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Numerical analysis of suction measures obtained during tests performed on a physical model of slope.

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Numerical analysis of suction measures obtained during tests performed on a physical model of slope.

Summary

This technical report illustrates the first result obtained carrying out a numerical analysis on the suction data measured during a test performed with a physical model of slope. The analysis consists of an interpolation of the measures along a bidimensional domain which corresponds to a vertical cross section of the soil sample. Along each section N. 10 Soil Moisture small tip tensiometers have been placed to measure suction at three different depths.
The main results of this analysis are aimed at identifying how the seepage process takes place inside the soil sample and how it characterizes the sample saturation before failure occurs.
The numerical analysis is carried out using the commercial software Surfer. This software is suitable to make interpolation of data inside a bidimensional or tridimensional domains by means of different mathematical relationships. In this case the method used is the Inverse Distance Weighting (IDW); it is a mode for multivariate interpolation, which assigns values to unknown points by using values from scattered set of known points.
The first result are here discussed.

Keywords: seepage, physical model of slope, suction measure, numerical analysis.

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Introduction

In the experimental activity made to study the effects of the rainfall on the natural slope stability it is employed a physical model of slope. This apparatus allows to simulate rain induced flowslides and it is equipped with devices and sensors suitable to measure physical variables correlated to the development of such phenomena.

The activity carried out until now on the slope prototype regards experimental tests aimed at understanding trigger of flowslide in pyroclastic soil. Each test is performed simulating a rainfall with constant intensity above the soil sample, inclined respect to the horizontal plane, up to reach failure.

The soil tested is a volcanic ash, made of non plastic silty sand with gravel (see fig. 1); it is the same soil involved in a significant rapid flowslide of 33000 m^3 occurred on 4th March, 2005 and affected a slope close to the Nocera town (Salerno).

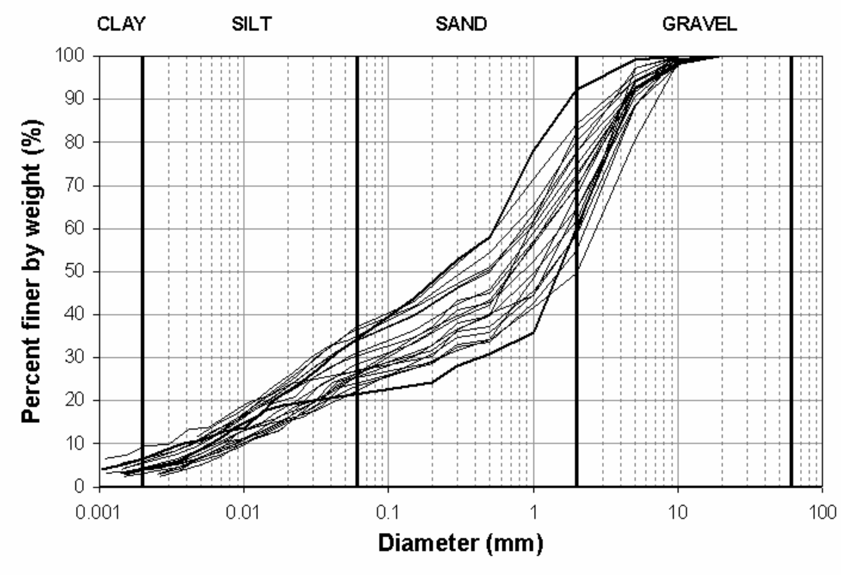

Figure 1. Soil grading.

The prototype's dimensions makes it possible to reproduce, with no scaling factors, small soil volume involved in the landslides, minimising the border effects (i.e., the interaction between soil and vertical walls of the prototype). Its large sizes also permit to install several transducers in a quite large soil mass, as tensiometers to measure suction, and TDR probes to measure water content by using the Time Domain Reflectometry, allowing the analysis of the evolution of physical variables during the test. The variation of water content of the whole sample can be estimated also by means of four load cells placed under the tank supporting the sample. During test the cells measure the weight variation of the soil sample due to both the seepage of rain water and falls of soil.

Up to now 10 tests have been carried out keeping constant layer thickness of about 40 cm, and rain history (rain intensity = 30 mm/h), while the initial state in terms of soil porosity and soil suction, along with the sample inclination have been varied (see Tab. 1).

Table 1. Sample characteristics.

Test N.	inclination (°)	w* (%)	porosity* (%)	S_r* (%)	suction* (kPa)
1	32	31.09	66.72	41.10	-
2	35	33.21	70.73	36.43	-
3	32	31.38	70.02	35.62	32.00
4	35	25.83	68.33	31.74	80.00
5	37	-	-	-	2.50
6	-	-	-	-	-
7	37	41.89	62.24	41.89	5.00
8	40	36.35	66.22	49.34	15.00
9	35	39.21	62.83	64.71	7.00
10	37.5	26.58	67.91	33.29	60.00

In the table 1 w* and S_r* are respectively the average of the water content, and the degree of saturation before test starts with:

- $w=P_w/P_s$

  P_w is the weight of the water inside the soil and P_s is the weight of the soil;

- $S_r=V_w/V_v$

  V_w is the volume of the water inside the soil and V_v is the soil pores volume.

As well the suction value in table 1 corresponds to the average of the value collected by tensiometers at the beginning of the test.

Notable results obtained from the first experimental experiences performed with the slope prototype regard the hydraulic behaviour of soil sample. During each test the sample hydraulic response has been characterized by measuring evolution of the sample weight, soil suction (approximately 20 measurement points) and soil volumetric water content (4 measurement points). In particular the tensiometers and TDR measures may be used to characterize the sample hydraulic behaviour, as the seepage process inside the sample due to the simulated rain, and to estimate the time after which the landslide may trigger.

In this report is described the first attempt to analyze the suction measures obtained from one of the tests performed, in order to understand how the seepage process determines the saturation of the sample until to reach the soil failure.

The first attempt is made considering the data collect during the test N. 4, where the sample was drier than the other ones, and so it was characterized by the higher initial value of suction (see Table 1).

1_ The experimental test analyzed

The experimental data used in the numerical analysis described above consist of suction measurement carried out during the 4th test performed with the physical model of slope. In this test the sample has a fixed slope of 35°, less than the friction angle of the soil used, and it is characterized by a lower initial value of degree of saturation (S_r) which means high value of suction, and a high value of porosity (see Table 1). The rain has been simulated with a constant intensity of 30 mm/h.

The dry condition of the sample affects the test performance, in fact the water required to saturate the sample is greater than in the other tests. Looking at the Fig. 2, which shows the weight variations of the sample measured during the test N. 4 and N. 10, it is possible to note as the water absorbed by the sample in the test N. 4 is almost two times the quantity of water absorbed by the sample during the test N. 10, even if in the latest test the initial value of suction was still high but less than test N. 4. In all for the 4th test it has been necessary almost a rain period of about 8 hours with an rain intensity of 30 mm/h, while for the test N. 10 needed a little more than 5 hours.

As indicated by the decreasing of the derivative of the curve in Fig. 2, storing water capability under constant rain intensity is not constant. In fact in the initial stage of the tests the hydraulic gradient, which drives the water drops within the sample, is greater as greater is the difference between the water pressure acting at the sample top surface (i.e. atmospheric pressure), and at the interior of the sample (i.e. soil suction). However, the gradient reduces with time, as indicated by the decreasing of the derivative of the curve. This effect is manly due to the progressive reduction of soil suction within the sample (Figg. 2 and 4).

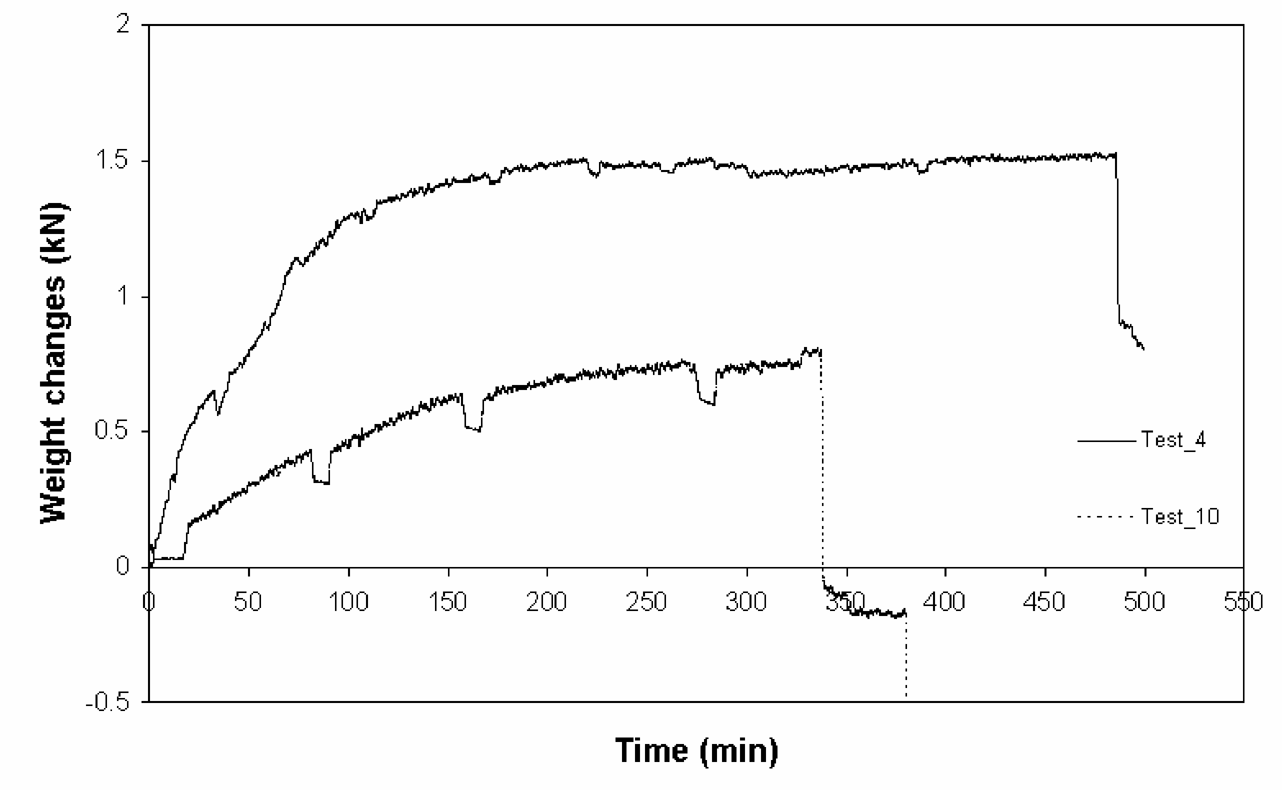

Figure 2. Weight variations of the samples measured during the test N. 4 and N. 10.

An additional contribution to the same effect is provided by the time needed for the seeping water to reach downstream the draining boundary which covers the lower sample vertical constraint. As well known, soil permeability increases during the wetting process. In the initial stages soil permeability increments should enhance water adsorption. However Fig. 2 indicates that permeability effects are not so relevant as that produced by the gradient reductions. This is due to the retention properties of the pyroclastic soil showed in Fig. 3. The water retention curves of Fig. 3 indicate the range of suction in which the soil move from the saturated condition to the residual (un)saturated condition is narrow, as well as the suction range in which the soil is saturated or near to the full saturated condition (i.e. suction ranging between 0 and 30 kPa). Therefore to increase the soil permeability until to reach value close or equal to its maximum (i.e. saturated permeability), it is necessary suction decreases significantly. At the same time as lower suction is achieved, the hydraulic gradient reduces drastically.

Consistently to what said before, initially the rain appears to the naked eye fully adsorbed by the sample surface and, then increasingly rejected by it, with enhancing run off.

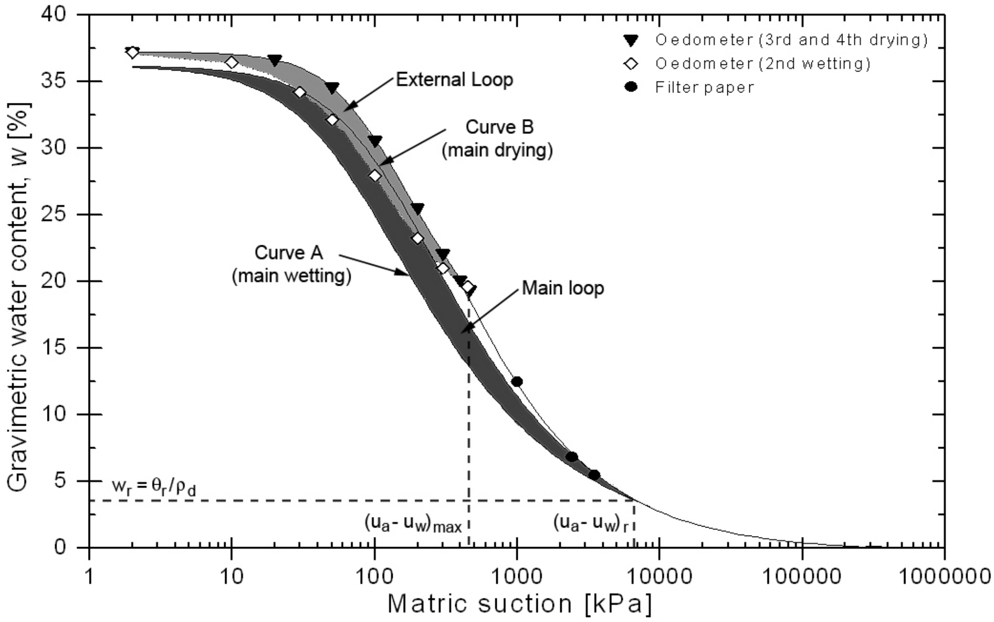

Figure 3. Water retention curves of pyroclastic soils.

2_ Suction measurement

The whole set of suction measures of the test N. 4 was showed in Fig. 4. It was collected by using N. 20 Soil Moisture tensiometers put in place inside the sample along two different vertical longitudinal sections (N. 10 tensiometers per section). Each section crosses the sample about 1 m from the nearest longitudinal border of the slope prototype. At the same time, they virtually intercept in the middle two of the four cones of water drops coming out from the rain simulation system.

As in other tests performed until now, in each section the instruments have been placed at three different depths of 40, 25, 10 cm from the sample surface which correspond: one to the base of the sample, another one is about in the middle of the sample thickness, while the last one is approximately slightly under the upper surface of the sample. Unfortunately the TDR probes have not been installed in this test, because the TDR system was not yet available.

All the tensiometers measures (Fig. 4) show suction drops drastically to the null value when the wetting front reaches the depth of the installation point. In fact, since the rain intensity adopted is significant it generates a wetting front inside the sample able to saturate the soil.

It is noteworthy that the decrease of suction at the base of the sample (green line in Figg. 4 and 5) shows some delay respect to the other suction patterns measured at upper levels. This because in the upper part of soil reached by the wetting front, it is generated a water flow along the slope direction.

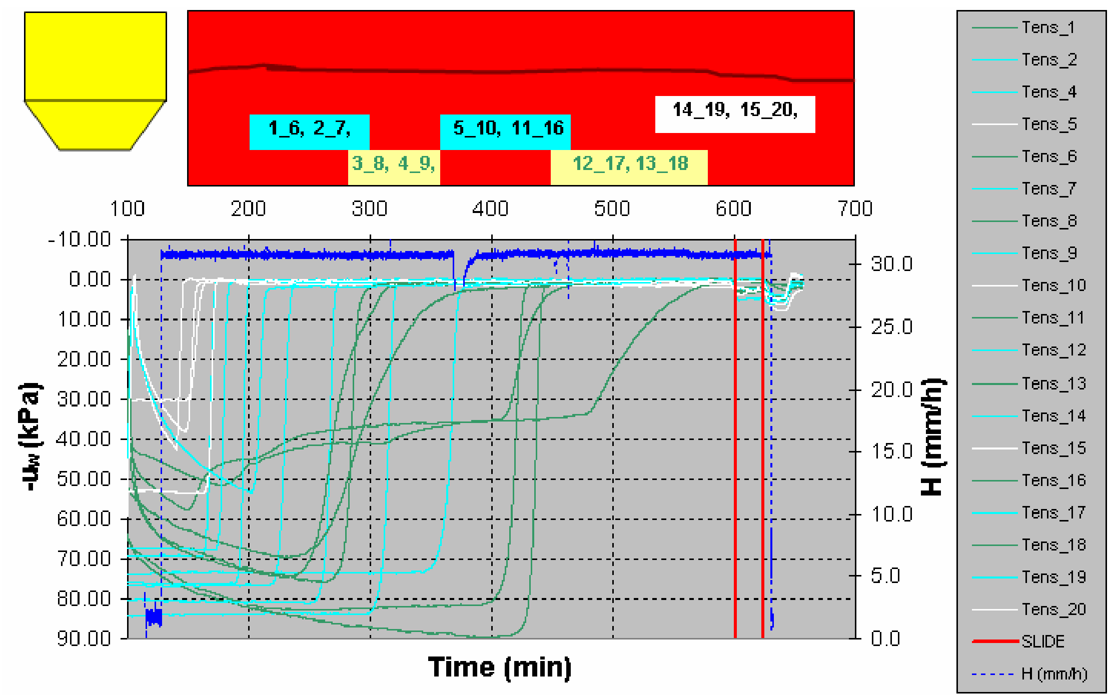

Figure 4. Development wit time of soil suction in each point of measure.

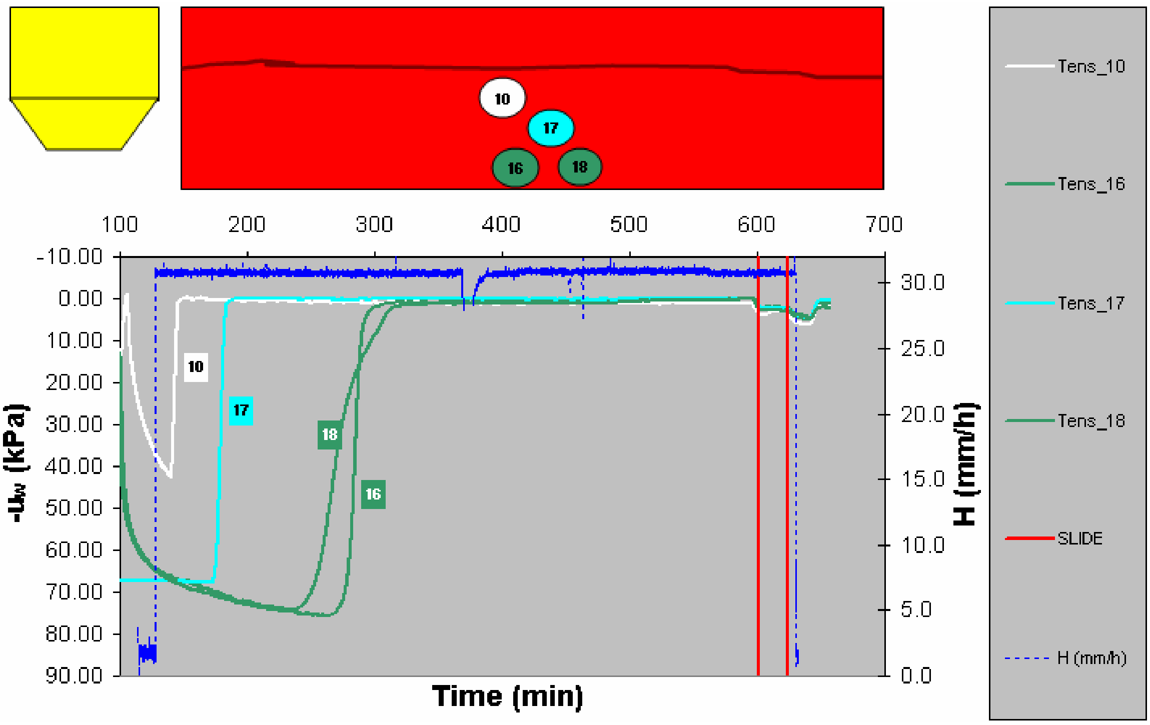

Figure 5. Development wit time of soil suction measured at four points located on the same vertical height.

The flowslide trigger is anticipated by soil suction changes. Suction at the bottom of the sample goes down to zero before the triggering time (see Fig 4 and tensiometers N. 16 and 18 in Fig. 5). In this kind of test, where the sample inclination is slightly less than the soil friction angle, trigger is caused by positive pore pressures developing at the bottom of the sample.

On the other hand, the flowslide trigger is clearly indicated by the load cells with an abrupt decrease in the sample weight (Fig. 2). The size of the weight drop is obviously related to the quantity of soil lost in the landslide.

3_ First results from numerical analysis

Choosing from the suction measures of Fig. 4 the values referred to a fixed time, it is possible to carry out an interpolation of the observed data and so to estimate suction along the whole section in this instant.

This kind of numerical analysis has been done using “Surfer”, a software suitable to make interpolation in a bidimensional or tridimensional domain. Starting from a set of known values this software calculates the interpolated value for each node of a grid defined inside the domain. It is possible to use different interpolator (i.e. different mathematical relationship); in this case the method chosen is the Inverse Distance Weighting (IDW), a weighted average interpolator which can be either an exact or a smoothing interpolator. With Inverse Distance Weighting the known data are weighted during interpolation such that the influence of one point relative to another reduces with distance from the grid node. The inverse distance weight is used to attenuate the influence of distant points, so estimated values are a function of the distance too, beside magnitude of surrounding points.

Weighting is assigned to data through the use of a weighting power that controls how the weighting factors drop off as distance from a grid node increases. The software assigns a non null weights only to the observed data points; normally the weights are fractions, and the sum of all the weights are equal to 1.0. Only when a particular observation is coincident with a grid node a weight of 1.0 is given to that observed to match the observed with the calculated value. Anyway it is possible to assign a non-zero Smoothing parameter, so that no point is given a weighting factor equal to 1.0.

The equation used for Inverse Distance Weighting is:

$$\hat{Z}_j = \frac{\sum_{i=1}^{n} \frac{Z_i}{h_{ij}^{\beta}}}{\sum_{i=1}^{n} \frac{1}{h_{ij}^{\beta}}}$$

$$h_{ij} = \sqrt{d_{ij}^2 + \delta^2}$$

where:

h_{ij} is the effective separation distance between grid node "j" and the neighboring point "i."

$\hat{Z}_j$ is the interpolated value for grid node "j";

Z_i are the neighbouring points;

d_{ij} is the distance between the grid node "j" and the neighbouring point "i";

β is the weighting power (the Power parameter);

δ is the Smoothing parameter.

In Fig. 6 there is the interpolation result obtained from the suction data registered at the beginning of the test N. 4 before rain start. The interpolation has been made considering as a sample section a plane domain 0.4 m thick and 3 m long. Here the sample is characterized by high suction values, especially at the base. Suction is slightly lower in the upper part as the sample was wetted some days before.

It is worthy of note that a smaller reduction of suction takes place along the sample too. Maybe this can be determined by the presence of a drain surface on the vertical constraint supporting the sample when it is inclined.

Similar interpolation analysis have been done considering other set of data referred to a certain number of instant. The results are showed in Figg. from 7 to 16. The data observed in the test have been showed inside each interpolation section.

The boundary conditions imposed are referred only to the presence of rain water over the sample surface and to the estimate position of the saturation front line when it is generated inside the sample. This latter condition is necessary to avoide non null suction unsaturated zone under the saturation front line.

The comparison between the subsequent interpolations indicates as in the initial phase of the test the upper part of the sample has been uniformly saturated, then, cause of a longitudinal water flow generated through the sample, the saturation of the lower part of the sample is delayed. Anyway, the wetting process seems to affect the rest of the sample starting from the inferior zone.

The results showed are referred only to a one of the two section considered. The analysis of the other data are still in progress.

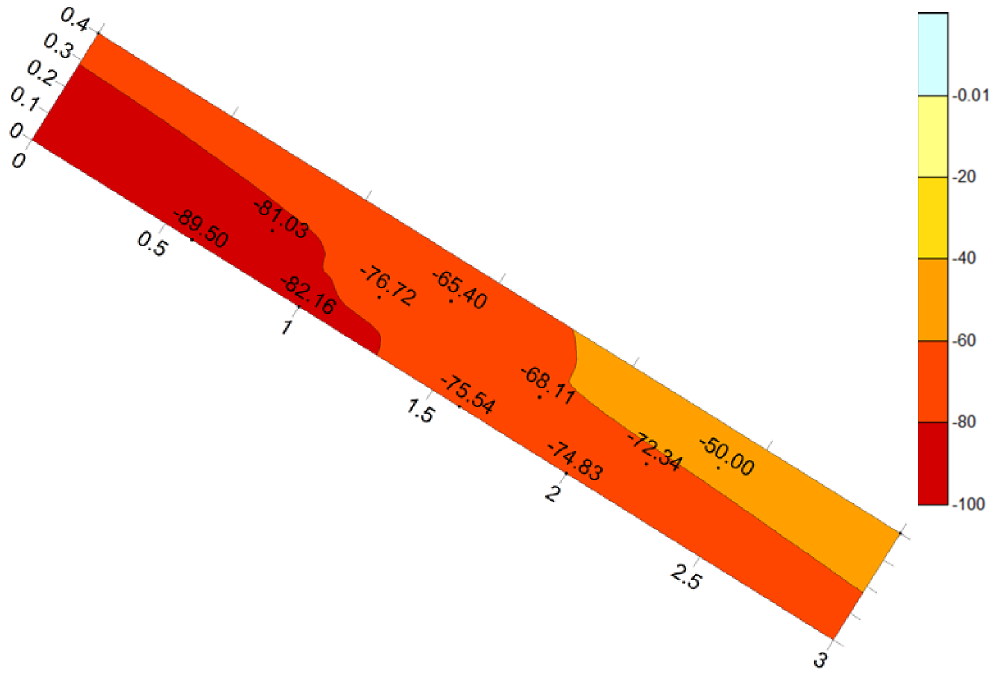

Figure 6. Results obtained from the interpolation of suction data registered at the beginning of the test N. 4 before rain start.

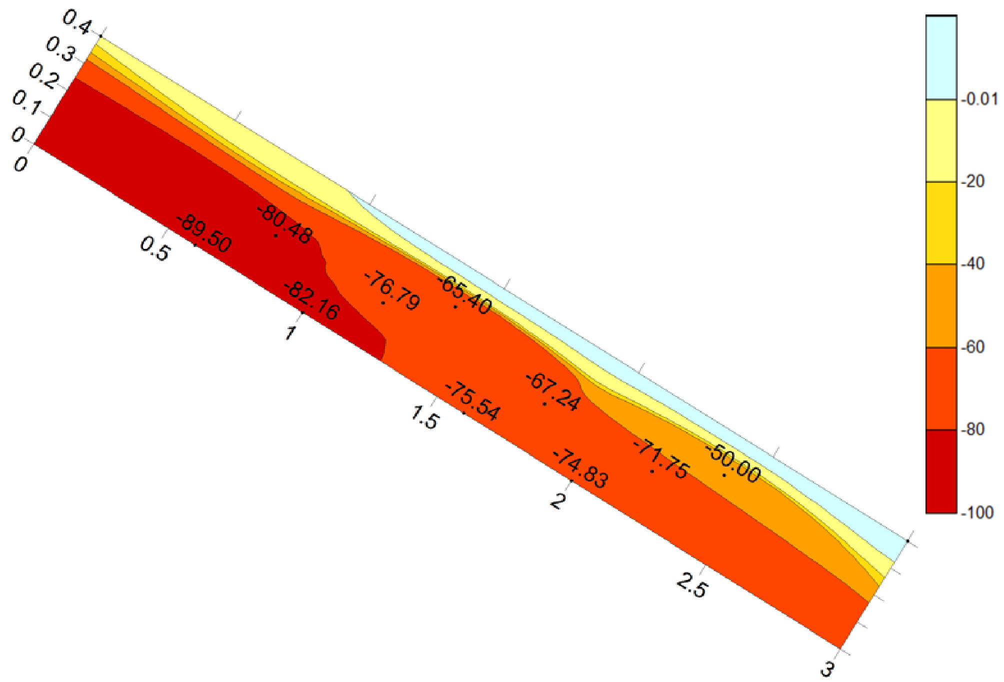

Figure 7. Results obtained from the interpolation of suction data registered after 10 min from rain start.

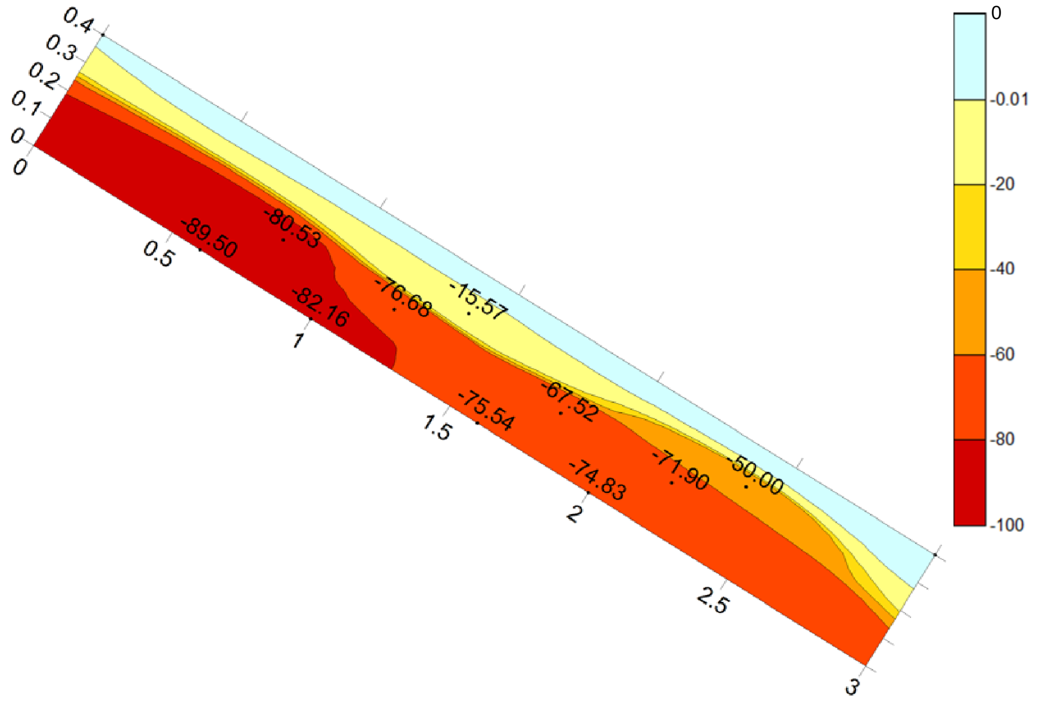

Figure 8. Results obtained from the interpolation of suction data registered after 24 min from rain start.

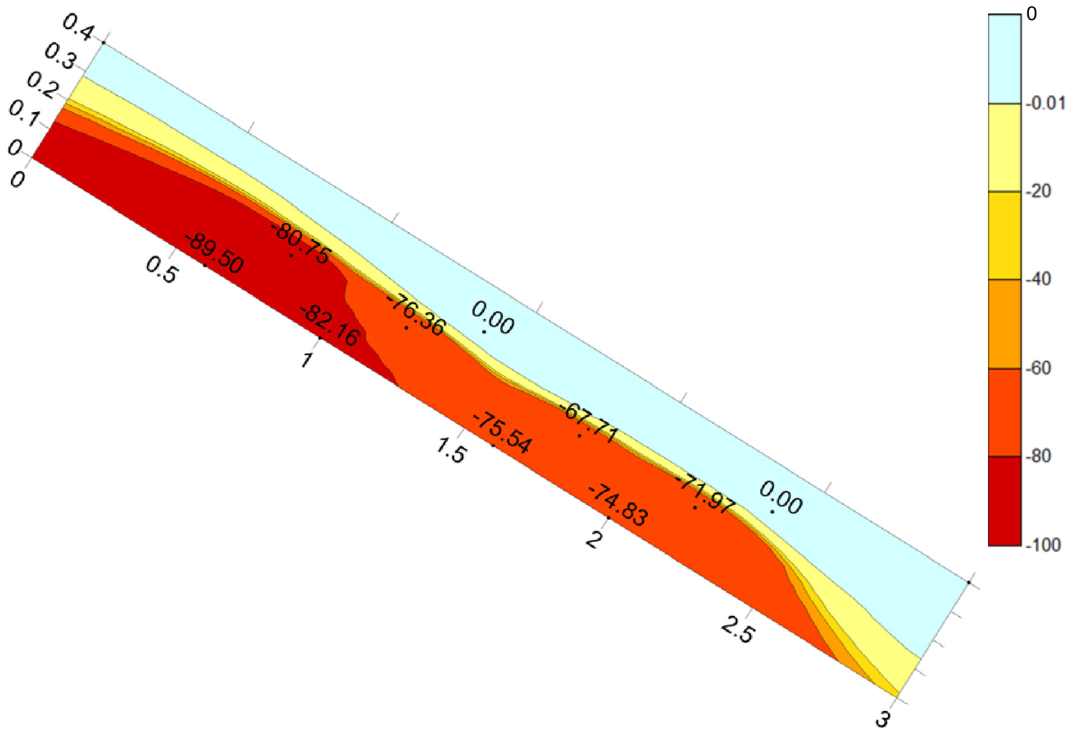

Figure 9. Results obtained from the interpolation of suction data registered after 50 min from rain start.

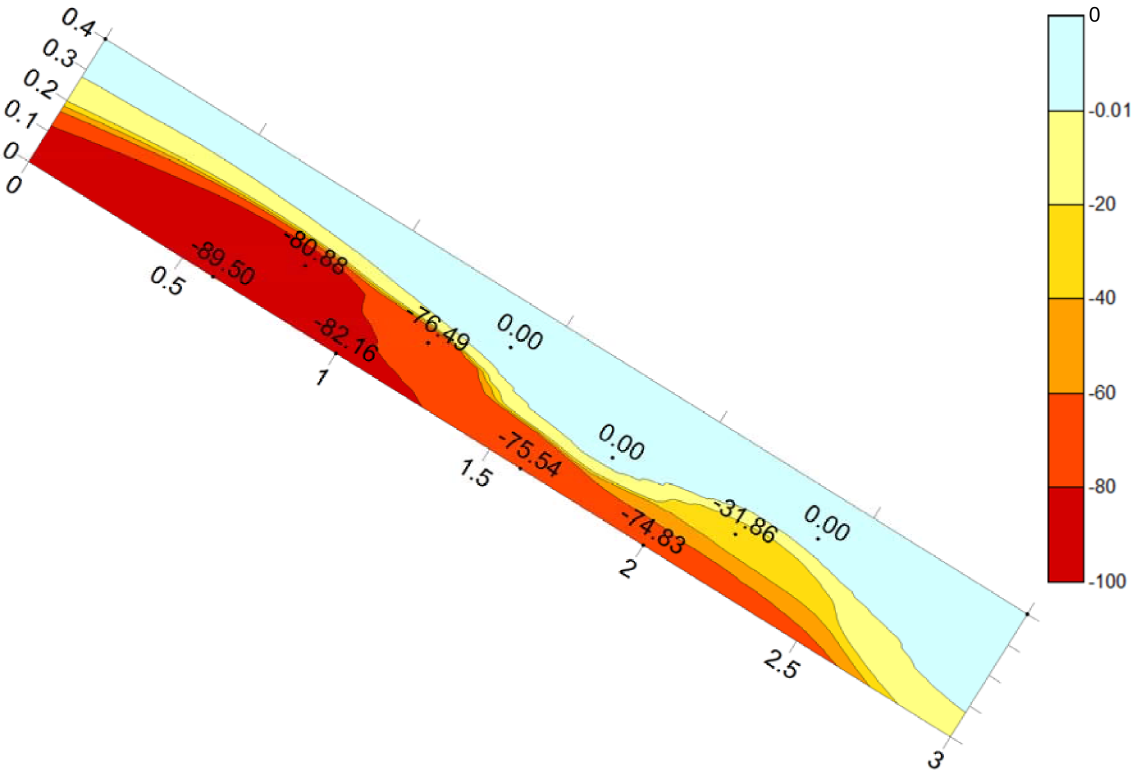

Figure 10. Results obtained from the interpolation of suction data registered after 1 hour 16 min from rain start.

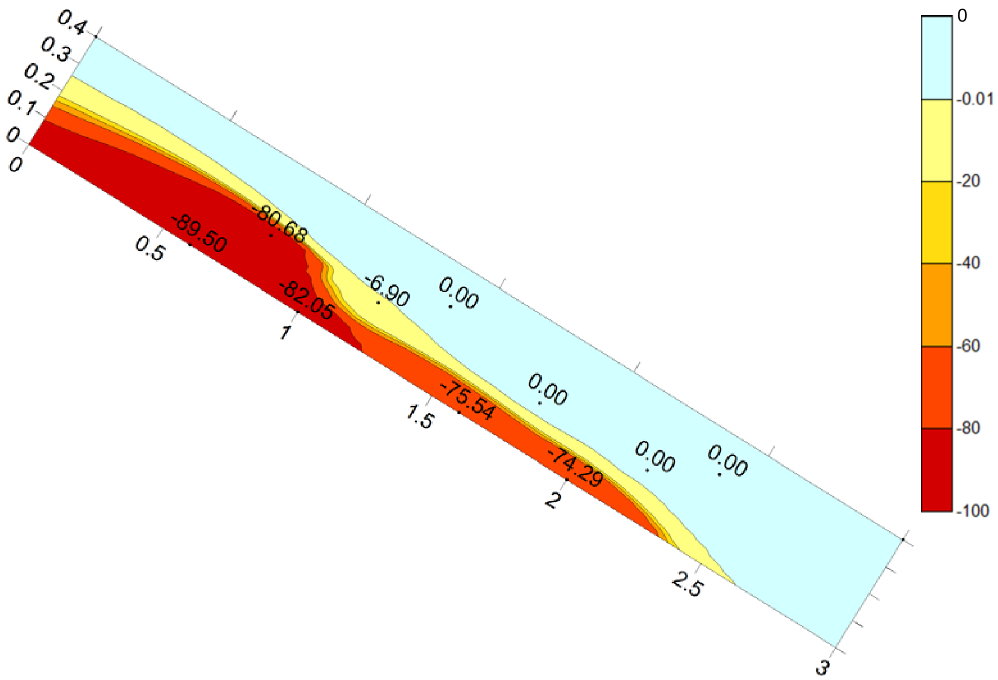

Figure 11. Results obtained from the interpolation of suction data registered after 1 hour 54 min from rain start.

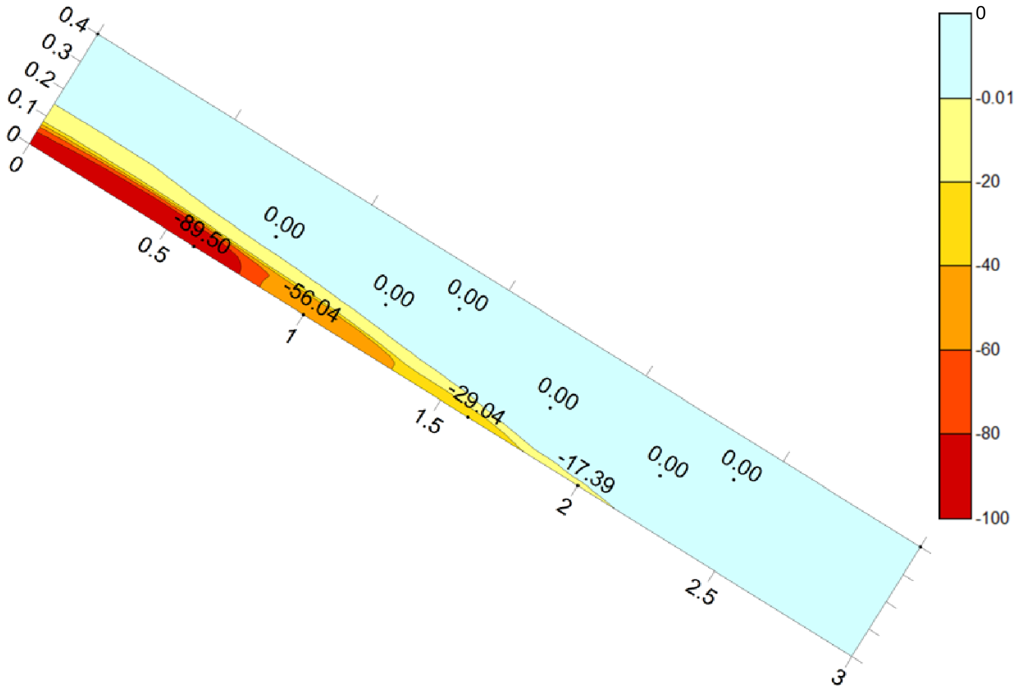

Figure 12. Results obtained from the interpolation of suction data registered after 2 hours 46 min from rain start.

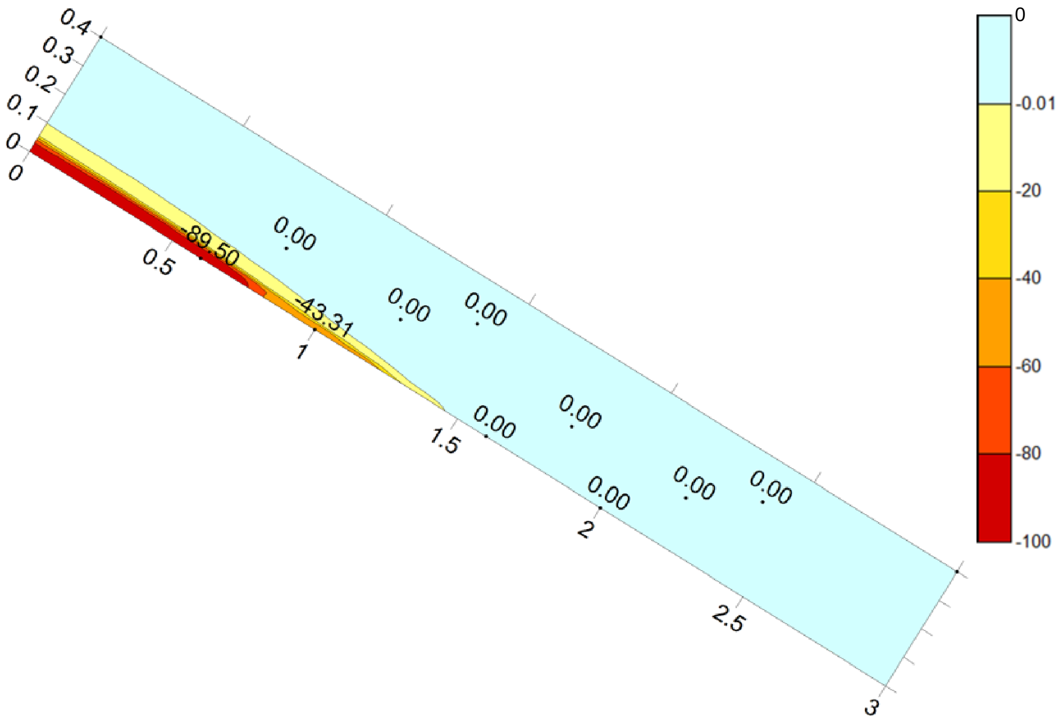

Figure 13. Results obtained from the interpolation of suction data registered after 3 hours and 50 min from rain start.

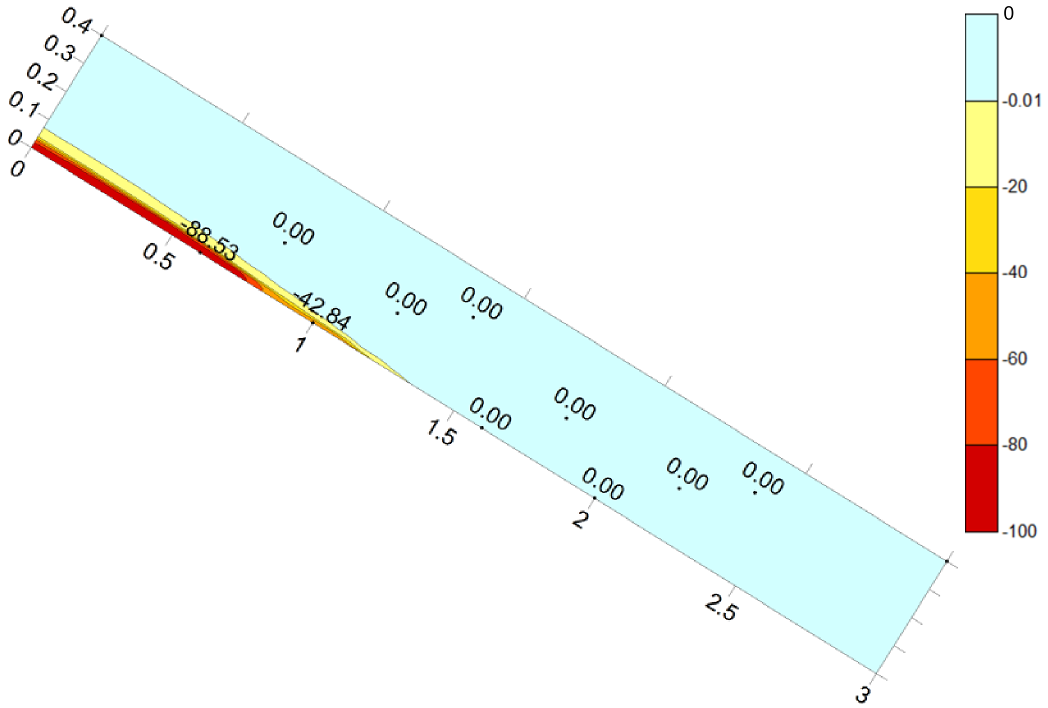

Figure 14. Results obtained from the interpolation of suction data registered after 5 hours from rain start.

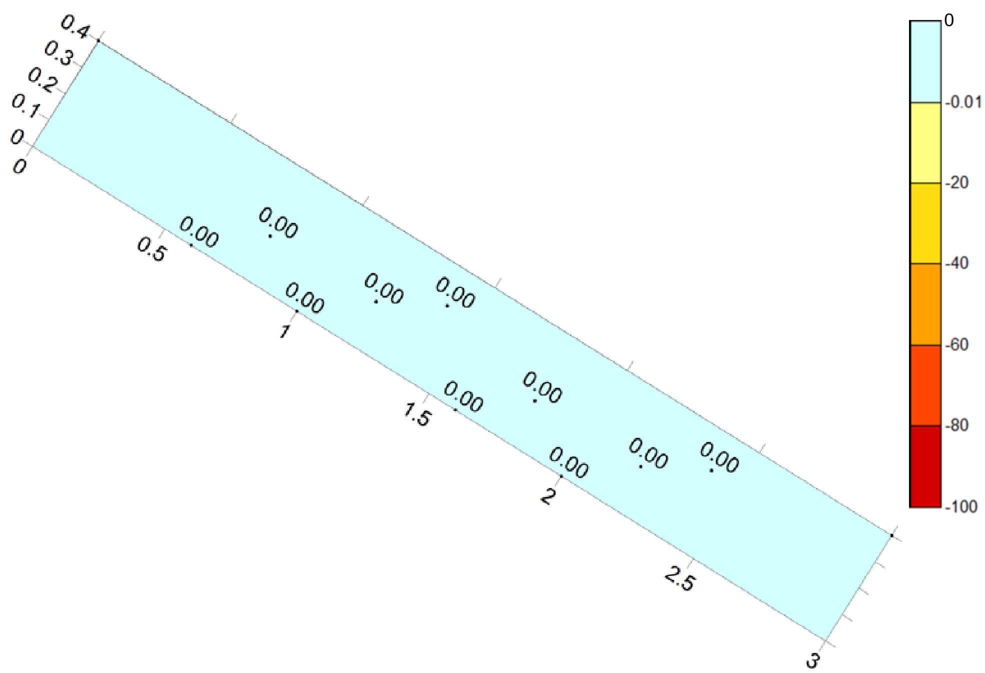

Figure 15. Results obtained from the interpolation of suction data registered after 6 hours and 20 min from rain start (1 hour and 40 min before slide trigger).

Conclusion

In this report it has been reported the first attempt to analyze the suction measures obtained during a test performed on the physical model of slope.

The analysis made consist of interpolations of the suction data along a longitudinal cross section of the soil sample at different time.

The results show the developed of the seepage process inside the sample and how it produced the saturation of the soil until to reach failure. They seems agree with the observed behaviour.

Further analysis of other suction data measured in different tests could give more detail about the development of hydraulic properties inside the sample determined by the simulated rain.