

## CENTRO EURO-MEDITERRANEO PER I CAMBIAMENTI CLIMATICI

ISC – Impatti sul Suolo e sulle Coste

# 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 first laboratory experimental tests aimed to investigate the response of model slopes in granular soils subjected to artificial rainfall.

The goal of the investigation is the assessment of the behaviour of representative slopes present in the part of the Campania Region covered by pyroclastic soils which pose major problems related to the triggering of catastrophic debris flows.

Keywords: slope stability, flume tests, 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 hydrogeological risks.

In order to develop short-term predictions of landslides induced by precipitations, the response of slopes to rainwater infiltration is a prominent problem. This can be obtained by numerical analyses which must be supported by a clear knowledge of soil behaviour as a consequence of infiltration. In situ monitoring is a fundamental aspect of the research, which can provide useful data. Unfortunately, monitoring is very useful only in the case of 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 far from slope failure. For this reason, physical modelling on small-scale and medium scale well instrumented prototypes is taking place in many parts of the world.

The report focuses on the results of some laboratory experiments through a heavily instrumented flume aimed to investigate the response of model slopes in granular soils subjected to artificial rainfall.

The goal of the investigation is the assessment of the behaviour of representative slopes present in the part of the Campania Region covered by unsaturated pyroclastic soils which pose major problems due to the occurrence of catastrophic debris flows.

## 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, thus depending on the degree of saturation,  $S_r$  (or on the volumetric soil water content,  $\theta_w$ ) which, in turn, is a function of the matric suction,  $u_a$ - $u_w$ , through a strongly non-linear relationship called Soil Water Retention Curve (SWRC). This relationship is a function of the soil porosity, and exhibits an hysteresis which depends on 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 which characterises evaporation (i.e. when suction increases). Therefore, in order to correctly simulate the seepage processes in pyroclastic soils is necessary to obtain the SWRC. 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 in situ one (n=70%) and a water content of 0.3, by layering a precise 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 applying steps of suction increase (evaporation test) or steps of suction decrease (infiltration test). At he 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 the obtained experimental points: the red triangles indicate data from evaporation test, while the white triangles data from infiltration tests. The results do not exhibit a significant difference in the path followed by the SWRC during the two processes, showing that volcanic ash doesn't exhibit a hydraulic hysteresis. Data are in good agreement with the expression proposed by van Genuchten (1980) ( $\theta_r$ =0.3;  $\theta_s$ =0.7; m=0.2; n=7;  $\alpha$ =1.7).



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

The unsaturated coefficient of permeability of volcanic ashes have been obtained from the interpretation of the transient phase of suction equalization (Kunze et al., 1965) in SCTX (suction controlled triaxial) tests and they are reported in figure 2. In the same figure the permeability values versus suction estimated using the expression proposed by Brooks and Corey (1964) and the permeability function obtained by Gardner's equation (1958) are plotted. 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).



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



### 3. 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"). The experiments have been conducted on air-fall unsaturated pyroclastic soils, taken at the sites of Cervinara and Monteforte Irpino, North-East of Naples.

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%).

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 to allow a free flux of water.

Artificial uniform rainfall is produced through spray nozzles located 0.4m above the ground surface.

Test	D4	D10_1	D10_2		
Investigated soil	Cervinara ash	Monteforte Irpino ash	Monteforte Irpino ash		
Rainfall intensity (mm/h)	56	50	45		
Duration of test (min)	29	27	58		
Specific weigh (kN/m <sup>3</sup> )	26.0	26.2	26.2		
Initial suction (kPa)	42÷45	27÷29	15÷17		
Initial water content W <sub>0</sub>	0.40	0.43	-		
Initial porosity n <sub>0</sub>	0.76	0.76	-		

able	1.	Test	conditions

A 9.5cm 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). Minitensiometers, to measure suction, have been installed at various depth and locations in the slope. In particular 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.



Figure 3. The instrumented flume

The infiltration test D4 lasted until slope failure. Test D10 was performed in two stages: during the first one, a rainfall intensity of 50mm/h was applied, followed by a dry period of 5 days during which the evaporation was monitored; during the second stage an uniform rainfall of 45mm/h was 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 course of both matric suction and settlement of the ground surface during each experiment is reported in Figures 4, 5 and 6.

During infiltration a marked suction decrease occurs starting from the ground surface towards the base of the layer as confirmed by the delay of the deep tensiometers installed at the bottom with respect to the superficial ones. This suggests that a wet front progressively moves downwards. The progressive saturation of soil is confirmed by the increase of volumetric water content (Fig. 7). Finally, laser sensors show that saturation is accompanied by significant volumetric strains which can attain values in the order of 7%.



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 D10\_1



Figure 6. Suction and settlement of the ground surface against time during test D10\_2

Moreover test D10-1 (Fig. 5) reveals that the advance of the wet front continues even after 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. Only after 20 minutes, all along the slope a uniform distribution of suction and water content is reached, indicating that infiltration has stopped. Since the stability of slopes in pyroclastic soils depends on suction, this result suggests that a critical condition may be attained even after the end of rainfall.

As expected, tests on uniform slopes confirm 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 against 29min in test D4) to trigger failure.

It is worth to note as a final remark that, during the final stage of the test, 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.



Useful information is also provided by records with TDR. Figure 7 shows some of the volumetric water content  $\theta_w$  profiles obtained at various times during experiment D4: the shape of the profiles is consistent with data of suction.

Coupling suction with the correspondent volumetric water content at the same depth, the water retention curves can be obtained. The WRC curve obtained from test D4 is compared in Figure 8 with that obtained through conventional laboratory techniques (see section 1).



Figure 6. Volumetric water content profiles at different times during test D4 (Damiano et al., 2008)



Figure 8. Water Retention Curve obtained from infiltration tests in flume compared with WRC obtained from conventional long-term laboratory tests (Olivares and Tommasi, 2008).



Although some dispersion is present, nearly all the points obtained by flume tests fall below Water Retention Curve estimated in laboratory, especially when saturation is approaching. This result indicates that during infiltration in the model slope, the soil has experienced a matric suction about 5kPa smaller than what could be expected from the water retention curve obtained with conventional long-term tests. 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 resemble real slope conditions, it is expected that this result would be confirmed also by field observations.

Moreover, this result suggests a useful indication in respect of slope behaviour, since the rate of the process seems to affect the soil response.

#### 4. 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. 9): the material has been taken from Cervinara site. In addition, a pervious lowermost boundary has been obtained by a geotextile sheet (side 1 in Fig. 9). 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 at the toe of the slope, a geotextile drain has been positioned (side 3 in Fig. 9).



Figure 9. Sketch of the instrumented flume during test on layered small-scale slope and side-view of the reconstituted layered soil deposit.

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



slope	e layer	· s	soil		h <sub>i</sub>	n <sub>i</sub>	Wi	
				[m]	[m]	[%]	[%]	
ea	uppe	r ash	ashes (B)		0.10	76.0	35.0	
yei	mediu	m pumi	pumices (A)		0.04	72.0	12.6	
la la	lower	r ash	ashes (B)		0.06	75.0	35.0	
test	slope	rainfall	characte	eristics	s b	ounda	iry	
FL20	angle					conditions *		
	α	i	Δt		7	2	ŝ	
Stage		[mm/h]			side	side	side	
I_a	0°	50	61'		a	b	а	
I_b	0°	0	6days 20h 10'		a	b	а	
ll_a	0°	27	2h 32'		а	b	а	
ll_b	0°	0	2days		а	b	а	
III_a	20°	27	21'		а	b	а	
III_b	20°	0	12days 21h		а	b	а	
IV_a	40°	18	4h 50'		а	b	а	
IV_b	40°	0	18days 17h 58'		3' a	b	а	
V_a	40°	85	1h 45'		а	b	а	
V_b	40°	85	5h	7'	а	b	b	
V_c	40°	0	3days 1	17h 24	a	b	b	
VI_a	40°	105	7h	25'	а	b	b	

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

\* a = pervious; b = impervious

During the test, water content (by the TDR technique), displacements (by laser transducers and the PIV technique) and suction (by mini-tensiometers) 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 10 shows the results of first infiltration test (stage I\_a in tab.2) and the following evaporation phase (stage I\_b in tab.2) in terms of suction against time: in the figure, the dashed line indicates the end of the rainfall. Saturation develops from the ground surface towards the base. However, in this case, the presence of the intermediate pumices 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 slopes in uniform deposits subjected to similar rainfall intensities 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.

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Figure 11. Test on layered slope - Stage II: suction against time

Starting from that moment a new infiltration phase began (stage II) and similar results have been obtained. Figure 11 illustrates suction readings during this stage: once again, the



influence of pumices layer is 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. in the 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.

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 an equalization period without rain (IVb) of about 19 days.

In Figure 11 are reported the results of monitoring in the phase IVa. As in the case of uniform deposits, a marked suction decrease appears throughout the soil mass, but in this case an instability condition has not been reached. 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 was attained after 250 minutes since no more changes in suction occurred. Final values of suction was in the order of a few kPa, just enough to assure the stability of the slope.



Figure 12. Test on layered slope - Stage IVa: suction against time

In the phase V the rainfall intensity was increased to a value of 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 attained (about 5hours). Even in this case, despite of the high rainfall intensity and the new impervious boundary at the toe of the slope, 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 the formation of a water ponding and, hence, the complete vanishing of suction.

### 5. Conclusions

Results of some instrumented flume tests on model slopes representative of typical geomorphological scenarios in Campania have been reported. The slopes have been subjected to artificial rainfall.

In particular, uniform 40° slopes and layered slopes tilted at 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 non fractured bedrock or on fine-grained soils characterized by a relatively low conductivity; the "pervious hypothesis" enables to consider the case of pyroclastic covers laying on highly fractured rock. Obtained results confirm the great role of the boundary conditions n slope stability.

Interesting results have been obtained from tests carried out on layered soils including an intermediate pumice layer. In fact, this acts as a "screen", delaying water infiltration in the lowermost layers and the onset of slope failure. In addition, a manipulation of data regarding the water content and the suction measured during the test, allowed to obtain the water retention curve of pumice (Olivares and Tommasi, 2008).

Finally, important information has been provided about the mechanisms leading to slope failure.

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