an important hysteresis as it can be appreciate in Fig.1e where in situ data collected at the depth of 0.25 m (continuous black lines) are overlapped to the main drying curve determined at laboratory (dotted black line). In field saturated conductivity is about $1.0 \cdot 10^{-5}$ m/s, one order more than that detected at laboratory (Fig. 1f). In Figure 2a,b daily rainfall and evapotranspiration from September 2010 to August 2012 are shown. The reference and the crop evapotranspiration, PET and AET, have been estimated by FAO-Penman Monteith equation [7] assuming grass as vegetation cover. During autumn - winter, rainfall prevails over the evapotranspiration that is about 0.4 mm/day and the soil is constantly able to sustain the atmospheric demand (atmospheric-limited phase). During spring, the evapotranspiration increases under the effect of higher vegetation activity reaching averagely 3 mm/day, while in summer it is equal to 1-1.5 mm/day because of reduced availability of water at soil surface (soil-limited phase). In figures 2c, d water storage estimated by using the volumetric water content measurements into top soil and suction data collected at the depth of 0.25 m every ten days are reported. By observing Figures. 2c,d it is possible to identify different periods: *i.* drier and *ii.* Wetter periods. During the dryer periods (t_A–t_B, t_C–t_D, t_E–t_F) the soil transfers water to the atmosphere from May/June to August but it retrieves all of water during autumn from September to November. During these months the hydraulic phenomena are transient and strong hydraulic gradients establishes at the top soil so that all the rainfall can be assumed infiltrating; During the wetter periods (t_B–t_C, t_D–t_E)the rainfall divides into infiltration and runoff, hydraulic permeability value is close to the saturated one and low hydraulic head gradients establish. From December to April/May a nearly steady state condition occurs, in fact the water storage is null and suction oscillates around the air entry value, 10 kPa. This condition represents a predisposing factor for debris flow and flowslide initiation. In Table 1 the monthly amount of rainfall, P, water flux crossing the top soil, Q_{top} and the reference and crop evapotranspiration, PET and AET are shown over the two investigated years. During autumn the infiltration ranges between 70-90% of rainfall, thus almost all the rainfall contributes to the increase of water into top soil. During winter, from December to April, the infiltration is about 45-60 % of rainfall, much smaller than in autumn, and the runoff increases a lot; the hydraulic conductivity is the maximum registered over the year and probably the lower surface hydraulic gradients highly affect the infiltration rates despite of higher conductivity values.

3. Physical prototype: lysimeter

The structure of the physical model [8,9] is constituted by a wooden tank (1.15 x 1.15 x 0.75 m), made of 3 cm thick boards, in which a pyroclastic soil layer of 1 m^3 is placed (Fig. 1b). The pyroclastic soil is the non-plastic silty sand taken from the Monteforte Irpino site at the depth of 3.30 from ground surface [2]. The grain-size distribution of this silty sand is very similar to that of other air-fall ashes of the macro-area F [6], including that of Nocera Inferiore which was involved in the 2005 flowslide (Fig. 1d). The physical model has been operating since May 2010; the soil surface is remained bare during the period observed here. At the boundaries, different conditions act: the lateral faces are impervious; at the uppermost surface, water flows are generated by interaction between atmospheric conditions and topsoil status; inward flows are induced by precipitation, while outward flows by evaporation phenomena. At the bottom, the layer lies on a geotextile interposed between the layer and the holed tank base; from a hydraulic viewpoint, it behaves as a seepage surface, that is, as an impervious surface while negative pore water pressures act near the surface, and as a free draining surface otherwise; at this regard, experimental results can be retrieved in [10]. A well-equipped weather station located in close proximity of physical model provides observations for: precipitation, wind velocity and direction, air pressure, relative humidity, solar and net radiation, soil heat flux; furthermore, suction, water content and temperature within the soil are monitored at four depths (15, 30, 50, 70 cm), respectively through jet-fill, TDR probes and thermistors (temperature is also monitored at 5 cm) (Fig. 1b). About the meteorological conditions, mean daily and yearly rainfall have been obtained by averaging data over six years (Fig. 1c), the large part of rainfall falls from October to April reaching a total of 120 mm per month, the total yearly amount is about 1000 mm. Regarding the hydraulic properties of ashy soil B, main drying path determined at laboratory by evaporation tests is reported with the paths of suction and water content measured at the depth of 0.15 m within the lysimeter (grey line) and at the depth of 3.30 at site (light grey line) in Figure 1e. The paths detected at physical prototype are very close to that at site by indicating the physical model could be used to investigate the hydraulic soil behavior. In Figure 1f the upper and lower limits of field permeability curves are reported with the saturated hydraulic conductivity determined at lab [3]. Beyond the observed precipitation, potential evaporation, PE, is estimated through the FAO56-Penman Monteith approach (Allen et al., 1998) by measuring directly air temperature, relative humidity, wind velocity and net radiation; concerning actual fluxes regulated not only by weather forcing but also by soil wetness conditions, infiltration rate (I=P-R, where R is surface runoff) and actual evaporation (AE) can be derived. The actual fluxes are quantified by measuring the current amount of water stored by the layer (the so-called water storage, WS) through three load cells. If no precipitation P and drainage D take place, the mass balance relates the changes in water stored ΔWS directly to AE ($\Delta WS = - AE$). During precipitation P, the actual evaporation AE can be assumed equal to the potential one and, in this way, if no drainage D takes place, ΔWS corresponds to the infiltration rate ($P\text{-}R = \Delta WS$). Figures 2e-h show the evolution of both surface inward (Fig.2e) and outward (Fig.2f) flows, of water storage (Fig. 2g) and suction measurements at the depth of 0.15 m (Fig.2h) over the two hydrological years 2010-2012. All data are reported at daily resolution. Inward flows are plotted as precipitation (P), infiltration (P-R) when drainage does not occur and infiltration (P-R) minus deep drainage (D) when drainage occurs; outward flows are plotted as potential evaporation (PE) and actual evaporation (AE). Concerning the water storage, initial water storage is set equal to 0 mm at the beginning of September 2010. Based on weather conditions, it is possible recognize homogeneous drier and wetter periods [4] (Fig. 2g): *i.* drier periods (t_A–t_B, t_C–t_D, t_E–t_F) during which monthly evapotranspiration prevails over rainfall; *ii.* wetter periods (t_B–t_C, t_D–t_E) during which, steady hydraulic conditions establish, in fact suction is almost constant close to the value of 10 kPa and the water storage is null [11,12]. Indeed different infiltration/evaporation patterns can be retrieved depending on potential flows and topsoil conditions (Table 2). From October to November the rainfall contributes to increase the soil water storage because the soil is still dry and the potential infiltration is therefore high. In subsequent months, instead, it is largely lost in run-off due to the wetter state of the sample and the low head gradients in the subsoil, related to low suction values in the topsoil. As expected, dry periods show strong reductions of water storage. During spring, in particular, the layer is able to sustain the evaporative demand due to antecedent wet conditions. Progressively with summer approaching, soil dries, precipitation values reduce (under higher PE values) and then actual evaporation becomes substantially lower than atmospheric demand.

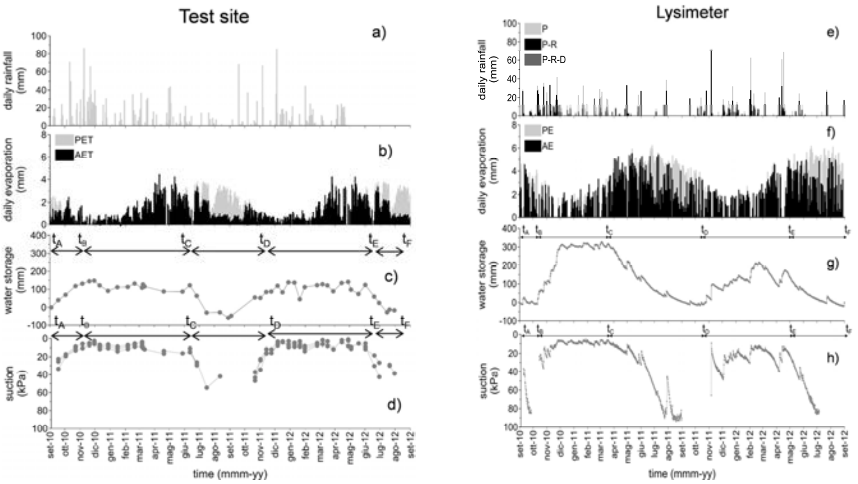

Fig. 2. Monitoring data at the test site from September 2010 to August 2012: (a) daily rainfall; (b) daily reference and crop evapotranspiration (PET, AET); (c) water storage estimated from water content measurements; (d) suction measured at the depth of 0.25 m (top soil). Monitoring data in the lysimeter: (e) daily rainfall and daily infiltration; (f) potential and actual evaporation; (g) measurements of water storage; (h) suction measured at the depth of 0.15 m.

4. Discussion and conclusion

Comparison between the hydraulic behavior and the soil-atmosphere interaction of two pyroclastic soil covers at different scales is discussed here. In both the cases, the cover exposed to the atmosphere is constituted by pyroclastic soils belonged to Somma–Vesuvius system, however the top soil at the test site is characterized by: (i) a smaller fraction of fine grained particles, (ii) lower porosity and (iii) higher saturated hydraulic permeability than the ashy soil B (Fig. 1d-f). Indeed the mean yearly rainfall occurring in Monteforte Irpino is 50% higher than that in Naples, due to major amount of rainfall concentrated from December to April. In spite of these differences some similarities in the SWB trend can be observed: in both the analyzed cases the dry periods last from May to August/September, however the decrease in water content, thus the increase in suction, is higher at physical model than that at site that is evidently due to the larger evapotranspiration fluxes registered in Naples (also under potential Urban Heat Island effect) than that in Monteforte Irpino. At the end of summer, from September, at both the scales the soil stores a lot of water and about all the amount of the rainfall infiltrates; in particular the soil retrieves the same water content that lost in summer. During winter, from December to April is the period most critical for slope stability; at either site and physical prototype, the infiltration ranges between 40-60%, the steady conditions establishes with a value of suction close to 10 kPa and the water storage variations are small. In spite of different grain size distributions and hydraulic properties, the hydraulic conductivity corresponding to the range of volumetric water content establishing in winter (0.32-0.37 at site [13] and 0.60-0.65 in the physical model) is the same at both the scale, approximately 10^{-7} m/s (see Fig. 1e). Therefore, over monthly time interval, the behavior in winter at both the scales is quite similar, the hydraulic conditions predisposing to the slope failure are well-reproduced by the physical model but the response to single rainfall events could be different than that at site due to difference in saturated hydraulic conductivity of the top soil. In light of this considerations, the differences observed are shortly due to the different scale, in fact field paths of suction and water content collected in ashy soil B are located very close to those registered at physical prototype and may be considered as part of similar hysteresis loops which differ according to wetting procedure and history of wetting and drying paths [14]. Therefore the hydraulic behavior of pyroclastic soil is well-caught by a physical prototype as proved in another paper presented here. Summing up, the results shown here point out: (i) same trend in SWB can be observed at both the scales even if the hydraulic properties of top soil and meteorological conditions are different. Moreover during winter, even if the rainfall at site in December, January and March is twice that in Naples, the monthly infiltration rate at both the scales is mainly affected by the same hydraulic conductivity corresponding to mean suction values equal to 10 kPa registered at either field and physical prototype. Therefore the different scales do not affect the seasonal trend in SWB; (ii) the hydraulic behaviour of pyroclastic soils is well-reproduced by a physical prototype as it is proved by the comparison between the paths of suction and volumetric water content registered in the ashy soil B at site and those collected in the lysimeter.

Table 1. Monthly data from Sep. 2010 to Aug. 2011 (first year) and from Sep. 2011 to Aug. 2012 (second year).

		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
First Year	P (mm)	-	180	441	130	78.4	84.1	209.5	83	100.4	47.3	48.4	-
	Q_{TOP} (mm)	-	150	273	50	50	80	90	30	-20	-38	-40	-
	Q_{TOP}/P	-	84%	62%	40%	64%	95%	43%	37%	-	-	-	-
	PET(mm)	-	27	9.1	10.7	11	23	35	62	65	61	72	-
	AET(mm)	-	25	8.4	10.3	12	25	35	72	70	48	41	-
	AET/PET	-	94%	93%	100%	-	-	100%	-	-	79%	57%	-
Second Year	P(mm)	-	40	85	195	51.6	163.6	33.6	188.2	-	-	-	-
	Q_{TOP}(mm)	-	35	70	70	-	70	-	80	-	-	-	-
	Q_{TOP}/P	-	85%	83%	36%	-	43%	-	44%	-	-	-	-
	PET(mm)	-	34	20	10	14	14	46	40	63	64	81	-
	AET(mm)	-	28	19	9.3	14	16	54	47	70	55	52	-
	AET/PET	-	100%	100%	100%	100%	-	-	-	-	86%	65%	-

Table 2. Monthly data from Sep. 2010 to Aug. 2011 (first year) and from Sep. 2011 to Aug. 2012 (second year).

		Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
First Year	P(mm)	56.2	139.4	250.8	74	123	65.8	153.6	54.6	40.2	27.2	57.2	0
	I(mm)	42.4	115.6	179.6	28.4	32.7	40.9	42.1	49.1	15.5	26.8	42.5	0
	I/P	75%	83%	72%	38%	27%	62%	27%	90%	39%	99%	74%	0%
	PE(mm)	72.3	49.7	15.4	23.1	30	36.4	58.6	95	108.8	134.1	120.5	113.9
	AE(mm)	46.6	27.5	11.3	18.6	19.5	31.7	48	87.7	91.6	75.8	60.5	46.1
	AE/PE	64%	55%	74%	81%	65%	87%	82%	92%	84%	57%	50%	40%
Second Year	P(mm)	20.6	71.2	79.6	139.8	41.4	172.8	28.2	215.8	53	1.6	44.4	17.2
	I(mm)	19	53.7	75	77	25	107.5	12.8	97.2	26.7	0.6	37.3	17.2
	I/P	92%	75%	94%	55%	61%	62%	46%	45%	50%	39%	84%	100%
	PE (mm)	88	55	46.6	22	42.7	24.9	87.2	62.4	113.3	110.5	105.1	92.2
	AE (mm)	36.1	30.5	34.2	18.2	34.8	19.9	78	44.2	85.6	57.7	49.3	44
	PE/AE	41%	55%	73%	83%	82%	80%	89%	71%	76%	52%	47%	48%

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