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Determination of the soil-water characteristic curve of the soil by physical modelling tests

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Abstract An increasing number of studies published in the last decade show that physical model experiments are becoming an increasingly popular and more available tool in the study of various problems, such as rainfall infiltration, surface runoff, hydromechanical response of soils and slopes, slope stability, effectiveness of remediation measures, hydraulic barriers, the impact of vegetation on slope stability, etc. The soil water characteristic curve (SWCC), which relates soil suction to soil moisture content, is one of the most important features in unsaturated soil mechanics. Together with the hydraulic conductivity function, it plays a crucial role in the transient rainfall infiltration process and thus has major influence on stability of slopes exposed to rainfall. However, numerous studies have shown that the direct measurement of unsaturated hydraulic parameters using conventional laboratory methods can be difficult, expensive, time-consuming, and involve many uncertainties. This is especially present for fine-grained soils, where unsaturated soil property functions cover a wide range of soil suction that these soils may typically exhibit, and where measurements necessary to determine SWCC typically require the combination of different measurement techniques and equipment. On the other hand, measurements in uniformly graded, coarse soils can be challenging due to the typically highly nonlinear and steep shape of the SWCC, where only a few kPa of soil suction can distinguish between saturated and residual soil moisture conditions. This study presents some preliminary results on determining the SWCC of a uniformly graded sand using a specifically designed physical modelling tests. A 30 cm high slope inclined at 35 degrees and instrumented with soil moisture and pore water pressure sensors was subjected to different simulated rainfall intensities to investigate whether the data on steady-state seepage conditions could be used for hydraulic characterisation of a slope material. The preliminary results indicate that the method is not only useful for this application, but that the approach is useful for the investigation of hydraulic hysteresis and its effects on soil moisture and pore water pressure conditions as well, which also affect slope stability.

Keywords physical modelling, landslides, rainfall infiltration, soil-water characteristic curve, unsaturated soil

Introduction

Claiming numerous victims and causing enormous economic losses in various geological and climatic contexts, landslides represent one of the most devastating geohazards in the world. Although they are often triggered by earthquakes, snowmelt, volcanic or human activity, rainfall infiltration, especially during exceptional rainfall events, is by far the most common triggering factor for landslides worldwide. Considering that, as the consequences of climate change become more pronounced, extraordinary rainfall events are increasingly becoming a common phenomenon, it is not surprising that more and more studies are pointing to the link between changes in precipitation characteristics caused by climate change and the frequency and magnitude of rainfall-induced landslides.

While the physical mechanism of how rainfall infiltration affects the stability of shallow landslides by reducing soil suction (e.g. Montrasio et al. 2016; Toll et al. 2016; Chen et al. 2018; Ebel et al. 2018; Marino et al. 2020), or how the rise in groundwater level associated with prolonged and heavy rainfall can cause slopes to become unstable due to increased pore water pressure (e.g. Comegna et al. 2013; Peranić et al. 2021; Pedone et al. 2022; Tagarelli and Cotecchia 2022; Peranić and Arbanas 2022), predicting the exact location and timing of landslide occurrence remains a major challenge for the landslide scientific community. The complexity of the problem arises from the fact that there are many factors and processes that influence the stability state of a slope, most of them being interrelated and essentially inseparable. Therefore, more and more studies are recognising the need for an interdisciplinary approach to understanding and mitigating the hazards posed by rainfall-induced landslides (e.g. Crozier 2010; Bogaard and Greco 2016).

The soil water characteristic curve (SWCC), which relates soil moisture to soil suction, represents a fundamental feature in unsaturated soil mechanics. In the context of the stability of slopes exposed to rainfall infiltration, it can be considered as a means of providing a link between the hydrological conditions in a slope and its mechanical aspects, i.e. slope stability. In other words, it enables a coupling between the hydraulic response of a slope, which is usually reflected in transient, seepage-induced soil moisture changes resulting from a complex interaction between the surface soil in the unsaturated part of a slope, the atmosphere and the vegetation, and the mechanical response, i.e. how the soil-moisture changes affect stress conditions, the deformations and the available shear strength of a slope. In general, these changes can be caused by both positive (downward) and negative (outward) net fluxes, depending on the interplay between evapo(transpi)rational demands and rainfall conditions on a slope. Due to hysteresis effects, modelling such processes typically requires defining sets of hydraulic parameters that are representative of the drying and wetting processes, i.e. defining the drying and wetting branches of the SWCC. Possible hydraulic paths that the soil can undergo depending on the acting boundary conditions should be constrained by the main drying and wetting branches of the SWCC. Together with the hydraulic conductivity function (HCF) and the rainfall properties, the SWCC plays a decisive role in the transient rainfall infiltration process and thus has a major influence on the stability of slopes exposed to rainfall.

However, direct measurement of SWCC using conventional laboratory methods can be challenging, expensive, time-consuming, and, include a great number of uncertainties (e.g. Ridley and Borland 1993; Oliveira and Fernando 2006; Cresswell et al. 2008). This is particularly present for fine-grained soils, where the unsaturated soil property functions cover a wide range of soil suction that these soils may typically exhibit, and where measurements to determine SWCC typically require the combination of different measurement techniques and equipment (Peranić et al. 2018). On the other hand, measurements in uniformly graded coarse soils can be challenging due to the typically highly nonlinear and steep shape of the SWCC, where only a few kPa of soil suction can distinguish between saturated and residual soil moisture conditions (Peranić et al. 2022; Crescenzo et al. 2024). This study encompasses such types of soil materials.

The study presents some of the preliminary results and experiences in determining the soil-water retention properties of a uniformly graded fine sand using specifically designed physical model tests. A 30 cm high and 35-degree inclined slope model instrumented with the soil moisture and pore water pressure sensors was subjected to increasing and decreasing simulated rainfall intensity to obtain data on steady-state seepage conditions that can be used to hydraulically characterise the slope material. The preliminary results indicate that the approach presented is not only useful for the hydraulic characterisation of the soil, but that the data collected during the experiment could also be useful for studying the effects of hydraulic hysteresis on soil moisture and pore water pressure conditions, i.e. its effects on the stability of slopes exposed to rainfall infiltration.

Methodology

The experimental setup includes a platform for testing slope models exposed to simulated rainfall conditions, a rainfall simulator and a comprehensive monitoring system that allows the hydraulic and mechanical response of the model to be monitored. The platform itself consists of steel elements and transparent Plexiglass side walls. The flume itself is 1.0 m wide, while the upper, inclined and lower segments of the platform are 0.3, 1.4 and 0.8 m long. The geogrid is usually attached to the bottom of the platform, which is made of impermeable steel plates with the afore mentioned dimensions, to prevent slippage of the installed soil material. The rotating hinge connection between the plates and the adjustable height of the steel columns supporting the upper part of the slope enable construction of slope models with desired inclination angles, for example from less than 20 to more than 45 degrees. The transparent Plexiglass side walls are 50 cm high and make it possible to observe the wetting front advancement during the test, as well as the movements at the side of the model. A three-level system of drainage lines inserted through the front-facing Plexiglass wall in the lower part of the flume, allows the water level condition in the model to be controlled during the test and fast drainage of the flume after a test is completed. The rainfall simulator comprises of three independent sprinkling branches that deliver water from the main control block. Each of the branches is equipped with different axial-flow full-cone nozzles, so that the system can generate different rainfall patterns and a wide range of rainfall intensities, depending on the working pressure and spray nozzle(s) used. More details about the platform and the rainfall simulator can be found in Pajalić et al. (2021) and Peranić et al. (2022). Several details about the platform are shown in Fig. 1.

Model build-up and instrumentation

The soil considered in the study, a uniformly graded fine sand (Tab. 1), was used for the construction of two slope models. In both cases, the dry sandy soil was thoroughly mixed with tap water to achieve a targeted gravimetric water content of 2%. Then the predefined amount of soil was placed into the platform and compacted in 5 layers according to Ladd's under-compaction method (Ladd 1974) to build the 30 cm high sandy slope model with homogenous conditions in terms of the initial porosity and moisture, as much as possible. From Tab. 1, the targeted initial porosity of 0.44 corresponds to 50% of the relative density of the sandy soil encompassed in the study. The compaction was carried out in a way that the number of finished (i.e. compacted) soil layers always increased from the lower to the upper part of the slope in order to ensure the stability of a model during the construction.

The first slope model was built directly on the impermeable steel plate, with the slope's toe extending to the end of the flume. However, moulding of the groundwater level in the lower part of the slope during the infiltration stage of the test resulted in most of the monitored points being submerged or taking too long to reach steady-state conditions for the applied rainfall intensity, especially at higher rainfall intensities in the later phase of the test. Therefore, to improve the drainage conditions in the model, the second model was built in the same way, but with 5 cm of gravel placed on the impermeable bottom of the flume before the sandy material was built in and compacted. A geosynthetic was laid on top of the gravel to prevent washout of fine sandy material

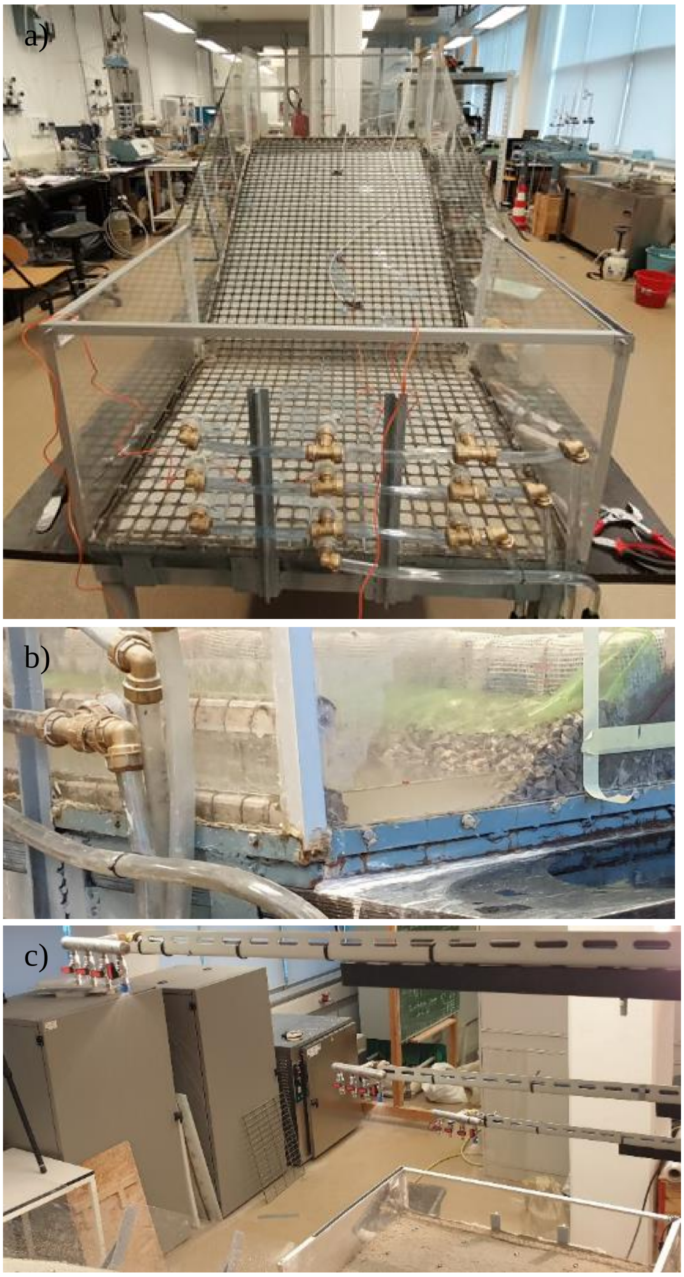

Figure 1 Some details about the testing platform: a) Empty platform prepared for model build-up with geogrid attached to the bottom steel plates and drainage elements in the lower segment of the flume; b) The use of drainage valves to control the boundary conditions (water level) during the experiment considered in the presentation; c) Three branches of the rainfall simulator during the experiment.

Table 1 Properties of the uniformly graded fine sand considered in the study.

Parameter	Symbol	Value	Unit
Specific gravity	G_s	2.7	(/)
Particle size	D_{10}	0.19	(mm)
Particle size	D_{60}	0.37	(mm)
Uniformity coefficient	C_u	1.95	(/)
Min./max. void ratio	e_{min} /e_{max}	0.64/0.91	(/)/(/)
Targeted init. porosity	n_i	0.44	(/)
Targeted init. relative density	D_i	50	(%)
Targeted init. (gravimetric) water content	w_i	2	(%)
Hydraulic parameters*			
saturated hydraulic cond.	k_s	3.3e-4	(m/s)
SWRC parameters	α	0.82	(kPa)
	n	2.7	(/)

*best-fit parameters obtained by numerical inverse modelling (Crescenzo et al., 2024)

into the coarser material during the rainfall infiltration. In addition, the geometry of the model was modified so that it terminates as an “infinite slope” at the bottom, to avoid or postpone rise in groundwater level and saturation of the monitored points in the sloping part of the model. This proved to be beneficial for the purpose of the investigation of hydraulic characteristics of the tested material, as it allowed a longer testing time and achievement of steady-state conditions for the monitored points, even with a relatively high rainfall intensity applied. The gabion wall was installed at the bottom of the slope to ensure that the toe of the slope would not be eroded during prolonged testing time and high rainfall loads applied. The two slope models at the start of the test are shown in Fig. 2. For the sake of brevity, only the results of the second, i.e. “the infinite slope” model are included in this paper.

After the building of the models was completed, the slope models were instrumented to monitor their hydraulic and mechanical response. Changes in soil moisture were monitored using TEROS 10 and TEROS 12 theta probes, while TEROS-31 mini-tensiometers (METER Group AG, Munich, Germany) enabled the measurement of pore water pressure in the positive and negative domain (i.e., soil suction). A central part of the slope model was vertically cut at three different locations, where three measurement profiles were established: one for the upper part (U-profile), and two profiles along the inclined part of the model, one in the upper part (I^U-profile) and one in the lower part (I^L-profile). The position of the profiles in the inclined part of the model was defined to be at one third of the floor plan section length. The sensors were then pushed into the slope model at the depths corresponding to the junction of layers formed during model build-up stage. Care was taken to ensure that minimum disturbance of the soil material was introduced, and that good hydraulic contact was established between the sensor unit and the surrounding soil (Fig. 3). In this way, a total of 18

Figure 2 Models with a 35-degree inclination built from clean, uniformly-grained fine sand at the beginning of the test: The case with impermeable bottom boundary condition and the slope's toe reaching the end of the flume (upper photo); The "infinite" slope model over a 5 cm thick layer of gravel to improve drainage conditions - the case considered in this study (lower photo).

sensors were installed within the slope model along three measurement profiles, as shown in Fig. 4.

A range of measurement techniques, such as photogrammetric equipment for multi-temporal landslide analysis of image sequences obtained from a pair of high-speed stereo cameras, terrestrial laser scanning, structure-from-motion (SfM) photogrammetry surveys, as well as accelerometers, strain gauges, etc. (for more details see Arbanas et al. 2020, 2022; Pajalić et al. 2021; Čeh et al. 2022) can be used to monitor the surface and/or displacements within the slope model. While these are usually crucial for investigating different aspects of landslide triggering mechanisms or different stages of landslide activity, this is not the case for the study presented here. The specific aim of the study, i.e. the investigation of the unsaturated hydraulic properties of the soil, which undergoes negligible volumetric deformations during the rainfall infiltration (Crescenzo et al. 2024), where the stability of the slope and the absence of larger shear deformations is the condition required for proper data analysis, the geodetic and geotechnical parts of the monitoring related to the displacements of the model essentially represent a tool that only checks the condition of negligible soil deformations during the test. In this case, no coupling between pore water pressure and soil deformations is required. Therefore, pins with marker points were placed on the surface of the model and a continuous monitoring of the 3D coordinates of the reference points was performed during the tests using the optical non-contact 3D measurement system ARAMIS 4M (GOM mbH, Braunschweig, Germany) only for the first model (upper photo in Fig 2). While further details on the measurement system can be found elsewhere (Pajalić et al. 2021; Čeh et al. 2022; Peranić et al. 2022), the results on the mechanical response of the models are irrelevant for the present study and thus are excluded from this presentation.

Once the slope model was built and instrumented with monitoring equipment, the model was covered with nylon to prevent loss of soil moisture through evaporation until the test was started. All sensors were connected to corresponding data logging units and appropriate recording intervals were selected.

Testing conditions

Starting from the initial (known) soil moisture and pore water pressure conditions, the slope model was subjected to a range of rainfall intensities until steady-state conditions were observed for the monitored points. Given the purpose of the study, rapid drainage of the sandy slope model was desirable. Therefore, the drainage valves were constantly open to prevent any pore water pressure build-up in the slope, i.e. to maintain the rainfall infiltration process through the model in partially saturated conditions.

Starting from relatively dry, i.e. near-to residual soil moisture conditions, the test was initiated with the relatively low rainfall intensity of 36.9 mm/h, which was kept constant for 66 minutes. As no further changes in pore water pressure and volumetric water content were observed, the working pressure and nozzles were combined so that the rainfall intensity was approximately doubled in the following test phase. The rainfall intensity was maintained at 78.6 mm/h until the 148^{th} minute of the

Figure 3 Detail of the installation of the soil moisture sensor and the mini-tensiometer at the monitored point I^L-6.

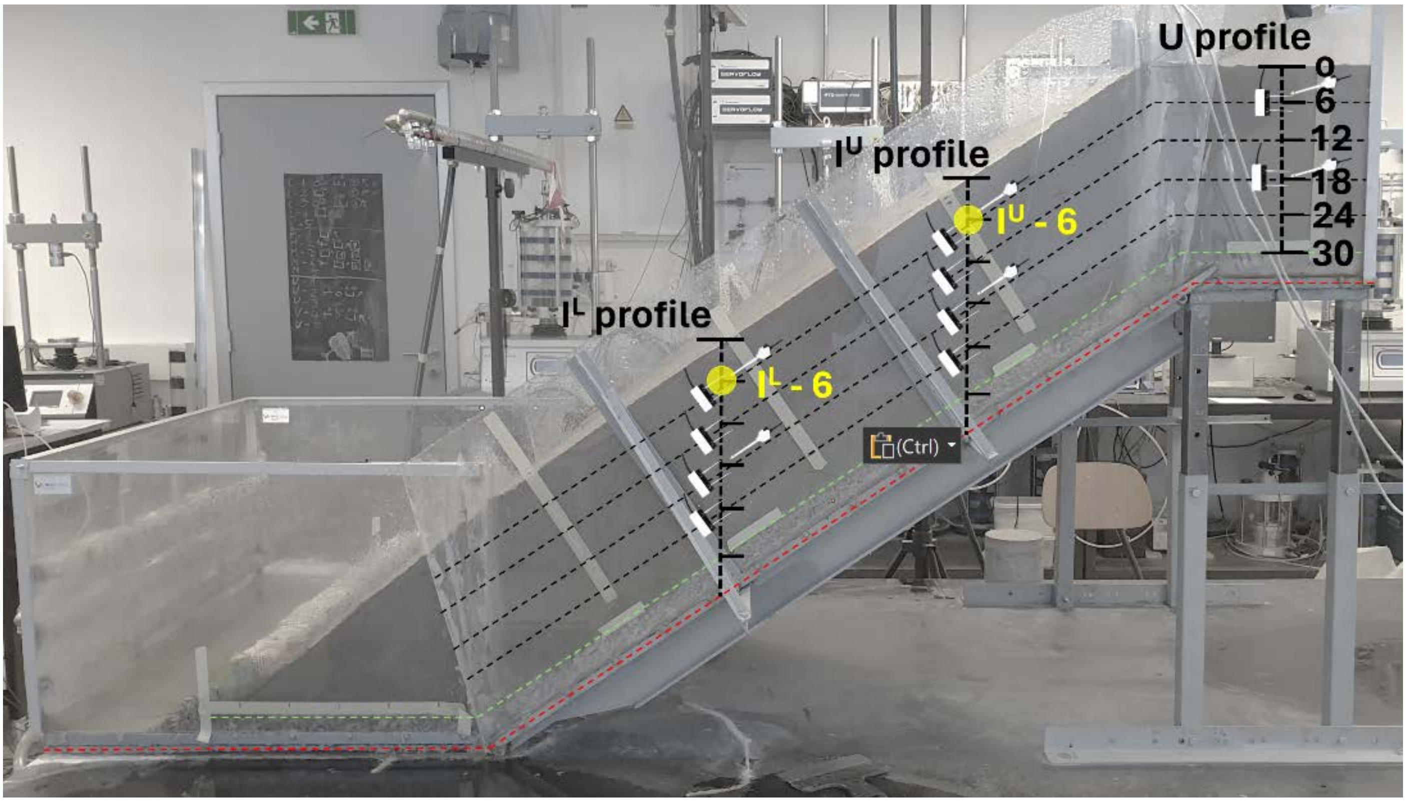

Figure 4 Schematic representation of the measurement profiles and the points at which the hydraulic response was measured in terms of volumetric water content ( ) and pore water pressure ( ). The two uppermost measurement points, for which the data on soil suction and volumetric water content are presented in the study, are outlined in yellow.

test. Again, steady-state conditions were established under the applied (constant) rainfall conditions so that the intensity of the simulated rainfall was again approximately doubled and maintained at 157.2 mm/h until the 180th minute of the test. Finally, the rainfall intensity was reduced to the starting value, i.e. 36.9 mm/h and was kept constant until the hydraulic equilibrium at the monitored points was observed.

After 306 minutes of the test the rainfall was stopped, and the first stage of the test was declared completed. However, the collection of the data from the hydraulic monitoring system was continued during the drainage stage of the slope in the following weeks. Finally, the second stage was carried out a few weeks later to test the model's response to extremely high rainfall intensity. In this case, the rainfall intensity of 300.3 mm/h was maintained for 34 minutes when the test was stopped as traces of slope failure have started to appear. The rainfall conditions for the two test stages considered in the study are summarised in Fig. 5.

Results and Discussion

The measured volumetric water content and pore water pressure values (i.e., matric suction in this case) for the U^I-6 and I^L-6 monitored points (locations in Fig. 4) are shown in Fig. 6. Some interesting points are discussed and outlined in the following part.

After the onset of rainfall, it takes about 10 minutes for the wetting front to reach monitored points and for theta probes and mini-tensiometers to register changes in volumetric water content and soil suction. While the readings on change in soil moisture appear to be more diffuse and the time to reach steady-state conditions is more than 20 minutes, an abrupt decrease in soil suction is observed in the data collected with the mini-tensiometers, and a much shorter time to reach constant reading values. In any case, from the 40th minute of the test, both monitored points appear to reach hydraulic equilibrium and constant readings for both soil moisture and suction. In the following phase of the test, the increase in soil moisture and pore water pressure seems to be immediate with the increase in rainfall intensity from 36.9 to 78.6 mm/h and steady-state conditions are established much faster for both monitored points. A very similar response is observed for the test period around the 148th minute when the rainfall intensity was further increased to 157.2 mm/h. It is interesting to note that despite the increase in rainfall intensity from 37 to 157 mm/h, soil suction remained unchanged, with the difference between the steady-state conditions for the two rainfall intensities being less than 0.3 kPa. The volumetric water content increased from about 0.22 to 0.26 with the same increase in rainfall load.

An interesting observation can be made for the drying response of the monitored points, which was

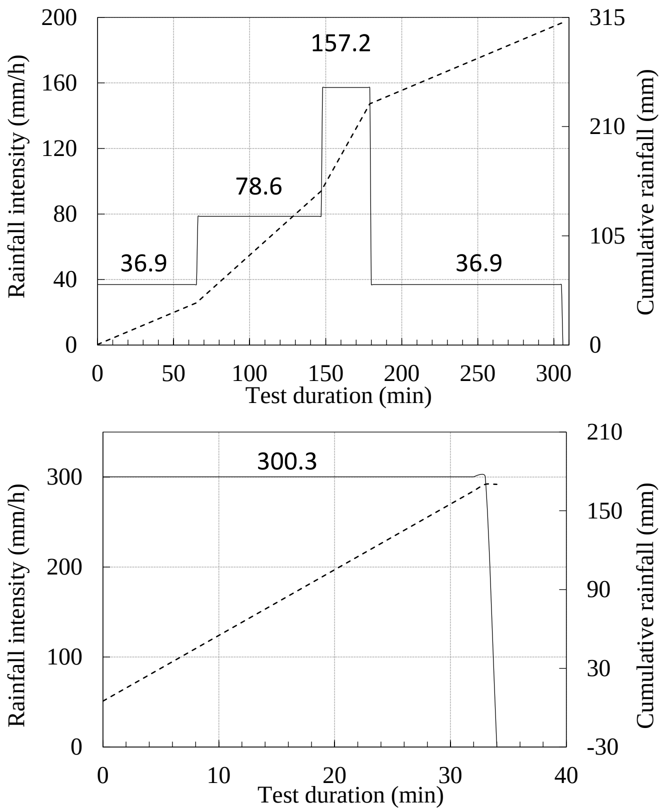

Figure 5 Rainfall conditions applied in the first (top) and the second (bottom) stage of the test.

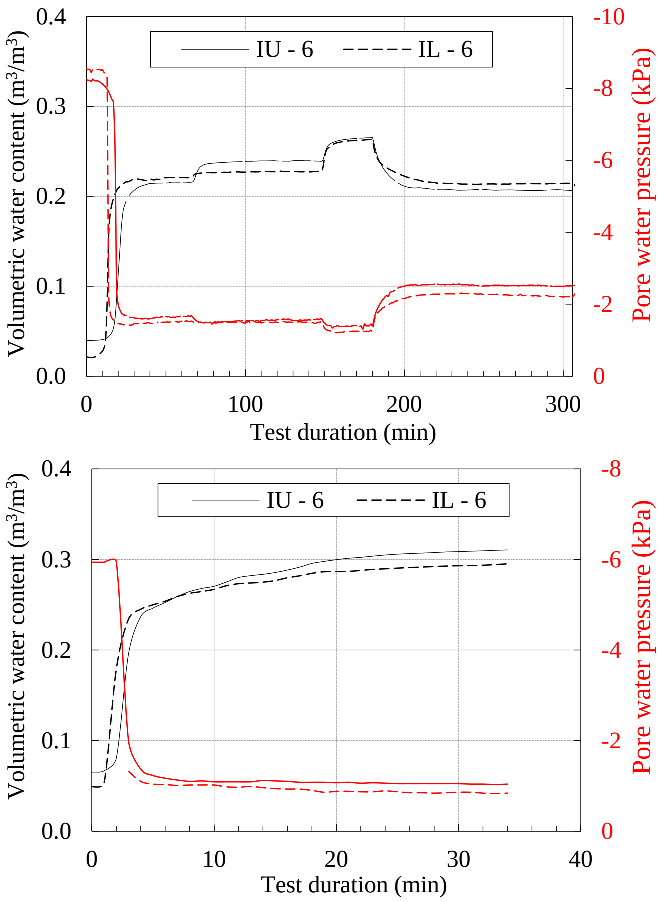

Figure 6 The volumetric water content and the pore water pressure (i.e. matric suction) for the monitoring points U^{I}-6 and I^{L}-6 (see Fig. 4) in the first (upper diagram) and second (lower diagram) stage of the test.

induced by the reduction in rainfall intensity from the 180th minute of the test. Now the response appears to be much slower, both in terms of soil moisture and change in soil suction, with both instrumented points approaching equilibrium conditions over the following 20 minutes or more. Unlike the steady-state volumetric water content conditions, which closely correspond to those from the first phase of the test, soil suction is evidently higher in the case where steady-state conditions are achieved by reducing rainfall intensity rather than by increasing it.

The data from the second stage of the test provides an interesting insight into the hydraulic response of the soil when exposed to an extremely high rainfall intensity of 300 mm/h. After allowing the slope model to drain freely for an extended period of time, the second test stage of the test begins with relatively dry conditions, although the soil suction value appears to be slightly lower than in the previous case. The wetting front has reached the monitored points much faster now, with changes in soil moisture and suction values observed within a minute or two after the rainfall was started. Again, similar considerations could be made regarding the diffuse nature of the changes in soil moisture and the abrupt changes in soil suction as before, although it is unclear whether the equilibrium volumetric water content conditions were reached by the end of the test, as it appears to increase slowly but steadily even after the 20th minute of the rainfall application. However, an important observation is that even with a rainfall intensity of 300 mm/h, the negative pore water pressure, i.e. soil suction, was still maintained at the monitored points.

All previously presented pairs of volumetric water content and soil suction are plotted in Fig. 7 with the soil suction in logarithmic form – a plane typically used to present SWCC. In the same figure, the SWCC obtained for the same soil by numerical modelling of small-scale slope model subjected to rainfall according to the methodology proposed by Crescenzo et al. (2024) is shown in a continuous black colour. The hydraulic paths that the monitored points undergo during the first stage of the test are summarised in Fig. 8 together with the SWCC branches obtained. While a detailed discussion on the SWCC branches, shown in dashed red (drying) and blue (wetting) lines, as well as the data presenting the hydraulic paths of the monitored points is beyond the scope of this presentation, it is worth noting the fit between the SWCC branches and the obtained data, while the wetting branch obtained by Crescenzo et al. (2024) falls close to the data obtained for the wetting path, albeit slightly more to the wet side.

These preliminary results suggest that the physical slope model tests could be useful not only for the hydraulic characterisation of the soil, but also for the investigation of a range of problems associated with rainfall-induced landslides.

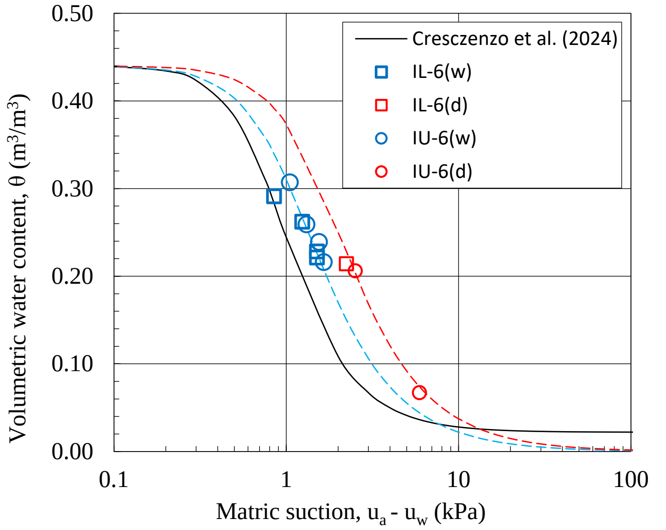

Figure 7 Steady-state volumetric water content and soil suction data obtained for the monitored points on the drying (red markers) and wetting (blue markers) paths, together with the SWCC numerically determined by Crescenzo et al. (2024).

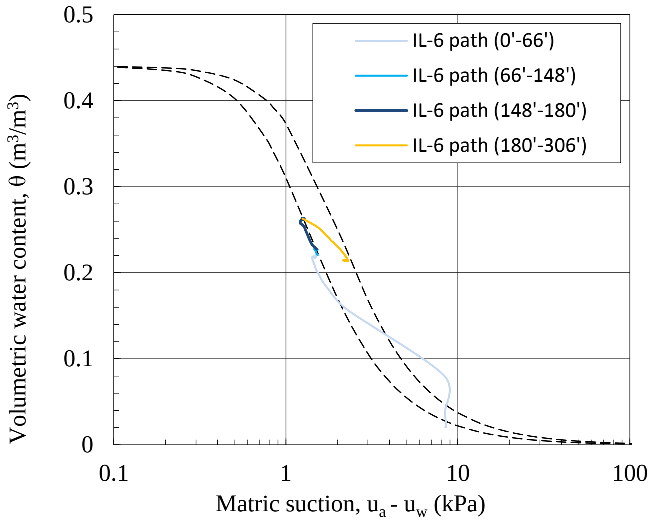

Figure 8 The hydraulic paths reconstructed for the monitored points during the first stage of the test, together with the branches obtained from the data presented.

Conclusions

In this study, some preliminary results and experiences were presented on the possible use of physical slope model tests to determine a SWCC of the uniformly graded sand. The study involved the 30 cm high, 35-degree inclined slope equipped with soil moisture and pore water pressure sensors and subjected to various simulated rainfall intensities. While these preliminary results suggest that the approach could be very useful to investigate different aspects of the hydraulic response of slopes exposed to a rainfall, e.g. for soil hydraulic characterisation, as well as to gain insight into the hysteretic hydraulic response of slopes and how this might influence the stability conditions of the slope, some aspects of the presented approach that could be improved were also discovered.

For example, using the very limited data presented in the study (for brevity, data from only two monitored points were included in the presentation), it is evident that for a soil under consideration, the possibility of applying a wider range of rainfall intensities, particularly those that would cover parts of the SWCC where residual conditions along the wetting path approach, or applying high rainfall intensities where the SWCC would approach saturated soil moisture conditions, would be extremely valuable to the approach.

In addition, the study considered a soil that undergoes negligible volumetric deformations when soil moisture (i.e. suction) changes occur. If the approach is to be generalised to fine-grained soils, where hydromechanical coupling would be required to obtain an adequate hydraulic characterisation of such soils, the approach should also use the geodetic and part of the geotechnical monitoring system, which would provide the data that would allow quantification of the deformations induced in different phases of a test. Additional considerations need to be made to distinguish between the various possible SWCCs that the approach could yield depending on the initial soil moisture conditions or hydraulic conditions to which the soil is generally exposed during the test.

Finally, the different responses observed under different rainfall conditions have direct impact on the stability state of a slope exposed to rainfall. However, the rainfall to which slopes are exposed in the field are much more complex and exhibit strong temporal and spatial variations (Peranić and Arbanas 2022). These are some of the aspects that should be further investigated to improve understanding and modelling capabilities and mitigate the hazard posed by rainfall-induced landslides.

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