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AMRA: Laboratory experiments on the response of model slopes subjected to rainfall

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AMRA:
Laboratory equipment

Summary

The report focuses on the results of laboratory tests aimed to investigate the response to artificial rainfall of model slopes constituted by granular soils.
The goal of the investigation is the assessment of the behaviour of representative slopes of the Campania Region covered by pyroclastic soils.

Keywords: slope stability, physical model, rainfall, infiltration, prediction of slope behaviour

JEL Classification:

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1. Foreword

Rainfall is the main cause of landslides. Therefore, a short-term prediction of precipitations can be a powerful tool to predict their consequences on land stability and to manage at the best the hydrogeological risk. However, the setting up mathematical models capable to reliably predict the probability of occurrence of rainfall-induced landslides is a challenging task: in fact, landslides triggering is affected by a number of variables, such as rainfall spatial and temporal variability, mechanical and hydraulic soil properties, slope morphology, vegetation coverage; furthermore, several variables should be monitored in order to establish reliable initial conditions, such as soil water content, soil suction, rainfall intensity.
In order to check and calibrate numerical models, the slope behaviour must be clearly understood. Field monitoring provides fundamental and useful data. Unfortunately, monitoring is very useful only in fine-grained soils whose response to infiltration can be investigated up to and also after failure. In contrast, the failure of granular soils is so sudden and fast that in situ monitoring cannot help very much since it may provide useful data only well before failure. For this reason, monitoring of small and medium scale well instrumented prototypes is becoming a fundamental investigation tool.
The report focuses on the results of some laboratory experiments carried out by a heavily instrumented flume. The goal of the investigation is the assessment of the behaviour of representative slopes located in that part of the Campania Region which is covered by unsaturated pyroclastic soils posing the major slope stability problems.

2. Water retention curve of pyroclastic soils

The features of seepage in unsaturated soils are strongly related to the amount of voids filled by water, which depend on the degree of saturation, S_r (or on the volumetric soil water content, θ_w) which, in turn, is a function of the matric suction, u_a-u_w, through a highly non-linear relationship called Soil Water Retention Curve (SWRC). This relationship depends on the porosity of soil, and exhibits a hysteresis which is a function of the applied stress-path. As a consequence, the dependence of the matric suction on the degree of saturation during infiltration (i.e. when suction decreases) can strongly differ from that acting during evaporation (i.e. when suction increases). Therefore, in order to correctly simulate the seepage processes in pyroclastic soils, the SWRC has to be determined. To this aim, at the Geotechnical Laboratory of the Seconda Università di Napoli, one of the A.M.R.A. partners, conventional experiments on reconstituted specimens of the Cervinara volcanic ash are being performed through both infiltration and evaporation tests.
The specimens are reconstituted within PVC graduate recipients at a porosity close to the field value (n=70%) and at a water content equal to 0.3, by layering a given amount of soil and compacting it every centimetre. After preparation the specimen is sealed to avoid evaporation until hydraulic equilibrium is reached. As suction equalizes, a minitensiometer is installed into the soil and the test starts by imposing by steps suction increase (evaporation test) or suction decrease (infiltration test). At the end of every step, a new equilibrium condition is reached, and measured suction and water content (which is obtained by weighting the specimen) can be assumed as representative of the SWRC.

Figure 1 shows experimental points: the red triangles indicate data obtained from evaporation test, while the white triangles data from infiltration tests. No significant difference can be recognized as a function of the imposed path of water content change, suggesting that such a volcanic ash doesn't exhibit a relevant hydraulic hysteresis. The water retention curve (SWRC) is typical of coarse soils, being characterized by a low air-entry value, a small residual water content and a steep slope in the transition zone. Such data are in a good agreement with the expression proposed by van Genuchten (1980) for θ_r=0.3; θ_s=0.7; m=0.2; n=7; α=1.7.

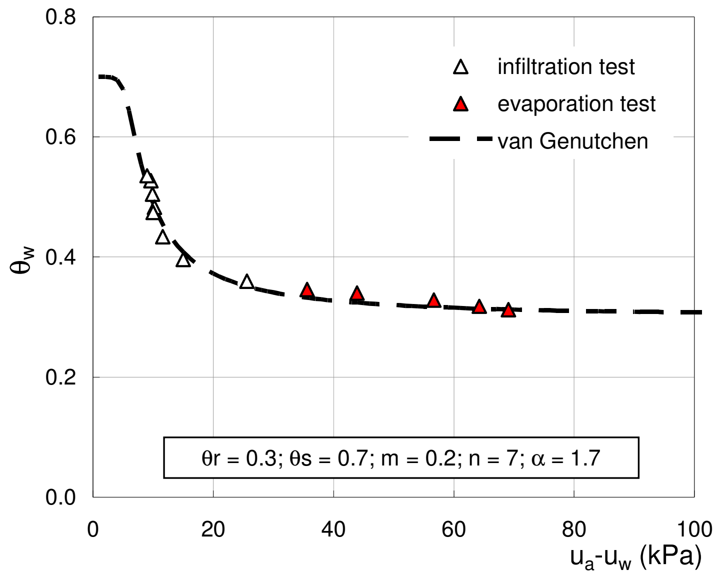

Figure 1. Soil Water Retention Curve of Cervinara volcanic ash from conventional tests.

The unsaturated coefficient of permeability has been obtained from the interpretation of the transient phase of suction equalization (Kunze et al., 1965) in SCTX (suction controlled triaxial) tests: the obtained results are reported in figure 2. In the same figure are plotted the permeability values estimated through the expression proposed by Brooks and Corey (1964) and the permeability function obtained by Gardner's equation (1958). In both cases in the range of suction between 0 and 80 kPa, permeability decreases by about two orders of magnitude as suction increases (Picarelli et al., 2006).

3. Results of laboratory investigation on infiltration process

In the following are presented the results of infiltration experiments on instrumented small scale model slopes. The tests have been conducted on air-fall unsaturated pyroclastic soils, taken at the sites of Cervinara and Monteforte Irpino, North-East of Naples.

3.1 Infiltration tests on uniform small-scale slope

A first series of infiltration tests on artificial slopes subjected to uniform rainfall has been performed in the flume apparatus described in the Technical Report titled "Laboratory equipment". The aim of this series of experiments is to reproduce the simple case of homogeneous infinite slope in order to assess the role of single factors on the infiltration process and on the mechanics of rupture. The scheme of infinite slope (thickness/length ratio smaller than 1/10) has been investigated, because of the typical morphological features in the concerned area (Technical Report "Messa a punto di modelli geotecnici per la simulazione degli effetti al suolo delle precipitazioni").

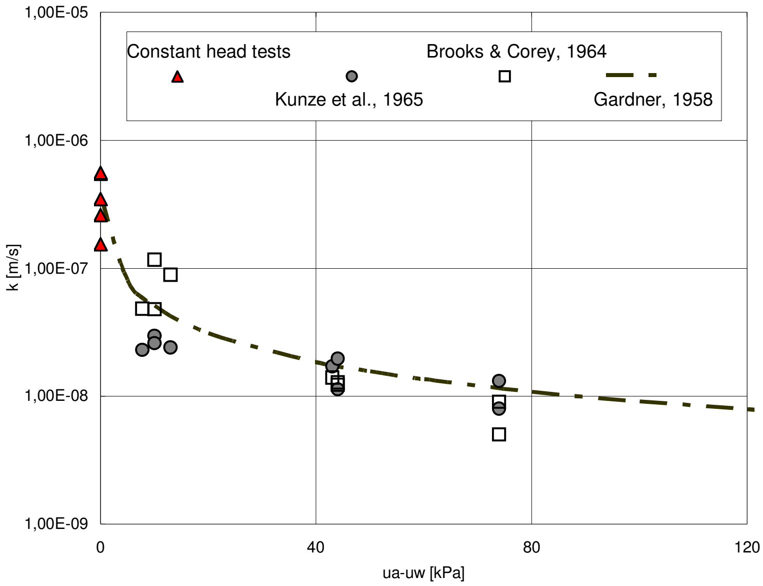

Figure 2. Unsaturated permeability on Cervinara volcanic ashes (Picarelli et al., 2006).

Significant data concerning each test are reported in Table 1. The experiments have been carried out on 10cm thick and 1.10m long 40° slopes reconstituted at a porosity very close to in situ value (n=76%) and at smaller values of porosity (n=68-72% tests D7 and D8) in order to assess its influence on slope behaviour.
At the bottom of the flume, an impervious boundary has been imposed, in order to investigate on the influence of a impervious layer. As a matter of fact, in both sites a weathered finer and slightly plastic ash layer is present just at the top of the bedrock, which consists of a fractured limestone (Olivares and Picarelli, 2003). At the toe of the slope a geotextile drain has been placed in order to let free water outflow when soil approaches saturation.
Artificial uniform rainfall is produced through spray nozzles located 0.4m above the ground surface.
A 10cm long TDR probe has been installed normally to the ground surface to monitor any change in the volumetric water content along the entire thickness of the soil layer (Greco, 2006). Soil suction was measured with minitensiometers installed at various depths and locations within the slope. In particular, in all the tests, two of them have been placed nearby the TDR probe, respectively 1.5cm and 5cm above the bottom. At the base of the slope, pore pressure transducers have been located to measure positive pore pressures due to formation of water ponding and laser displacement sensors and digital video-cameras have been used to monitor displacements of the ground surface in the direction of the slope and normally to it. A sketch of the instrumented flume is reported in Figure 3.

Table 1. Test conditions

Test	D4	D7	D8	D9_1	D9_2	D10_1	D10_2
Investigated soil	Cervinara ash	Monteforte Irpino ash					
Rainfall intensity (mm/h)	56	54	55	50	55	50	45
Duration of test (min)	29	95	76	23	58	27	58
Specific weigh (kN/m^3)	26.0	26.2					
Initial suction (kPa)	42÷45	65÷81	29÷34	33÷45	14÷19	27÷30	15÷17
Initial water content w_0	0.40	0.39	0.50	0.47	-	0.43	-
Initial porosity n_0	0.76	0.69	0.72	0.76	-	0.76	-

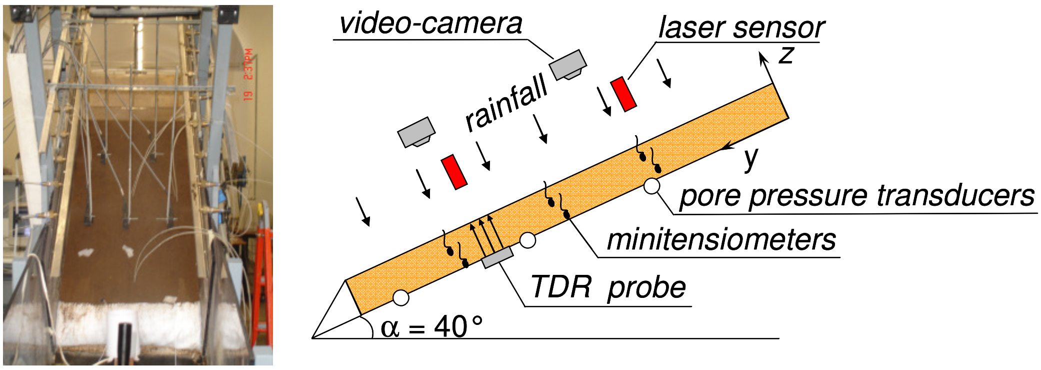

Figure 3. The instrumented flume

The infiltration tests D4, D7, D8 lasted until slope failure. Tests D9 and D10 were performed in two stages: during the first one, a rainfall intensity of 50mm/h was applied, followed by a dry period of few days during which the effects of evaporation were monitored; during the second stage uniform rainfalls respectively of 55mm/h and 45mm/h were applied until slope failure.

In all cases, although the rainfall intensity was much higher than the saturated hydraulic conductivity of soil, no significant surface runoff was observed. This demonstrates that the potential infiltration of soil never has been exceeded.

The courses of both matric suction and settlement of the ground surface during each experiment are reported in Figures 4, 5, 6, 7, 8, 9 and 10.

During infiltration a marked suction decrease occurs starting from the ground surface towards the base of the layer as shown by comparison of readings by shallow and deep tensiometers. This suggests that a wet front progressively moves downwards. The progressive saturation of soil is confirmed by the increase in volumetric water content (Fig.12). In all cases, suction growth was characterized by a steep front, accounting for most of the suction change observed during the entire experiment, followed by a long further slow increase until slope failure.

Finally, laser sensors show that saturation is accompanied by a significant volumetric strain which can attain values in the order of 7% in soils laid down at high initial porosity (tests D4 – D9 – D10). On the contrary, volumetric deformation during saturation is practically negligible in slopes having a lower initial porosity (tests D7 and D8).
Looking at the results of tests D9-1 and D10-1 (Fig. 7 and Fig. 9), it has to be remarked that the advance of the wet front continues even during the dry phase: in fact, as rain stops, the tensiometers located in the middle of the slope record a small increase in suction, while the deepest ones display a decrease in suction. In the test D10-1 (Fig. 9) a uniform distribution of suction and of water content is reached only 20 minutes after the stop of the rainfall. This suggests that a critical slope stability condition could be attained even after the end of rainfall.

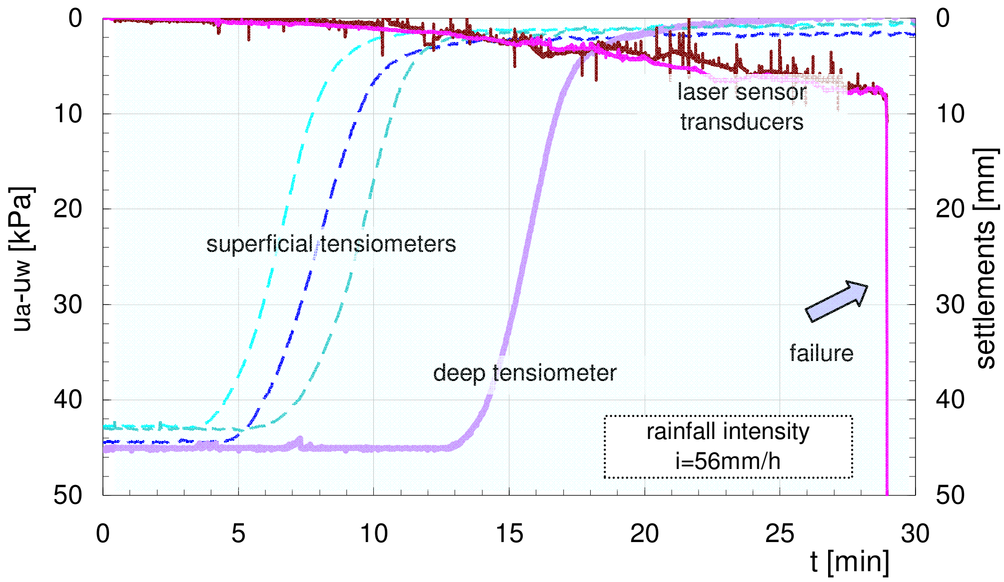

Figure 4. Suction and settlement of the ground surface against time during test D4

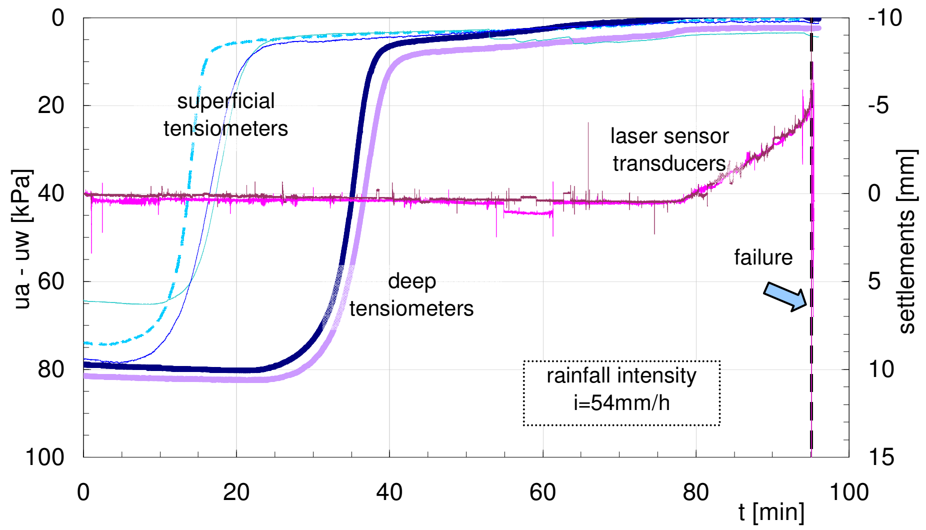

Figure 5. Suction and settlement of the ground surface against time during test D7

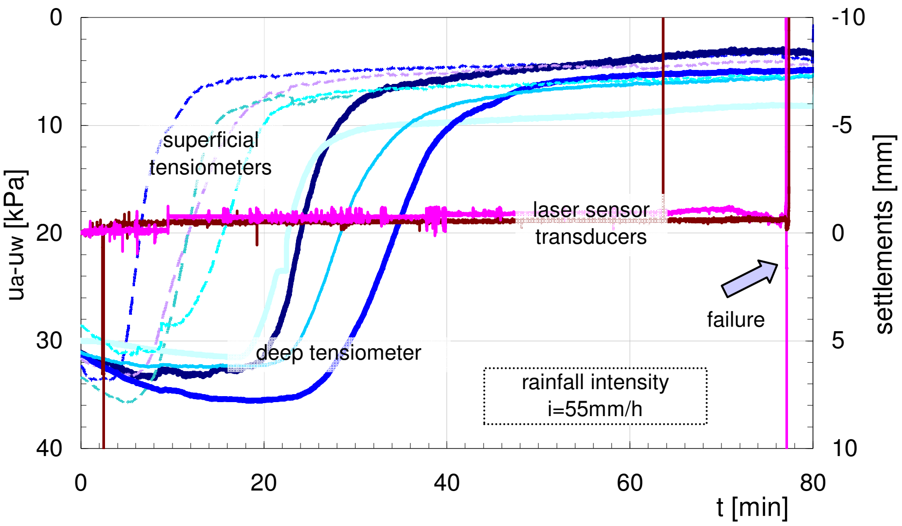

Figure 6. Suction and settlement of the ground surface against time during test D8

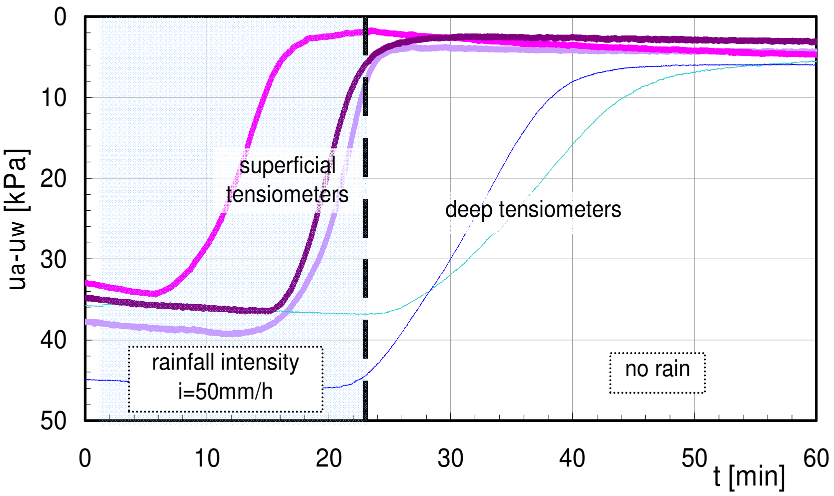

Figure 7. Suction against time during test D9_1

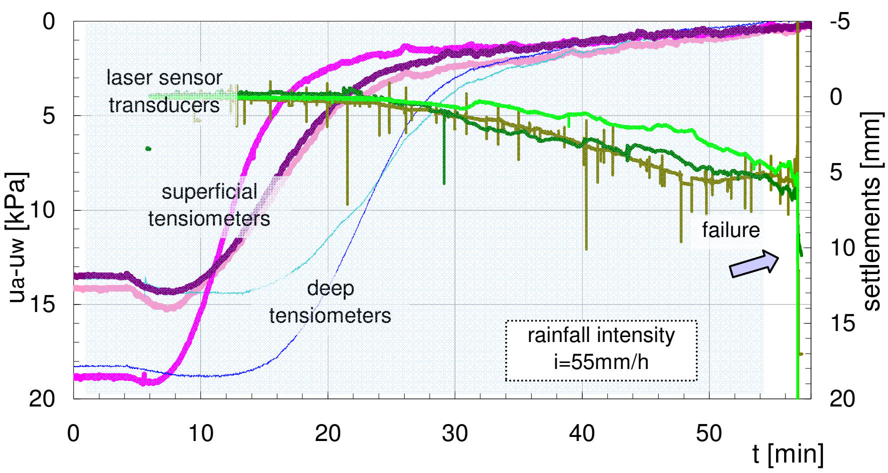

Figure 8. Suction against time during test D9_2

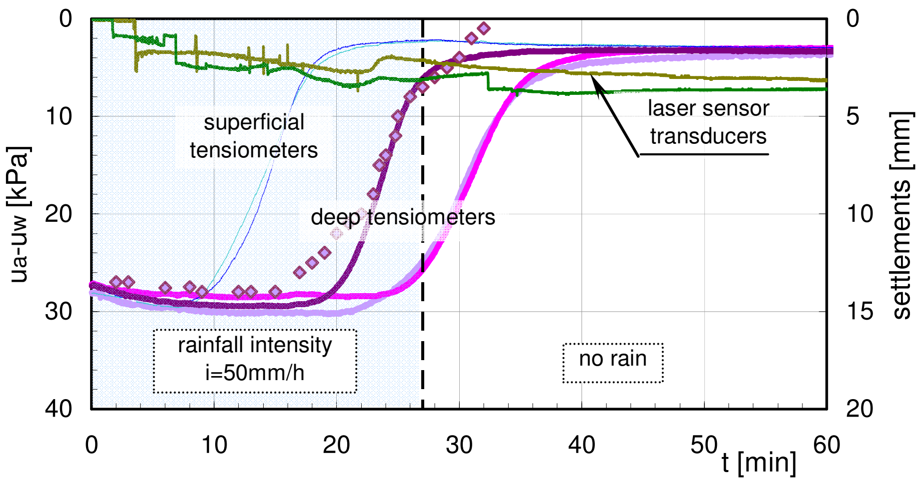

Figure 9. Suction and settlement of the ground surface against time during test D10_1

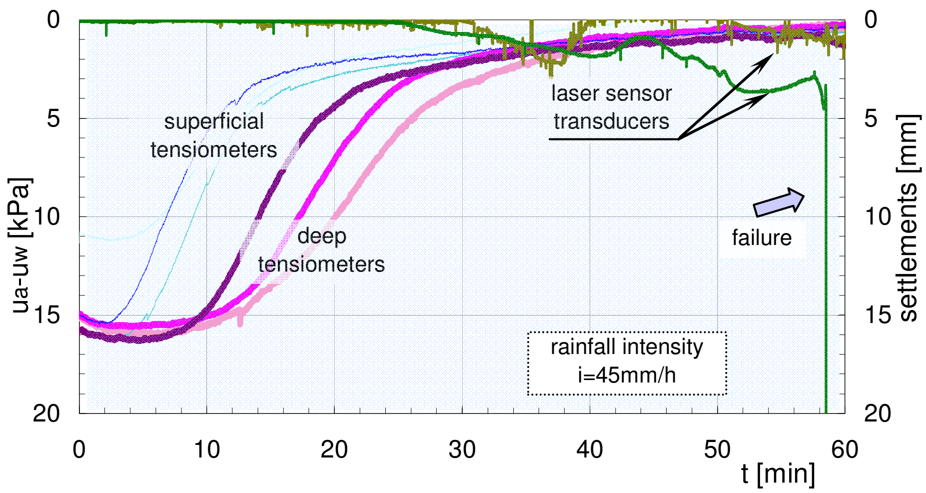

Figure 10. Suction and settlement of the ground surface against time during test D10_2

Such tests on uniform slopes show that rainfall intensity plays a fundamental role. In fact, a comparison of the results of tests D4 and D10_2 demonstrates that, despite the greater initial water content of soil, in test D10_2, a lower rainfall intensity (45mm/h) requires a double time (58min in test D10_2, 29min in test D4) to trigger failure. Moreover, also soil porosity seems to significantly affect infiltration. Results of tests D7, D8 and D9_2 show that, under the same rainfall intensity, slopes with a lower initial porosity require a longer rainfall to fail.

Porosity also influences the mode of failure since different failure mechanisms are displayed by slopes reconstituted at different initial porosity. In fact, in all tests performed on loose soil (porosity higher than 70%), failure involved the whole layer which displayed a clear flow-like evolution; in contrast, in tests performed on dense soil, failure involved only the uppermost part of the slope and an evolution in flowslide in not so evident.

Finally, it is worth to note that, during the final stage of the test prior to failure, the pore pressure transducers start to record positive values which progressively increase as a consequence of formation of water ponding at the impervious bottom of the flume. Figure

11 shows the pore pressure increases at the base of the model slope during tests D9-2 and D10-2.

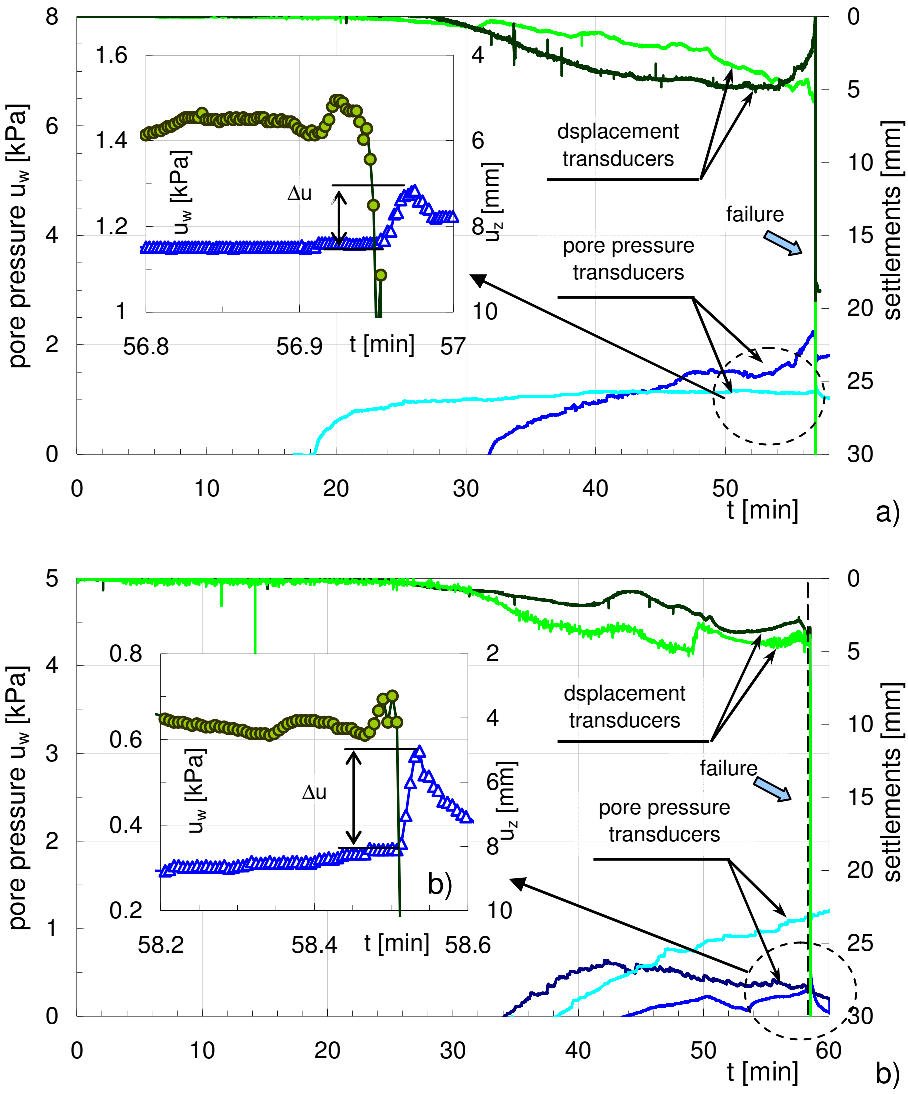

Figure 11. Pore pressures at the base of model slope during: a) test D9-2; b) test D10-2

Useful information is also provided by records with TDR. Figure 12 show some of the volumetric water content θ_w profiles retrieved by TDR readings during the experiment D4 on Cervinara ash. Similar results have been obtained on Monteforte Irpino ash. During all tests, the shape of the water content profiles is consistent with suction profiles: they are all characterised by steep gradients during infiltration. This behaviour is typical of coarse soils whose hydraulic conductivity suddenly reduces for low water contents. Afterwards, also the deepest part of the soil deposit starts wetting and the profiles tend to become softer.
Coupling suction with the correspondent volumetric water content at the same depth, the water retention curves (WRC) of tested soils have obtained. In Figure 13 the curve obtained from test D4 on Cervinara ash is compared to that obtained by conventional laboratory techniques (see section 1). The WRC curve of the Monteforte Irpino ash is

shown in Figure 14 where is reported the same curve determined by long-term conventional tests (Nicotera and Papa, 2007).

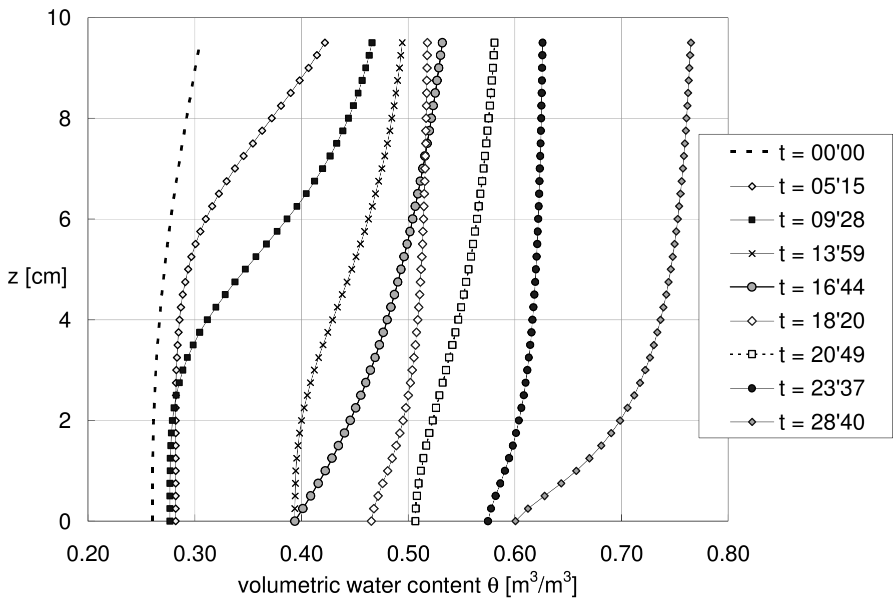

Figure 12. Volumetric water content profiles at different times during test D4 (Damiano et al., 2008)

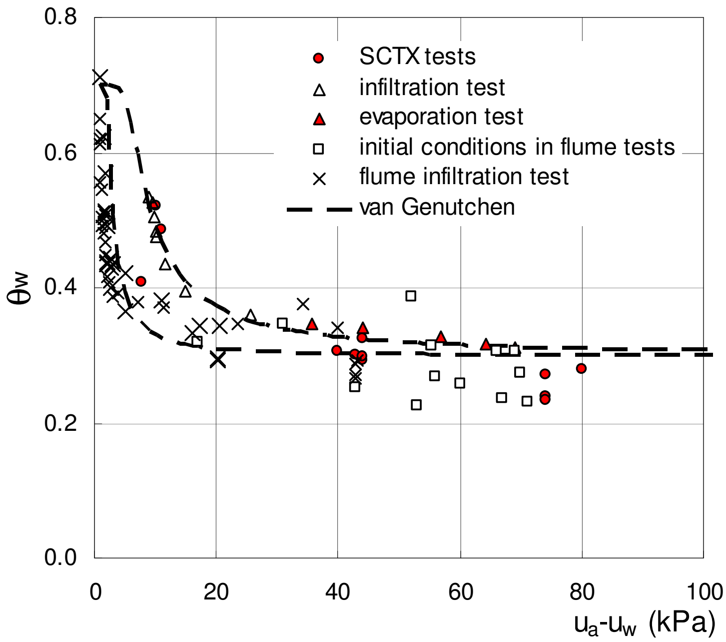

Figure 13. Cervinara volcanic ash: Water Retention Curves obtained from infiltration tests and conventional long-term laboratory tests (Olivares and Tommasi, 2008).

Matric suction observed during infiltration experiments was, nearly in all cases, significantly smaller than what could be expected from WRC determined in laboratory, especially when saturation is approaching, being about 5kPa smaller than what could be expected. As a consequence, the contribution of suction to slope stability appears smaller than expected. Since the infiltration rate and the boundary conditions adopted during the experiments correspond to real slope conditions, this result should be confirmed by field observations.

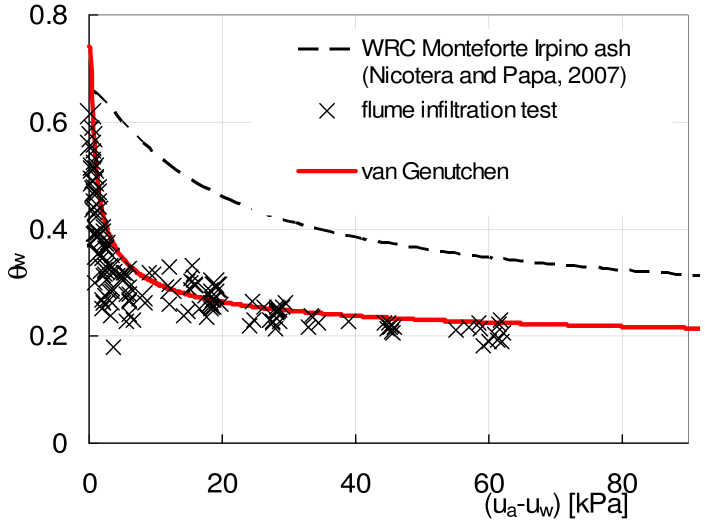

Figure 14. Monteforte Irpino ash: Water Retention Curve obtained from infiltration tests and conventional long-term laboratory tests (Nicotera and Papa, 2007).

3.2. Infiltration test on layered small-scale slope

As rainfall-induced shallow landslides can be strongly influenced by local stratigraphic conditions, it has been decided to perform a test on a layered model slope. The slope presents a pumice layer interbedded between two ashy layers (Fig. 15): the materials have been taken from Cervinara site. In addition, a pervious lowermost boundary has been obtained by a geotextile sheet (side 1 in Fig. 15). The thickness of each layer and the geometry of the slope are indicated in Table 2. Finally, to simulate a hydraulic boundary condition of free flow, a geotextile drain has been positioned at the toe of the slope (side 3 in Fig. 15).

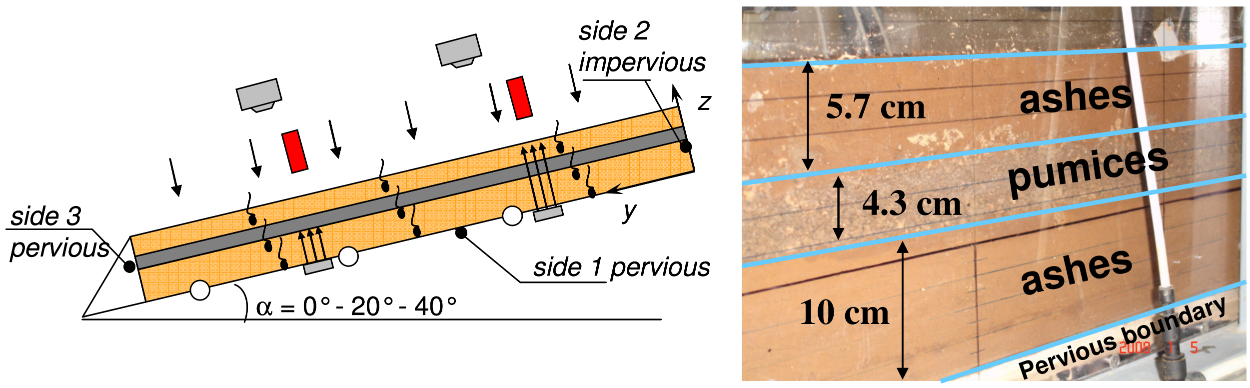

Figure 15. Sketch of test on layered small-scale slope and side-view of the soil deposit.

The test has been performed through different stages adopting various slope angles (0° - 20° - 40°) and alternating wetting periods (constant rainfall with intensity varying from 18 to 105mm/h) and dry periods (evaporation stages) as in Table 2.

Table 2. Test on layered slope: geometry, initial and boundary conditions.

slope	layer	soil	L [m]	h_i [m]	n_i [%]	w_i [%]
layered	upper	ashes (B)	1.7	0.10	76.0	35.0
	medium	pumices (A)	1.7	0.04	72.0	12.6
	lower	ashes (B)	1.7	0.06	75.0	35.0

Stage	slope angle α	rainfall characteristics *i* [mm/h]	*Δt*	boundary conditions * *side 1*	*side 2*	*side 3*
I_a	0°	50	61'	a	b	a
I_b	0°	0	6days 20h 10'	a	b	a
II_a	0°	27	2h 32'	a	b	a
II_b	0°	0	2days	a	b	a
III_a	20°	27	21'	a	b	a
III_b	20°	0	12days 21h	a	b	a
IV_a	40°	18	4h 50'	a	b	a
IV_b	40°	0	18days 17h 58'	a	b	a
V_a	40°	85	2h 05'	a	b	a
V_b	40°	85	5h 2'	a	b	b
V_c	40°	0	3days 17h 24'	a	b	b
VI_a	40°	105	7h 25'	a	b	b

* a = pervious; b = impervious

During the test, water content, displacements and suction have been monitored.
Initially (stages I and II), an angle of 0° has been adopted in order to investigate a monodimensional infiltration process by imposing two different rainfall intensities: 50mm/h and 27mm/h applied after a dry period of about 7 days.
Figure 16 shows the results of the first test (stage I_a in Tab.2) and the following evaporation phase (stage I_b in Tab.2) in terms of suction against time: the dashed line indicates the end of the rainfall. Saturation develops from the ground surface towards the base. However, the presence of the intermediate pumice layer causes a marked delay in the infiltration process: in fact, under a rainfall intensity of 50mm/h, the wet front reaches the depth of 10cm (bottom of the pumices) only after 60min from the start of the rainfall. On the contrary, during tests on 10cm thick uniform slopes subjected to similar rainfall intensity and initial conditions the wet front requires less than 20 minutes to reach a depth of 10cm. It is also important to note that infiltration proceeds downward for about 40h after the stop of rain, as revealed by tensiometers located at the bottom of the layer (deep tensiometers) which measured a continuous decrease in suction. An equilibrium condition is reached only after 7 days. Then, a new infiltration phase begin (stage II).
Figure 18 illustrates suction readings during this stage: once again, the influence of pumices has to be highlighted. The comparison between the measurements in the two ash layers across pumices shows a rapid response in the top layer (about 20 min after the beginning of the test, superficial tensiometers start to record a decrease in suction) with a different trend and a marked delay in the bottom layer: here (i.e. at the level of

intermediate tensiometers), significant changes in suction occur about fifty minutes later. Furthermore, the comparison between the two suction measurements performed in the same bottom ash layer (intermediate and deep devices) highlights a negligible difference despite of the different depth: once the wet front reaches the top of the deepest ashy layer, it advances quicker within it.

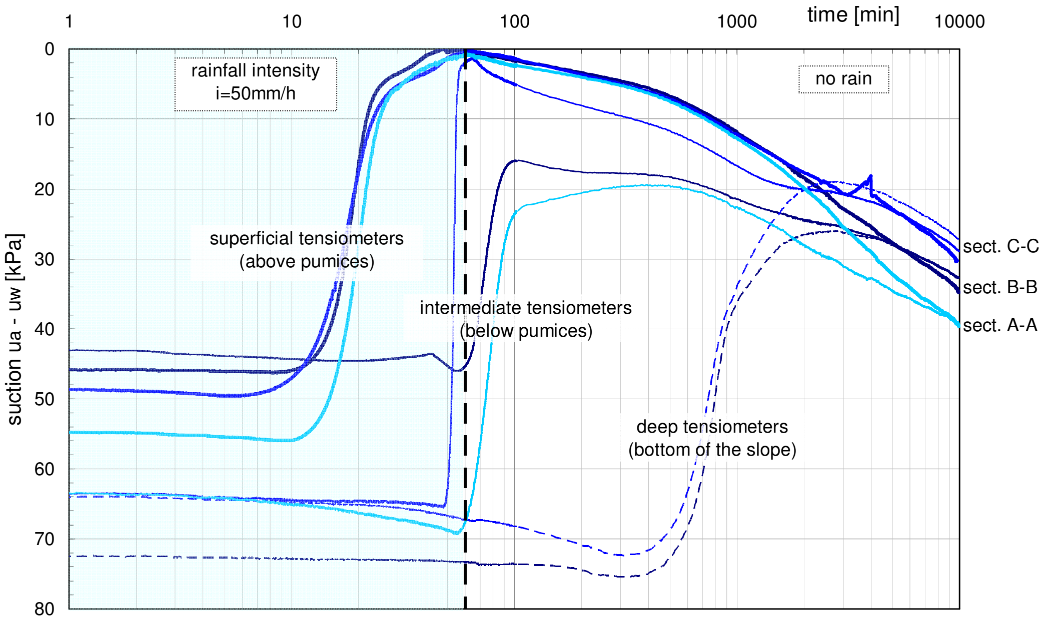

Figure 16. Test on layered slope – Stage I: suction

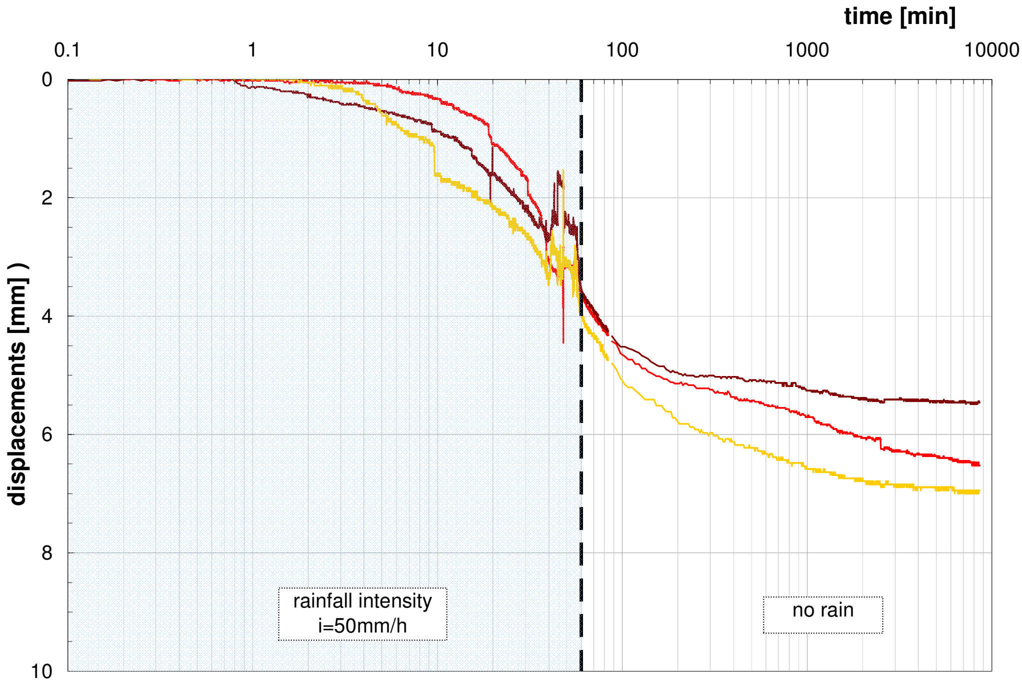

Figure 17. Test on layered slope – Stage I: settlement of ground surface

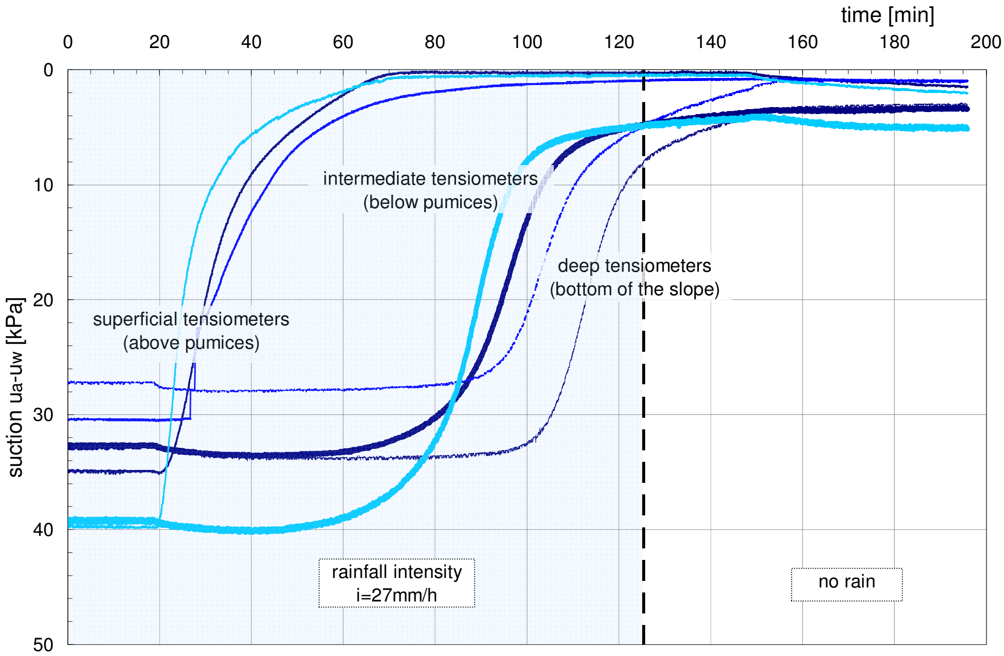

Figure 18. Test on layered slope – Stage II: suction

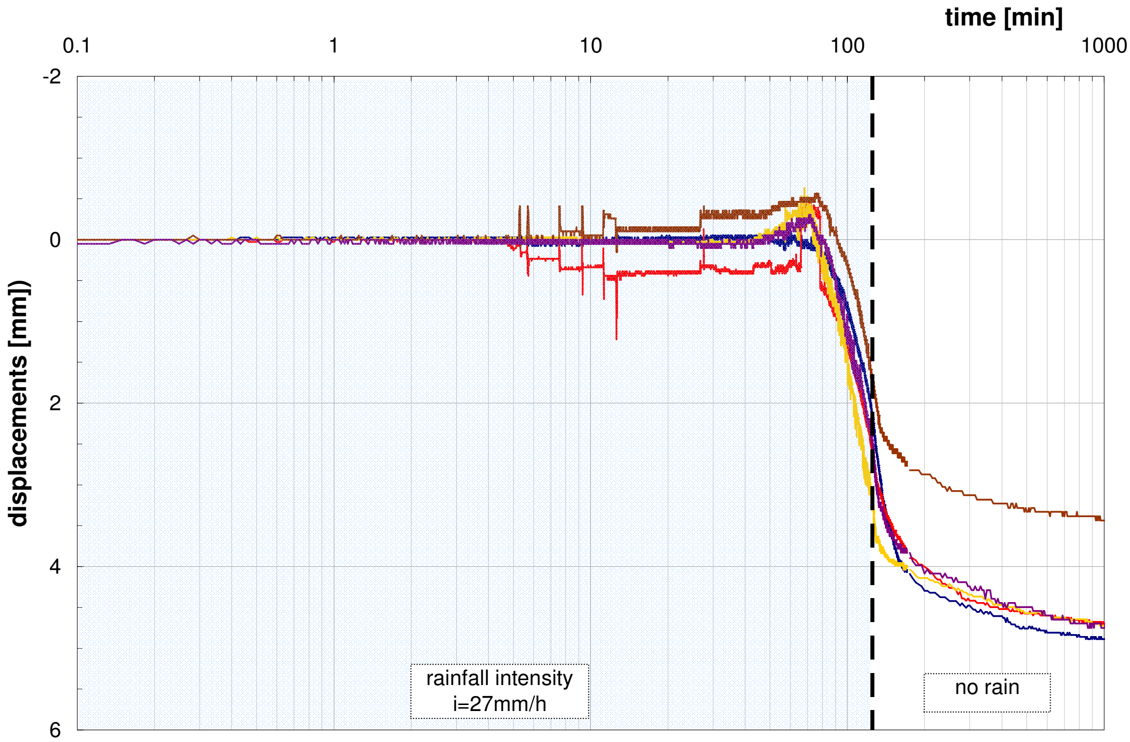

Figure 19. Test on layered slope – Stage II: settlement of ground surface

During such infiltration stages the soil deposit undergoes a settlement in the order of 1cm (Fig. 17 and 19) corresponding to a volumetric deformation of about 5%. It is also interesting to note that settlement continues even after the stop of rain as an effect of progressive saturation of the lower soil layers.

In the phase IV, the slope has been tilted to an angle of 40° and a rainfall intensity of about 18mm/h has been imposed for 4 hours and 50 minutes (IVa) followed by dry period (IVb) lasting about 19 days.
In Figure 20 the results of monitoring in the phase IVa are reported. As in the case of uniform deposit, a marked suction decrease appears throughout the soil mass, but in this case failure has not been attained. Seepage seems to develop in a similar manner as during the stage II in spite of the different slope angle. Readings also show that, under a rainfall intensity of 18mm/h, a steady condition is attained after 250 minutes since no more changes in suction occur. Final values of suction is in the order of a few kPa, just enough to assure the stability of the slope.

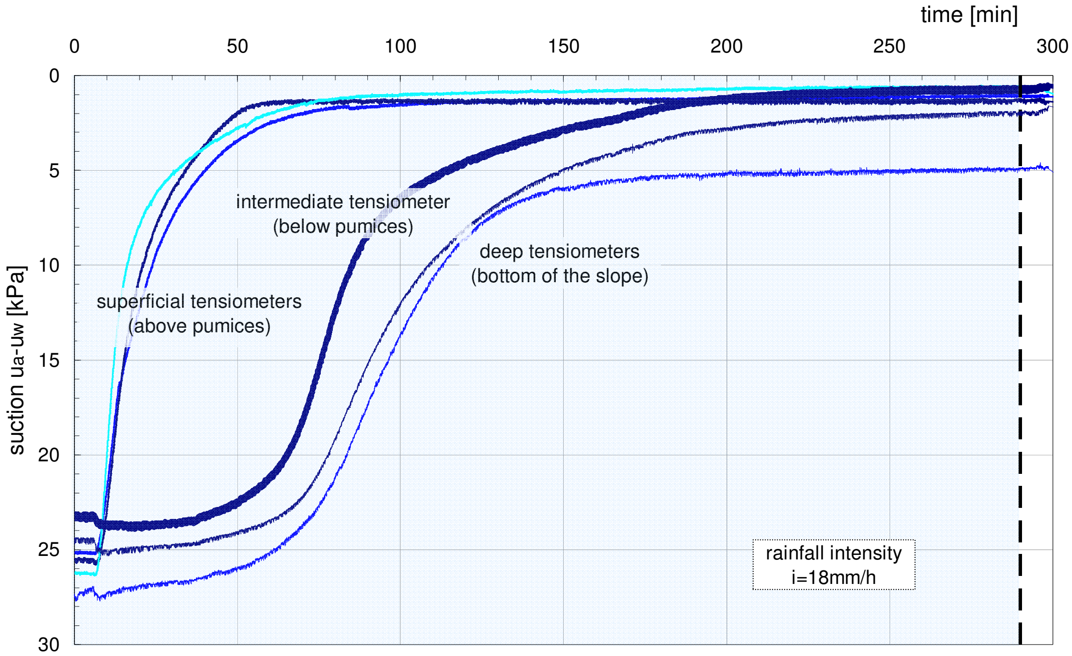

Figure 20. Test on layered slope – Stage IVa: suction

In the phase V the rainfall intensity was increased to 85 mm/h. After 105 minutes, an impervious diaphragm was installed at the toe of the slope, across the layers (Vb; side 3 impervious), and the rainfall intensity was kept constant until a steady condition was reached (about 5hours). The measurements of suction against time during this stage are illustrated in Figure 21. As it can be seen, the diaphragm disturbed the minitensiometers which started to record an increase in suction. On the other hand, the effect of disturbance seemed to vanish after some minutes. It's interesting to note that the impervious boundary didn't affect the following seepage process: even in this case, despite of the high rainfall intensity and the new impervious boundary, no failure occurred.
This result seems to confirm the great influence of the pervious boundary at the bottom of the slope which doesn't allow formation of a water ponding and, hence, the complete vanishing of suction.

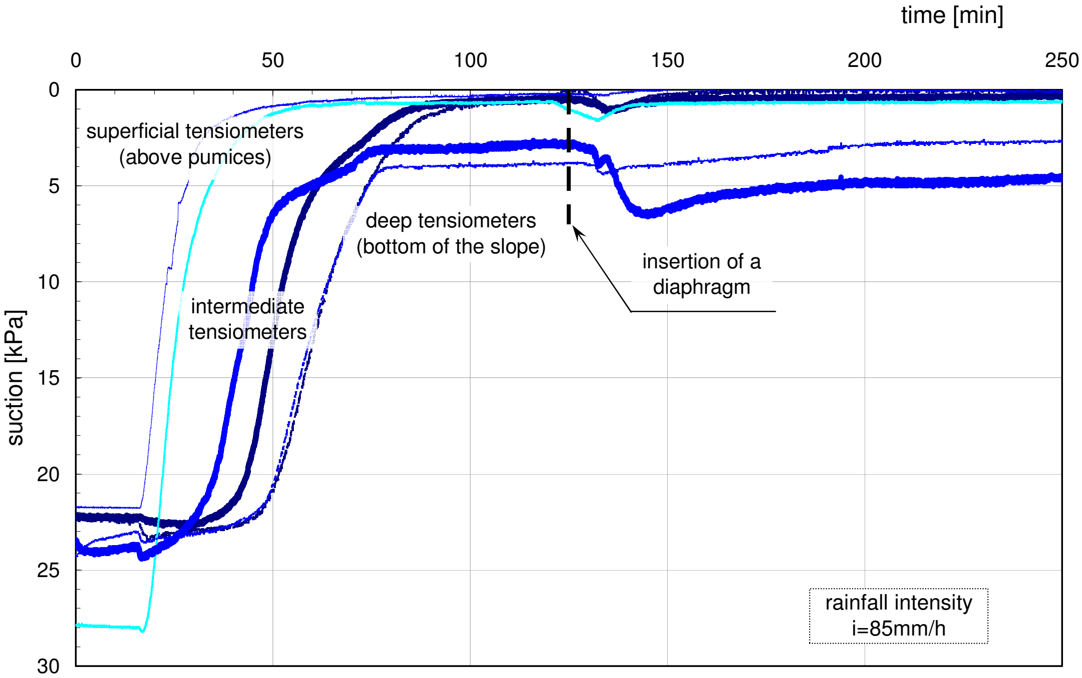

Figure 21. Test on layered slope – Stage V: suction against time

4. Conclusions

Results of experiments on infiltration in model slopes consisting of pyroclastic soils have been reported.
Through infiltration and evaporation stages, the WRC curve of volcanic ashes has been obtained. The results show that this depends on the infiltration rate. Such a result has to be carefully considered in numerical analyses. In addition, a manipulation of data regarding the water content and the suction measured during the test, allowed to obtain the WRC of pumice (Olivares and Tommasi, 2008): this is of fundamental importance because no data were available up to now.
Through the tests, the two typical geomorphological scenarios of uniform infinite slope and of layered slope including an intermediate pumice layer has been investigated. In particular, uniform 40° slopes and layered slopes with different inclinations (0°-20°-40°) have been tested. Both pervious and impervious conditions have been reproduced at the bottom of the slope: the “impervious hypothesis” is representative of slopes resting on fine-grained soils; the “pervious hypothesis” enables to consider the case of pyroclastic covers laying on highly fractured rock.
Interesting results have been obtained from tests carried out on layered slopes. In fact, the intermediate pumice layer acts as a “screen”, delaying water infiltration in the lowermost layer and the onset of slope failure. The results also confirm the great role of the boundary conditions on slope stability since the presence of a pervious base didn’t allow the 40° slope to fail, while the same slope resting on an impervious boundary attains a complete collapse.
The tests also confirm the important role played by soil porosity and rainfall intensity on the mode and time of failure.

5. References

Damiano, E., Greco, R., Guida, A., Olivares, L. (2008). “Early warning of fast landslides triggering based on instrumented slope data analysis”. Proc. International Environmental Modelling and Software Society (iEMSs), M. Sànchez-Marrè, J. Béjar, J. Comas, A. Rizzoli and G. Guariso (Eds.), Barcelona.

Greco, R. (2006). “Soil water content inverse profiling from single TDR waveforms”. Journal of hydrology, pp. 325-339

Nicotera, M.V. and Papa, R. (2007). “Comportamento idraulico e meccanico della serie piroclastica di Monteforte Irpino”. In Piattaforme Evolute di Telecomunicazioni e di Information Technology per l'Offerta di Servizi al settore Ambiente PETIT-OSA a cura di C. Nunziata Aracne editrice srl Roma ISBN 978-88-548-1184-3

Olivares, L. and Picarelli, L. (2003). “Shallow flowslides triggered by intense rainfalls on natural slopes covered by loose unsaturated pyroclastic soils”, Géotechnique, Vol. 53, 2, pp. 283-287.

Olivares, L. and Tommasi, P. (2008). “The role of suction and its changes on stability of steep slopes in unsaturated granular soils”, Special Lecture, Proc. 10th International Symposium on Landslides and Engineered Slopes, Xi’An, 1: 203-216.

Picarelli, L., Evangelista, A., Rolandi, G., Paone, A., Nicotera, M.V., Olivares, L., Scotto di Santolo, A., Lampitiello, S., Rolandi, M. (2006). “Mechanical properties of pyroclastic soils in Campania Region”, Proc. 2nd Int. Work. on Characterisation and Engineering Properties of Natural Soils, Singapore, 3: 2331-2383.