Determination of soil water retention curve of residual soil from a flysch rock mass

J. Peranić & Ž. Arbanas
Faculty of Civil Engineering, University of Rijeka, Croatia

V. Foresta & S. Cuomo
Department of Civil Engineering, University of Salerno, Italy

M. Maček
Faculty of Civil and Geodetic Engineering, University of Ljubljana, Slovenia

ABSTRACT: Soil water retention curves (SWRCs) are known as the main tool for assessment of unsaturated soil property functions and are used to extend the conventional saturated soil mechanics with unsaturated soil mechanics principles. This paper presents experimental procedures used for determination of the SWRC on undisturbed samples from flysch material. Soil samples were taken from the Valići Landslide (out of the City of Rijeka, Croatia) colluvium material (residual soil) that is composed of completely weathered siltstones from the flysch bedrock. Different laboratory devices and techniques were used to assess the suitability of used procedures and to determine a wide range of suction values present in this type of soil material. Within low range of matric suction (below 200 kPa), the standard pressure plate extractors and HYPROP device were used. Measurements were extended to the middle suction range using two different suction controlled oedometer devices, with different capacities of high air entry porous disks (HAEPDs). Dew point potentiometer WP4-T was used to measure medium and high suction values. As the conclusion, some advantages and drawbacks of used procedures for the specific type of soil are presented.

1 INTRODUCTION

Numerous landslides that have occurred in the flysch deposits along the northern Adriatic coast of Croatia were mainly caused by heavy rain. Previous landslide studies were mainly focused on pore water pressure increasing caused by long-term heavy precipitations (Arbanas et al., 2014) and effects of weathering process on the shear strength of residual soils from Paleogene flysch rock mass (Vivoda Prodan et al., 2016). However, no efforts were made to assess the influence of negative pore water pressure that occur in flysch slopes above phreatic line, in terms of unsaturated soil mechanics.

In order to obtain an insight on the influence of unsaturated soil behavior on infiltration process and shear strength of soil material, series of laboratory tests have been conducted to obtain data for quantification of hydraulic conductivity and water storage capabilities of residual soil from flysch deposits near the ground surface. This data should ensure a basis for further investigation of instability phenomena that occur in slopes built in this material.

Preliminary estimations indicated on low values of saturated hydraulic conductivity in this type of soil, commonly measured as a lower limit for silts. Because of no previous experiences about hydraulic properties of the soil in unsaturated conditions, a significant effort was made to determine relationships between the matric suction values and water content. Different testing conditions were used to simulate possible circumstances in the field (overburden pressure, evaporation and infiltration process). The established soil water retention curves (SWRCs) could be used for estimation of unsaturated soil property functions (USPFs) that would ensure a good insight in hydro-mechanical properties of the soil and avoiding of time-consuming and costly direct measurements of unsaturated soil behavior.

The first measurements of matric suction were conducted in the Geotechnical laboratory of Department of Civil Engineering, University of Salerno (UniSa), Italy. Tests were performed using the standard (RP) and volumetric (VE) pressure plate extractors and the suction controlled oedometer device (SCOED). Another type of suction controlled oedometer device that allows back pressurization and saturation of specimen was used in the Geotechnical laboratory of Faculty of Civil Engineering, University of Rijeka (UniRi), Croatia. Series of tests were conducted in the Geotechnical laboratory of Faculty of Civil and Geodetic Engineering, University of Ljubljana (UniLj), Slovenia, where the HYPROP evaporation method device with mini tensiometers was used to measure matric suction and hydraulic permeability in the wet part of the SWRC. Dew-point potentiometer WP4-T device was used for measurements in the high-suction range.

Standard measurements using pressure plate extractors and WP4-T device were combined with the wax dipping and water displacement technique, enabling determination of specimen density after equilibrating at imposed suction values. In this way, the results obtained by standard pressure plate extractors and WP4-T apparatus enabled determination of all volume-mass soil properties. By combining the results obtained using different devices and techniques, the SWRC was determined through all three characteristic zones: below the air entry value (AEV), in the transition zone and residual zone, providing useful results for future research on rainfall infiltration mechanisms.

2 MATERIAL AND STUDY AREA

The Rječina River Valley in the outback of the City of Rijeka, Croatia, is well known by numerous historical and recent landslides on both slopes of the valley (Arbanas et al., 2014). The valley is composed of the Cretaceous and Paleogene limestone situated at the top of the slopes, while the Paleogene siliciclastic rocks and flysch are situated on the lower slopes and in the bottom of the valley. The flysch rock mass is characterized by lithological heterogeneity as a result of frequent vertical and lateral changes in lithological sequences, including marls, siltstones, and sandstones (Vivoda Prodan et al., 2016).

The weathering process in flysch rock masses has a significant influence on the major geomorphological process on flysch slopes in the study area: landslide phenomena. Small- to medium/large-scale landslides with slip surfaces within the flysch rock mass have been observed, as well as many small reactivated landslides in the colluvium of ancient landslides (Arbanas et al., 2014; Vivoda et al., 2012). The colluvium material is very heterogeneous and it is mostly composed of residual soil where silty and clayey particles are mixed with different content of siltstone debris. The most of landslides were triggered after long-term previous precipitations that caused the rise of groundwater level affecting on raising of pore water pressures and decreasing of shear strength of the soil material in a slope.

Previous landslide studies did not account for the the influence of negative pore water pressure on slope stability. Because of the complexity of this material, the negative pore water pressure would have an important role in landslide (re)activation. Determination of the SWRC is the first step in analyses of unsaturated soil behavior in slopes composed of residual soils from flysch rock mass.

Undisturbed soil samples were taken from the surface of the Valići Landslide in October 2016 and series of tests were conducted to determine basic index properties of soil. Sampling depths for all samples were from 0.5 to 1 m. Natural water content ranged from 28% at the ground surface to 10% at depth of 1m. In situ densities from 1.91 to 2.13 g/cm^3 were measured and soil particles specific gravity G_s of 2.70 was determined.

Particle size distribution was determined using the wet and dry sieving methods and sedimentation tests in three different laboratories: University of Rijeka (UNiRi), University of Zagreb (UniZg) and Univrsity of Salerno (UniSa) (Fig.1). Results show that silt (56%) and clay (31%) particles prevail in soil samples. Liquid limit w_L of 45% and index of plasticity I_p of 21% classify material as a clay of medium plasticity, CI. Samples are characterized by general heterogeneity and the occasional presence of roots, organic matter and silt grains that vary in size and weathering degree.

3 DEVICES BASED ON AXIS TRANSLATION TECHNIQUE

Pore water pressure in unsaturated soils is generally negative with a respect to an atmospheric pressure. Due to cavitation-associated problems, direct measurements of negative pore water pressure below 70 kPa using standard tensiometers are not possible (Vanapalli et al., 2008). Axis translation technique is widely used for measurement and control of matric suction since it avoids the water cavitation problems by artificially raising the atmospheric pressure experienced by a soil sample (Marinho et al., 2008). Basic idea of the axis translation technique is applying a pressure differential across the saturated high air entry porous disk (HAEPD) that separates air and water phase. Working principle of HAEPD can be described by means of the capillary model, considering that ceramic disk is produced to have small pores of relatively uniform size. Once saturated, surface tension at the air-water interface disables passage of air through it, separating air and water phase. Maximum pressure differential that the high air-entry value (HAEV) ceramic disk can withstand without air

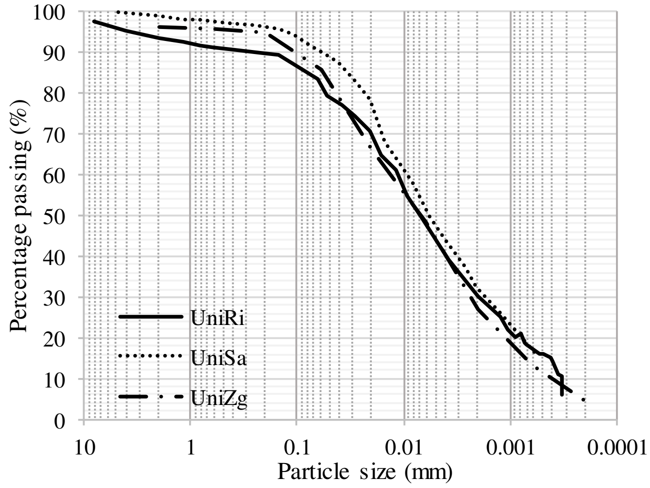

Figure 1. Grain size distribution test results.

passing through it is called the air entry value (AEV) of ceramic disk. For the same height of ceramic disk, larger pores imply higher permeability and lower AEV, and vice versa. Matric suction that exists in a specimen is equal to the difference between air pressure and water pressure (Fredlund et al., 2012).

3.1 *Pressure plate extractor apparatus*

Since introduced in 1930's (Richards, 1941), pressure plate devices have been used extensively for determination of the SWRCs for different types of soil. The great part of SWRC database existing today was obtained by using this type of device. Instead of directly measuring pore water potential, device is used to bring the sample to a desired water potential by using the axis translation technique (Hilf, 1956).

Pressure plate extractor manufactured by SoilMoisture Equipment Corp. with 1500 kPa ceramic plate was used for obtaining the first insights in matric suction vs. water content relationship. The device is used for obtaining the drying branch of SWRC, usually without volumetric measurements of expelled pore water from a sample.

3.1.1 *Testing programs*

Undisturbed specimens with a natural water content w_n of approximately 23% were used in tests. Due to low hydraulic conductivity and possible long equilibration time, low height cutters were used to produce specimens. In total 7 specimens with 10 mm height and 51 mm diameter were used in RP-1 and RP-2 tests.

Testing procedures were slightly modified after each test, according to obtained test results and material behavior in previous tests. Drying was started from natural water content in the first test (RP-1) and multiple weight measurements were conducted during each equilibration step. The idea was that a series of weight measurement could provide information about equilibration conditions by plotting changes of specimen weight in time. It seems that after the third measurement, where specimens were equilibrated at the 160 kPa of matric suction, hydraulic contact between specimens and the ceramic disk was lost and all further weight changes were caused only due to evaporation at a rate of approximately 1.0E-04 g/min.

The second test was performed using same specimens from the RP-1 test, except the specimens 1 and 2. After being submerged in de-aired water for 48 h, specimens were cleaned from excess water, weighted and installed on the saturated moist ceramic plate inside the pressure plate. The equilibration of samples was monitored by installing a burette on the outlet tube. According to the test results, 24 h was enough time for specimen equilibration. After saturation, no larger swelling was observed on specimens. The total volume measurements using the caliper during RP-2 test were not effective since the material was very soft at higher water contents and measured values were inconsistent. Although RP-1 and RP-2 tests did not yield useful results that could be used for SWRC determination, experiences and observations of material behavior indicated the necessity of modifications in testing procedure.

According to experiences from two preliminary tests, a 48h of equilibration time was adopted and attention has been focused on obtaining more intimate hydraulic contact between the ceramic disk and the specimen. Specimens were slightly pushed towards the ceramic disk which was pre-wetted with a few drops of water while rotating them for approximately 45 degrees. No significant amount of material was left on ceramic disk, while results show good agreement with results obtained by using other devices. Volume changes of specimens during matric suction increasing were measured more precisely by using a melted wax for coating of specimens after every equilibration step. The same procedure of density measurements was used with the WP4-T device.

Wax melted at 80° C degrees was used to seal the specimen. The volume of specimen coated in wax is obtained by immersion in a cup of water placed on a precise scale. Change of the weight recorded on scale before and after the immersion of wax coated specimen represents the volume of displaced water. The weight of wax used to seal the specimen and known wax density enable calculation of the volume of used wax, while the difference between the volume of displaced water and volume of wax is equal to the total volume of a specimen. Figure 2 shows the sample during preparation with visible siltstone grain, saturation of specimens inside the pressure plate extractor during the RP-3 test, and details of specimen coated in wax and wax removal after measurements.

In total 7 undisturbed and 2 remolded specimens were prepared for the RP-3 test. Before saturation, matric suction of 36 kPa was measured using the SCOED for natural water content of 26%. Specimens were dried up to 715 kPa of matric suction in the RP-3 test. Only two specimens were used in the RP-4 test. One specimen was removed from the last stage of equilibration in RP-3 test (RP-4se4) and one new undisturbed specimen (RP-4se8) was prepared. Both specimens were consolidated at a normal stress of 200 kPa in standard oedometer device but only the RP-4se4 was submerged in water. Specimen RP-4se8 was protected with a plastic bag to minimize the evaporation from sample during consolidation.

3.1.2 *Results*

The obtained test results show a good agreement with the results obtained using other devices and techniques, suggesting that adopted testing procedure provides a good quality data for SWRC characterization for this type of soil. Table 1 summarizes

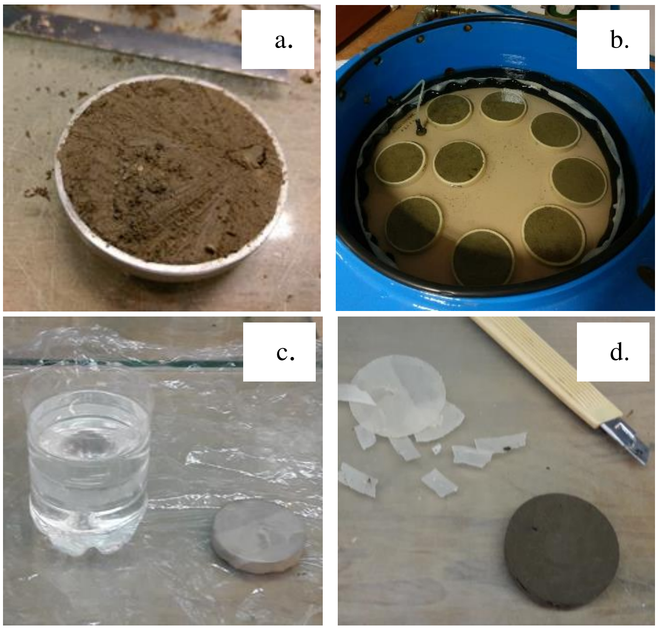

Figure 2. Some details of specimen preparation for RP-3 test (a: soil sample, b: saturation inside the pressure plate extractor device, c: specimen coated in wax, d: wax removal after measurements).

Table 1. Summary of results for RP-3 test, sample no.1.

Matric suction, ψ (kPa)	Total volume, V (cm^3)	Water volume, V_w (cm^3)	Void ratio, e (/)	Water content, w (%)	Volumetric water cont., θ (%)
10*	20.43	7.48	0.79	24.29	36.62
65	19.90	7.32	0.74	23.77	36.78
125	19.60	6.99	0.72	22.69	35.66
210	19.29	6.60	0.69	21.43	34.22
350	19.01	5.94	0.67	19.29	31.25
490	18.82	5.56	0.65	18.05	29.54
600	18.68	5.22	0.64	16.95	27.95
700	18.66	4.92	0.64	15.97	26.36

results for sample no. 1 in the RP-3 test. Matric suction was not measured after the saturation, but the value of 10 kPa was used based on measurements performed with mini tensiometers on undisturbed specimens saturated in similar conditions.

Fig.3 shows results of the RP-3 and RP-4 tests together with some results obtained using the WP4-T and HYPROP devices in the drying process.

3.2 *Volumetric pressure plate extractor apparatus*

Volumetric pressure plate extractors with 200 kPa ceramic plate and hysteresis attachments were used to determinate hysteresis properties of the soil for low matric suction values. In its basic form, the device can be used as a standard pressure plate extractor for determination of the drying branch of SWRC. When used with hysteresis attachments, volumetric measurements of water leaving or entering the specimen can be precisely monitored, enabling

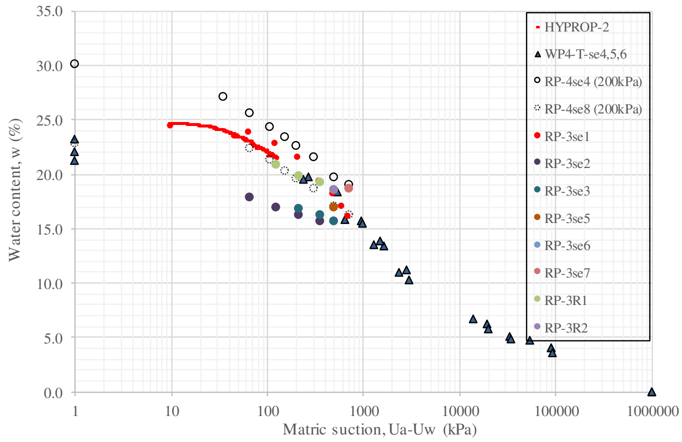

Figure 3. Results for RP-3 and RP-4 test with results obtained using WP4-T and HYPROP devices in drying process.

determination of equilibrium conditions when no further water volume change occurs for imposed suction value. On the other hand, water from the ballast tube and burette can be soaked in by the specimen if a matric suction is decreased, providing results of the wetting part of SWRC. Air diffused through the HAEV ceramic disk to water compartment and tubing can be flushed by use of roller and air trap.

The first two tests (VE-1 and VE-2) were carried out simultaneously using two specimens from the 1500 kPa pressure plate extractor dried at the matric suction of 300 kPa. The wetting test was performed first, decreasing the matric suction from 200 kPa towards 0 kPa (VE-1w and VE-2w tests). The specimen was saturated in water outside the apparatus and drying test (VE-1) was performed again in order to compare the results with results obtained in pressure plate extractor apparatus.

Due to possible problems with hydraulic contact between specimens and ceramic disk, as it was experienced from tests RP-1 and RP-2, samples were taken out for weight measurements after each step of equilibration. Time of equilibration was determined from the plot of water volume change readings on burette vs. time. It was concluded that a sample has equilibrated for imposed conditions when no further volume changes were observed. In order to ensure a better contact between the HAEV ceramic disk and specimen, small weight was added on the top of the specimen.

Figure 4 shows the SWRC in terms of matric suction (kPa) vs. moisture content (%) for VE-1w and VE-2w tests and results obtained by the WP4-T device for a wetting process. Results obtained using the volumetric pressure plate extractor apparatus with hysteresis attachments seem to be in a good agreement with other results, except for the first step of equilibration of both wetting tests. In the first step, the water content seems to be slightly lower than expected, indicating that specimens probably did not reach equilibration at imposed suction of 200 kPa.

3.3 *Suction controlled oedometer apparatus*

Two different suction controlled oedometer devices enabled more advanced investigation of soil-water retention properties through control of stress state variables (net vertical stress and matric suction), measurements of axial deformations of sample, and water volume variations through the test. Automated data acquisition through the test is another important advantage compared to the previously described devices, especially for the long-lasting wetting tests. The main advantage of the suction controlled oedometer apparatus (SCOED) at UniSa is advanced diffused air flushing system, consisted of two double-walled burettes coupled to a differential pressure transducer and a peristaltic pump. Porous stones with 200 and 500 kPa AEV were used to perform different types of test. The hydraulic consolidation cell (Hydrocon) for unsaturated samples (Controls S.p.A.) used at UniRi enables saturation of a sample through back pressurization in a confined system. Device was equipped with 1MPa AEV porous stone. Flushing of defused air beneath the HAE disk was performed by rapid opening of flushing port connected to the water compartment beneath the HAEVD, using pressurized water directly from the air/water bladder.

The described devices were used to perform multiple (main and scanning) drying and wetting tests with different net vertical stresses. Tests UVH-1 was performed by using the Hydrocon device to obtain main drying curve for the net vertical stress of 25 kPa, while the test OEUVCJ01 was performed by using the SCOED as scanning drying and wetting test at 200 kPa of the net vertical stress. All results are summarized in terms of volumetric water content (%) vs. matric suction (%) in Figure 5. Due to hysteresis, moisture contents are somewhat lower for wetting than for the drying test. The similar results were noted using other devices and techniques.

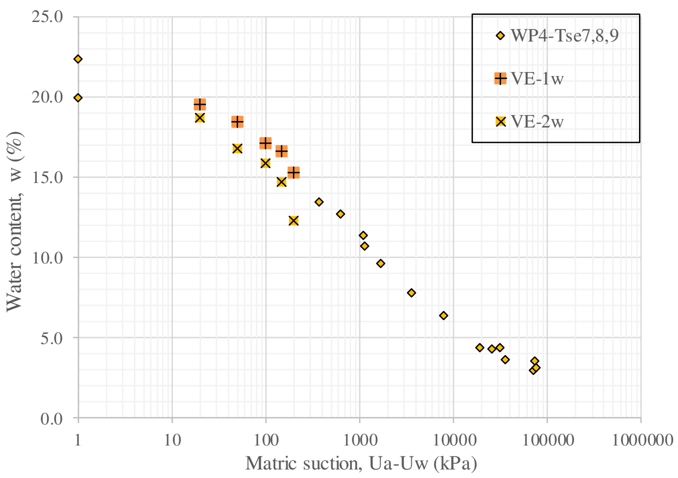

Figure 4. Results from VE1w and VE2w tests with results obtained using WP4-T device in wetting process.

4 HYPROP EVAPORATION METHOD DEVICE

Due to shortcomings of axis translation technique for measurements of the soil suction at high degrees of saturation (Olson & Langfelder 1965; Bocking & Fredlund 1980), the HYPROP evaporation method device was used to determine the wet part of SWRC more precisely.

The tests were performed on undisturbed specimens previously saturated by submerging in a water. Placed on a precise scale, water loss from the specimen due to evaporation is automatically recorded while the negative water pressures are measured directly using two mini tensiometers installed in predrilled boreholes at different heights. Information on hydraulic gradient and water flux can be used for calculation of the unsaturated hydraulic conductivity according to the Darcy-Buckingham law (Schindler et al., 2015). Results for the HYPROP-2 test are shown in terms of moisture content (%) vs. matric suction (kPa) in Figure 3. Calculated hydraulic conductivities range from 1,0E-09 m/s up to 3,5E-10 m/s.

5 DEW POINT POTENTIOMETER WP4-T

The WP4-T (Decagon Devices Inc.) potentiometer device was used for measurements in dry area of the SWRC, with extension to the medium range. The WP4-T potentiometer measures the total suction by vapor pressure method. Total suction is measured by measuring water vapor pressure above the soil specimen and then calculating suction by using Kelvin's equation. A water vapor pressure could be calculated from the dew point temperature, which is measured by cooling the mirror which reflectance is changed when dew appears. From the measured temperatures of mirror and air, vapor pressure above the sample and saturated vapor pressures can be calculated. More detailed description of the dew point device can be found in Leong et al. (2003) and Campbell et al. (2007).

5.1 *Specimen preparation*

In the first test (WP4-T-1), 8 undisturbed specimens were prepared and equilibrated at different water content. After resting for a few days in sealed metal container, a total matric suction was measured using the WP4-T device. Density of specimens was measured using the caliper or wax dipping and water displacement technique. Finally, specimens were oven-dried for determination of the water content.

Another test was performed using 9 undisturbed specimens prepared at the natural water content. The first three specimens (WP4-T-3se1, 2 and 3) were submerged in water and left to saturate during 24h. Measurements on the next three specimens were performed starting from the natural water content and slowly drying on air (WP4-T-3se4, 5 and 6). Evaporation rate was reduced by using the sealing plastic bags. The last three specimens were used to perform measurements in the wetting process (WP4-T-3se7, 8 and 9). Air-dried specimens were wetted with a small amount of water and rested for approximately 24 hours in a covered plastic cup. Specimen weight was then recorded and specimen suction was measured in the WP4-T dew-point potentiometer. This procedure was repeated until the suction measurements became too low. Multiple measurements of suction and density were performed on all specimens during the wetting process.

Figure 5 shows the test results in terms of the volumetric water content (%) vs. matric suction (kPa). Hysteresis between drying and wetting process and the influence of starting moisture conditions can be clearly distinguished.

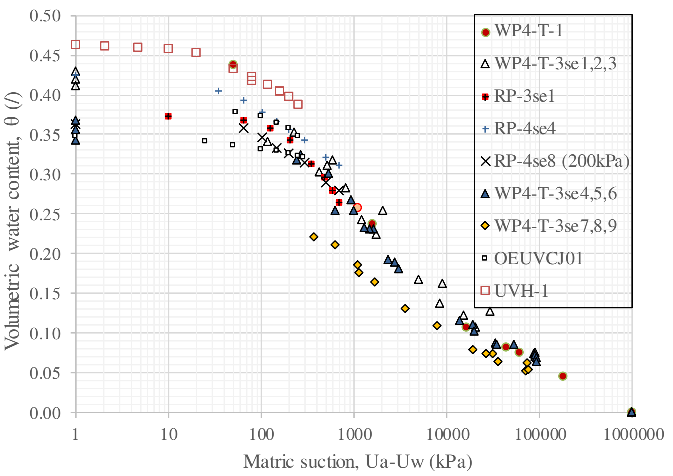

Figure 5. Results obtained using different devices and techniques for SWRCs determination.

6 CONCLUSIONS

Standard pressure plate extractors and WP4-T dew point potentiometer are commonly used for SWRC measurements in terms of the (matric) suction vs. water content. Combining of density measurements with measurements of water potentials enabled determination of the SWRC in terms of the volumetric water content and degree of saturation, as well. This is particularly useful if the volumetric water content needs to be measured for a wide range of (matric) suction and/or in the high range of suction where the axis translation technique and standard tensiometers have limited usage. The suction controlled oedometer devices have proved to be very useful for volumetric measurements up to the AEV of the used porous disk, enabling continuous data acquisition during a long-lasting process of equilibration. The results were obtained for different values of the net vertical stress in drying and wetting process. Finally, the WP4-T device was very useful for measurements in the dry part of the SWRC, where the axis translation technique has obvious limitations. Coupling the results of used experimental procedures enabled necessary data for water retention characterization of residual soil from a flysch rock mass.

7 ACKNOWLEDGEMENTS

The part of laboratory equipment used for laboratory testing was provided in the frame of the Project “Research Infrastructure for Campus-based Laboratories at the University of Rijeka”, co-funded in part by Ministry of Science, Education and Sports of the Republic of Croatia and the European Fund for Regional Development (ERDF).

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