Experimental and Numerical Investigation of One-Dimensional Infiltration into Unsaturated Soil

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Abstract. Infiltration characteristics of an unsaturated soil are of interest in both seepage and stability analyses and should be evaluated carefully. In this study, a new large-scale one-dimensional infiltration column test setup was developed, with an inner diameter of 0.24 m and a length of 1.3 m. In the tests conducted, 1.0 m of the column height was filled with soil and 0.3 m remained above for constant water head. The column was instrumented with five pairs of in-situ volumetric water content sensors and suction sensors. This paper explains the methodology used in the construction of the test setup and how the unsaturated properties were calculated for the tested soil, namely the soil water characteristic curve (SWCC) and soil permeability function (SPF). Infiltration tests were performed on a fabricated homogeneous clayey sandy silt similar to naturally available materials representative for Norwegian conditions. Soil specific SWCCs were established under steady state boundary conditions using the sensor outputs, and the results are presented. The instantaneous profile and wetting front advance methods, and relationships based on the SWCC were utilized to establish SPFs, and the results are discussed. A sensitivity analysis was run on the SWCC curve fitting parameters and effects of the parameters on infiltration time are presented. The results from the combined experimental and numerical analysis show that it may be possible to use the new test setup to develop unsaturated soil relationships, but accuracy and measurement range of the sensors are crucial to obtaining consistent results.

Keywords: Infiltration · Column testing device · Unsaturated soil · SWCC · Wetting curve

M. Barla et al. (Eds.): IACMAG 2021, LNCE 125, pp. 251–259, 2021.
https://doi.org/10.1007/978-3-030-64514-4_20

1 Introduction

Many places around the world are affected by rainfall-induced landslides. This type of landslide often occurs in unsaturated soil slopes in remote or difficult to access areas, and conventional soil mechanics does not commonly consider the effects of negative pore-pressure, or suction, in effective stress calculations for slope stability. The soil water characteristic curve (SWCC) defines the relationship between moisture content and suction in soil due to interaction between the air and water phases in a saturating or desaturating soil. SWCC can be used to derive relationships for unsaturated soil permeability and water storage. As the rainfall infiltration begins to saturate the soil, the suction levels in the soil tend to decrease, which can result in slope destabilization.

In this study, a large-scale infiltration column was designed and constructed to perform constant head infiltration tests on soil typical for Norwegian conditions. The column was instrumented with moisture content and suction sensors to monitor changing soil conditions during infiltration. The sensor data was used to create a soil specific SWCC for the tested material. Soil permeability functions (SPFs) were also derived using combinations of three methods: statistical SWCC interpretation, sensor measurements, and visual interpretation. A numerical model using PLAXIS was created to simulate infiltration, and infiltration times were compared to the experimental model. Finally, a sensitivity analysis was performed on the SWCC parameters using the numerical model to evaluate the influence on infiltration time. The results of this study and the observations made during the tests are providing insights into the large-scale laboratory infiltration testing and sensor performance.

2 Column Design and Characteristics

The infiltration column shown in Fig. 1 is made of acrylic plexiglass, stands 1.3 m tall with an internal diameter of 0.24 m, and has a wall thickness of 5 mm. The bottom of the column slides onto a base assembly made of polyoxymethylene (POM) and seals around an o-ring to prevent water leakage. A filter system of perforated stainless-steel plate overlaid with geotextile cloth is placed between the column base and the soil to minimize fines migration out from the sample base. The top of the base assembly is etched with drainage paths leading to a central drainage channel exiting the base at the valve shown at the bottom of Fig. 1a.

The soil column was filled with 1.0 m of soil, leaving 0.3 m above the soil to be filled with water. Within the soil column, five sensor clusters, containing one volumetric water content sensor (METER Group, ECH2O EC-5) and one suction sensor (METER Group, TEROS 21), were placed at intervals of 0.15 m, starting from a depth of 0.15 m from the top of the soil. The sensors were connected to a laptop through dataloggers, where the software package LabView (Version 18.0.1f2) was used to record sensor readings. Then, a constant head of water was applied at the top of the soil column using a water supply system, shown in Fig. 1b. An airtight water tank was placed directly above the soil column with an outlet from the tank base leading vertically downwards to the soil column. The outlet of the hose was placed at the desired

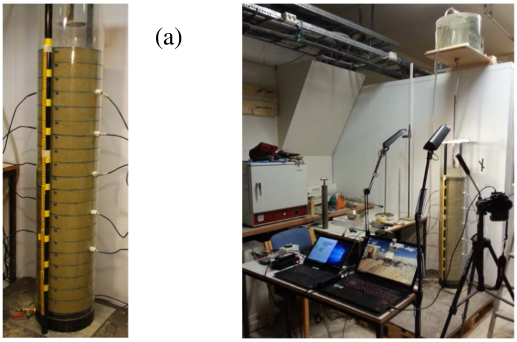

Fig. 1. Infiltration column test setup: soil column (a) and complete test setup (b)

water level and would only allow water refilling to occur when the water level dipped below the hose outlet.

3 Material Characteristics and Placement

The material used in testing was created from three separate available soil samples, and the combined material used for testing contained on average 12% clay, 47% silt and 41% sand based on sieve and hydrometer testing for each infiltration test conducted. The grainsize distribution was selected based on initial testing using a smaller permeameter cell and numerical modeling to find an acceptable infiltration rate and generation of suctions detectable by the range of the chosen suction sensor.

The residual gravimetric water content of the sample was found to be around 7%, to which the tested sample was moisture conditioned before placement in the column. This was to focus on obtaining the transition zone of the SWCC and reduce infiltration time.

The sample was placed into the column in 0.05 m lifts at a dry density of 1415 kg/m^3. At each sensor cluster level, the sensors were placed horizontally on top of a compacted lift and the cables pulled through the cable glands (Fig. 2). The subsequent lift was carefully added and compacted as normal.

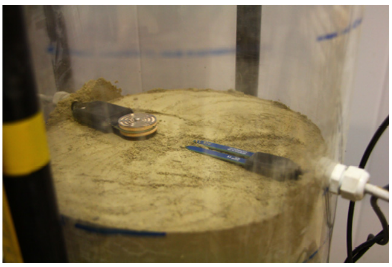

Fig. 2. Sensor placement

4 Testing and Results

Three infiltration tests were completed with initial conditions shown in Table 1. New soil samples were prepared for test-1 and test-3, and the soil from test-1 was used after drying and replacing it into the column for test 2. The sensor readings were set to begin recording at the same time as the water head was applied to the soil sample. The following sections provides the results obtained from the infiltration tests, and discussions are made on the testing and results in Sect. 5.

Table 1. Initial testing conditions

Variable	Test 1	Test 2	Test 3
Soil source	New	From test 1	New
Dry density (kg/m3)	1415	1415	1415
Gravimetric moisture (%)	7.00	7.00	7.00
Water head above soil (cm)	10	10	20

4.1 Soil Water Characteristic Curve

The readings from the VWC sensors and suction sensors during testing were used to create a SWCC for the tested material. Figure 3 shows the average SWCCs found using the van Genuchten-Mualem (van Genuchten 1980; Mualem 1976), Fredlund-Xing (Fredlund and Xing 1994) and Brooks and Corey (Brooks and Corey 1964) formulations with the sensor readings greyed out behind. The SWCCs were fit using a least-squares linear regression to data by minimizing the R2 value. Maximum and minimum bounding curves are also shown for the van Genuchten-Mualem fit.

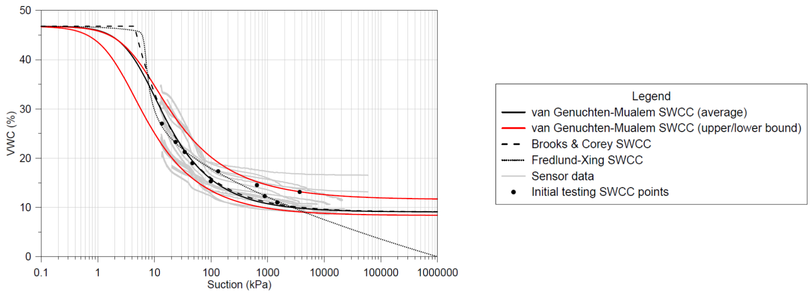

Fig. 3. Soil water characteristic curves with sensor readings

4.2 Soil Permeability Function

Three methods were used to evaluate the SPF of the tested material. First, the van Genuchten-Mualem formulation based on the SWCC was used. Second, the instantaneous profile method was applied as per ASTM D7664-10(2018)e1 (ASTM 2010) using the instrument data directly. Lastly, the wetting front advance method, proposed by Li et al (2009), was attempted using a combination of sensor data and visual observations. Figure 4 shows the different SPFs for the tested material. The detailed description of the methods and applications can be found in Robinson (2019).

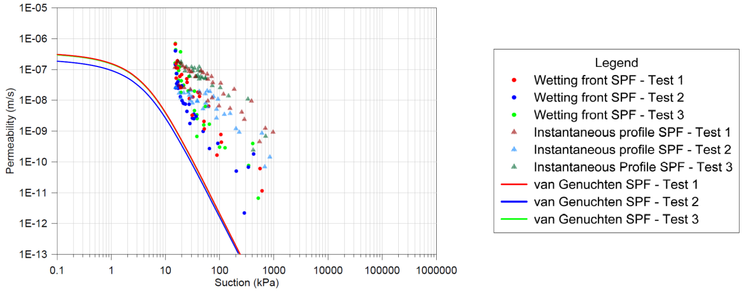

Fig. 4. Soil permeability functions generated by the van Genuchten-Mualem formulation (continuous curves), instantaneous profile method and the wetting front advance method

5 Discussion on Experimental Testing

Several observations were made on the soil and infiltration characteristics before and during the test. Firstly, occasional voids were observed during the compaction of the soil in the column. These occasional voids could be the reason of non-linear infiltration trends and uneven infiltration across the sample surface. In addition, consolidation took place in the soil column as the soil saturated. Therefore, voids developed below the cable glands where the instrument cables passed through the column wall, and the voids were larger below sensors close to the surface than sensors at a depth. An example of sensor output record is shown in Fig. 5, normalized to the maximum of each sensor reading.

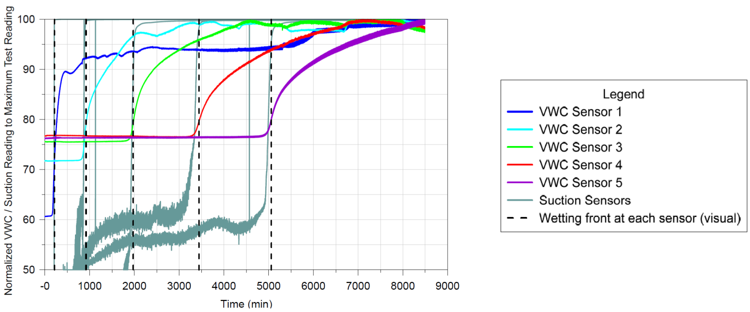

Fig. 5. Both volumetric water content and suction sensor outputs

Variation in the VWC readings from the sensors can be attributed to the void development. The VWC reading from sensor 1 stabilizes slightly below 95% of the maximum reading level until around 5500 min, where the saturation level begins to increase again, indicating the voids may have filled with water as the test progressed. In the initial tests with the sensors, the suction sensor was found to be highly susceptible to error depending on the wetting front advance rate due to non-linear response time of the sensor. Since each test was completed in different timeframes and the wetting front slowed with infiltration depth, the data scatter could be partially explained by the suction sensor response time.

Three methods, namely the instantaneous profile method, wetting front advance method, and SWCC-SPF relation, were used to determine the SPF. The instantaneous profile method averages sensor readings across the sensor locations at the same time "instant", which has the potential to introduce averaging errors. Due to the response times of the different sensors, at the same time instant, the VWC or suction along the profile for one sensor is relatively linear while the other sensor is not. The wetting front advance method averages the sensor readings at the same sensor location but at two points in time. This method relies on the clarity and interpretation of visual observations of the wetting front during testing to estimate the depth of wetting front advance. Photos obtained during testing were of good quality, however since the wetting front advance was slow in some cases, discerning small changes in wetting front location was challenging. For example, the suction sensor could go from dry to wet and beyond the measurement limit without significant visual changes on the wetting front. The van Genuchten-Mualem SPF was determined using the average curve fitting parameters obtained by fitting the SWCC. As shown in Fig. 4, the results obtained using various methods gave different results, which can partially be explained by trapped air in the sample. Available flow channels were likely blocked from the trapped air, thus reducing the measured permeability of the sample to below the saturated permeability. If the true saturated permeability was higher by one order of magnitude, the van Genuchten-Mualem SPF would be in a similar range to the instantaneous profile and wetting front advance methods.

6 Numerical Infiltration Study

The laboratory infiltration tests were reconstructed in the software package PLAXIS 2D to evaluate if the infiltration times could be predicted. An axisymmetric transient flow only analysis with the same dimensions as in the laboratory model was created. The hydraulic properties required for a flow only analysis includes the initial void ratio, saturated permeability, and SWCC parameters. The initial void ratio was 0.98 for all tests and the calculated permeability was used from each infiltration test. The SWCC parameters input were from the average van Genuchten-Mualem formulation as shown in Table 2a. Due to high non-linearity in the SWCC, the numerical control parameters in PLAXIS required modifications to the minimum and maximum step size, and tolerance level in order to provide consistent and stable results. Simulations were run for each of the three laboratory infiltration tests, and the comparison of laboratory and numerical infiltration times are shown in Table 2b.

Table 2. Average van Genuchten SWCC parameters (a) and infiltration time comparison (b)

(a)

Parameter	Value
S_{res}	0.2114
S_{sat}	1.0
a (1/kPa)	0.1796
n	1.600
l	0.5

(b)

#	Lab. Test (min)	PLAXIS (min)
1	3735	13464
2	8207	21935
3	3124	12672

The infiltration times computed by PLAXIS were between 2.7 and 4 times longer than the experimental infiltration times. A sensitivity analysis was then run on the input parameters to determine which had the largest influence on the infiltration time. In the van Genuchten-Mualem formulation, the infiltration rate is directly dependent on the saturated permeability. As the saturated permeability is presumed higher than obtained, this would increase the infiltration time in the numerical model. The other parameters influencing infiltration are the van Genuchten-Mualem curve-fitting parameters.

Since the SWCC was based on sensor readings with large scatter, some error was introduced to the numerical model with these parameters. The van Genuchten-Mualem "a" and "n" parameters were varied individually to see the effect on the shape of the SWCCs and SPFs and the resulting changes in infiltration times, keeping all other variables constant. The best combination of "a" and "n" giving the infiltration time as 3143 min for test 3 is 0.2 m^{-1} and 2.3 respectively. Results show that combining several parameters could yield infiltration time similar to those obtained in the laboratory. The parameter combinations giving the closest infiltration time to that of the column time were plotted as SWCCs and SPFs with the original data, as shown in Fig. 6.

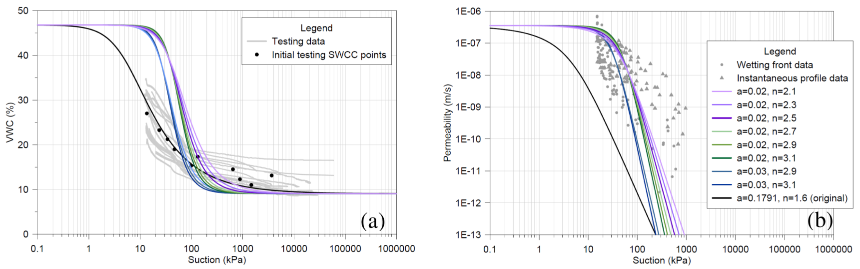

Fig. 6. SWCCs (a) and SPFs (b) giving numerical infiltration time similar to laboratory test

7 Conclusions

An instrumented large-scale infiltration column was successfully constructed, and three tests were performed. Based on sensor data, SWCCs and SPFs for each test were determined. The laboratory tests were then modeled using the finite element software PLAXIS 2D, and the infiltration times were compared. The sensors were evaluated through their performance during testing. The VWC sensor provided a quick response to changing moisture conditions, however, results fluctuated slightly during infiltration testing possibly due to voids forming beneath the sensor. The suction sensor showed slower equalization time, particularly in dry soil conditions, which affected SWCC and SPF determination. The measurement range of the suction sensor was insufficient to measure the transition zone of the SWCC and should only be used in materials with high air entry value and lower permeabilities.

The derived SWCCs and SPFs from sensor data depended on the reliability of the sensor readings. A large amount of scatter in the data led to low confidence in the unsaturated soil relationships, as was shown when compared to numerical modeling results, as the numerical model gave infiltration times 2.6 to 4 times that of the laboratory model.

A back-analysis on SWCC parameters showed one parameter set is not a unique solution for a soil, and that multiple parameter sets could give similar infiltration times. Parameter sets giving infiltration times within 20% of the column infiltration time were plotted and found to be steeper and with a higher air entry value than what was found for the average SWCC from sensor data, however, the SPFs plotted similarly to the SPFs found by the instantaneous profile and wetting front advance methods.

The results from the combined experimental and numerical analysis show that it may be possible to use installed soil sensors to develop unsaturated soil relationships. However, the accuracy and measurement range of the sensors are crucial to obtaining consistent results. Numerical analysis is an approximation of a complex physical process, and the combination of uncertainty in input parameters and simplifications during modeling can lead to different results from experimental findings.

Acknowledgments. The authors gratefully acknowledge the support from the Research Council of Norway, the partners through KlimaDigital (www.klimadigital.no), and to a strategic initiative by NTNU related to Resilient and Sustainable Water Infrastructure (www.sfiwin.com).

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