New device for experimental determination of the soil-water retention surface

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Abstract. While it has been recognized that the soil-water retention properties are affected by the soil void ratio, standard test methods for determination of soil-water retention curves do not account for soil volume changes, assuming a condition of constant volume. However, significant volumetric changes are expected when characterizing highly plastic soils, even for comparatively small changes in water content. This paper presents a new testing device that allows continuous measurement of three relevant variables: void ratio, matric suction, and water content. This set up is used along wetting paths in order to determine the soil-water retention surface. The set up allows continuous measurements of the relevant variables by using displacement sensors and a scale system. The new equipment is described in detail, and a set of tests results are presented in order to show its capabilities. The results indicate that, rather than a characteristic soil water retention curve, the new device can be successfully used to characterize a soil water retention surface defined by matric suction, water content, and void ratio [ψ,w,e].

Keywords. Unsaturated soils, soil-water retention surface, experimental device

1. Introduction

Unsaturated soils have a peculiar hydraulic behavior that results by the fact that water is held within the throats of the pores by capillary action resulting in tortuous water paths that leads the hydraulic conductivity values to vary orders of magnitude within a comparatively narrow suction ranges.

The relationship between the capillary pressure (or matric suction), and water content has been traditionally represented using soil water retention curves (SWRC). Methods available to obtain this relationship include the Hanging Column Test, Pressure Extractor, Chilled Mirror Hygrometer, and Centrifuge Test (ASTM 2008). SWRC’s have often been assumed to be independent of the soil void ratio. Even the most commonly used SWCC mathematical models such as Van Genuchten (1980) and Brooks and Corey (1964) do not account for changes in void ratio.

Recent work has been carried out in order to study the coupled hydro-mechanical behavior of the soil by monitoring systematically the effect of changes in suction (ψ) on the water content (w), and the void ratio (e). In this way it has been possible to define a Soil-Water Retention Surface (SWRS) in the [ψ,e,w] space (Salager 2007).

Yet, most results for the SWRS have been obtained with the same techniques and equipment used for the testing of SWCC’s, where void ratio changes are not monitored during the test, but measured only at the end of each stage. Accordingly, different soil samples need to be prepared at same initial conditions and taken to different final conditions. Even though it has been possible using this approach to define a surface that correlates the three relevant variables, theoretically this is only valid if samples compacted at the same initial void ratio have the same internal structure, and that intermediate steps would not affect the soil structure and hydraulic behavior.

This paper presents the development of an enhanced device based on established techniques that allows continuous monitoring of the soil void ratio and water content during testing while different stages of suction are applied to the soil sample. The device also allows the control of the vertical total stress variable. The equipment is based on the pressure chamber test and allows testing soils samples within a wide range of suction levels, even for comparatively low suction values where most changes in void ratio occur and where this third variable truly affect the hydraulic response (Salager et al 2010).

Typical pressure chamber equipment used in research and practice are initially analyzed. Then the new equipment's capabilities, functioning and limitations are described in detail. Finally, a set of results is presented in order to illustrate the performance of the new device.

2. Equipment

The equipment developed, as part of this research, is an enhanced pressure chamber that allows the determination of the relationship between matric suction and volumetric water content based on the axis translation technique. However, unlike typical pressure chambers, this device allows measuring the change in volume of the sample during the test, using a double ended, double action air piston. This feature also makes possible running tests under a controlled external load. This section provides a brief overview of conventional pressure extractor device, the characteristics of the new device and the complementary systems.

2.1. Overview of the pressure extractor method

The pressure extraction method is based on the axis translation technique, where the air pressure in the chamber is controlled, allowing controlling the air pressure in the pores of the sample. The chambers are typically metallic and contain one or several soil samples that remain in contact with a ceramic plate of a high entry pressure.

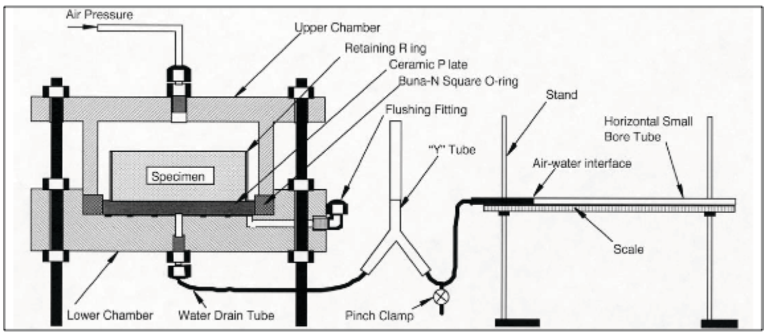

Figure 1. Schematic of Pressure Extractor ASTM D6836-02 (2008).

Figure 1 shows all the components of the pressure extractor standardized test (ASTM D6836-02 (2008)); one sample inside of the metallic chamber is exposed to the air pressure and in contact with a ceramic disc at the bottom. The base is connected to an outflow system used to measure the inflow and outflow from the chamber in order to determine changes in water content of the sample. An air trap is included within this circuit to flush any air diffused through the ceramic disc. Other setups rely on the determination of oven dried gravimetric water content at the end of testing, allowing to determine only one point of the SWRC each time.

2.2. General Overview of the UTEXAS Pressure Chamber

The improved chamber presented in this paper involves a base and cap machined using aluminum. The base has a series of grooves that connects two diametrically opposite points for water inflow/outflow. This allows water to be flushed through the base to remove any diffused air below the ceramic disc (**Figure 2**). A ceramic disc of high entry pressure is placed over the grooves and an o–ring is used to avoid pressure looses in the chamber from the bottom.

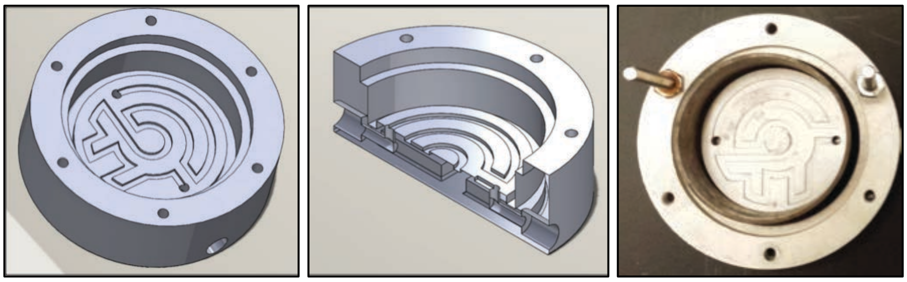

Figure 2. Base detail: a) 3D view of base design. b) Cross section showing grooves, inlet, and outlet connections. c) Picture of the base.

The soil sample is compacted into a brass ring, which is then placed inside of the base. An o-ring is used to hold the sample in position, and it seals the air pressure inside the chamber. A hard plastic porous disc of negligible weight is placed on top of the sample to facilitate good contact with the vertical rod and load distribution. The cap is then placed and tightened onto the brass ring. In addition to hold the sample, the brass ring also applies pressure over the ceramic disc and o-ring providing a good seal between the water beneath the ceramic disc and the increased air pressure above it.

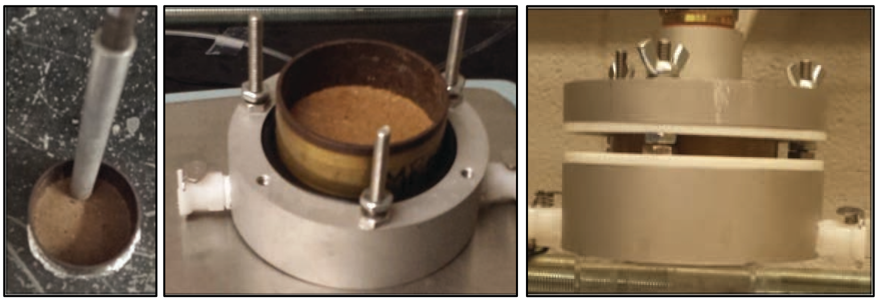

Figure 3. a) Compaction, b) sample mounted in the base, c) base assembled with the top disc and o-ring holders.

The cap includes a third o-ring used to seal the air pressure imposed at the top of the sample. In **Figure 3** there is a view of the different stages of the test: a) soil being compacted into the brass ring; b) the sample is placed into the base; and finally c) the base is assembled including two o-ring holders to manage high air pressures.

Besides providing a connection to the compressed air line, the cap also includes a central opening used to connect an air piston. This double acting, double end piston allows applying an external vertical load, and monitoring the vertical displacement of the sample while maintaining the pressure inside the chamber (**Figure 4**). This chamber enables, the total stress to be used as an independent variable of analysis (Matyas 1968), similar to the approach used in suction controlled oedometers.

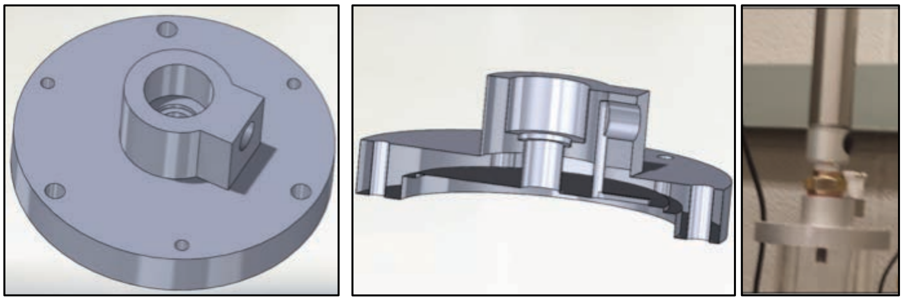

Figure 4. a) 3D view of the cap, b) cross section, and c) piston connected to the cap.

2.3. Vertical displacement and monitoring system

A bracket is attached to the piston to hold an LVDT that is used to monitor vertical deflections continuously. The bracket, LVDT and all the connections have a weight that remains constant during the entire test. In tests involving wetting paths the void ratio tends to increase with increasing water content. Since lateral displacements are constrained, changes in height correspond to the total volume change, and then the measured vertical displacements can be used to calculate changes in void ratio.

2.4. Complementary systems

In the conventional set up illustrated in **Figure 1**, changes in water content are calculated by measuring the inflow/outflow with a capillary tube. This method is simple and can be easily calibrated and installed. Accuracy can be improved by using comparatively thin tubes. However, measurements can be compromised by the presence of diffused air in the system, which is read as an additional outflow. Long-term readings may also be affected by evaporation and leakage. **Figure 5** (a) shows the implementation of capillary tubes used with a set of Tempe cells, (b) air trapped during the test, and (c) an air trap used to purge the air present in the system.

In order to avoid the problems associated with capillary tubes the new device measures the change in weight of the sample in order to obtain the change in water content. This is achieved by measuring the change in weight of the entire system, since once the whole system is saturated the only source of weight variation is the weight of the sample itself. A precision scale Ohaus Adventurer Pro AV3102C with a range up to 3100g and 0,01g of precision was used for weight measurements (**Figure 6**). The change in mass is then used to calculate water content by mass balance.

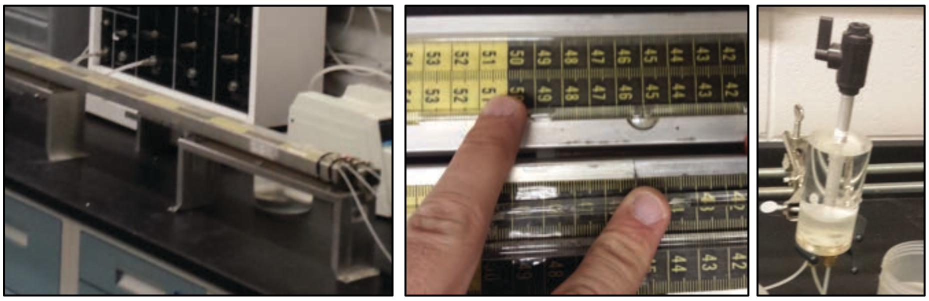

Figure 5. View of: outflow capillary tubes (a), readings affected by bubbles (b), and air trap connected to the flushing system(c).

A flushing system was incorporated to minimize the problems associated with air diffused through the ceramic disc to the outflow system and therefore affecting its readings. It includes a flushing loop, an air trap, and a peristaltic pump. The air trap has two connections, one for the loop and other connected to the outflow tube. The water level inside of the trap should be the same as that in the sample base and the outflow tube. The peristaltic pump, forces flow from the base to the air trap, then through the pump and finally back to the base. The pump runs at comparatively low RPM during the entire test and is primed before final readings are taken.

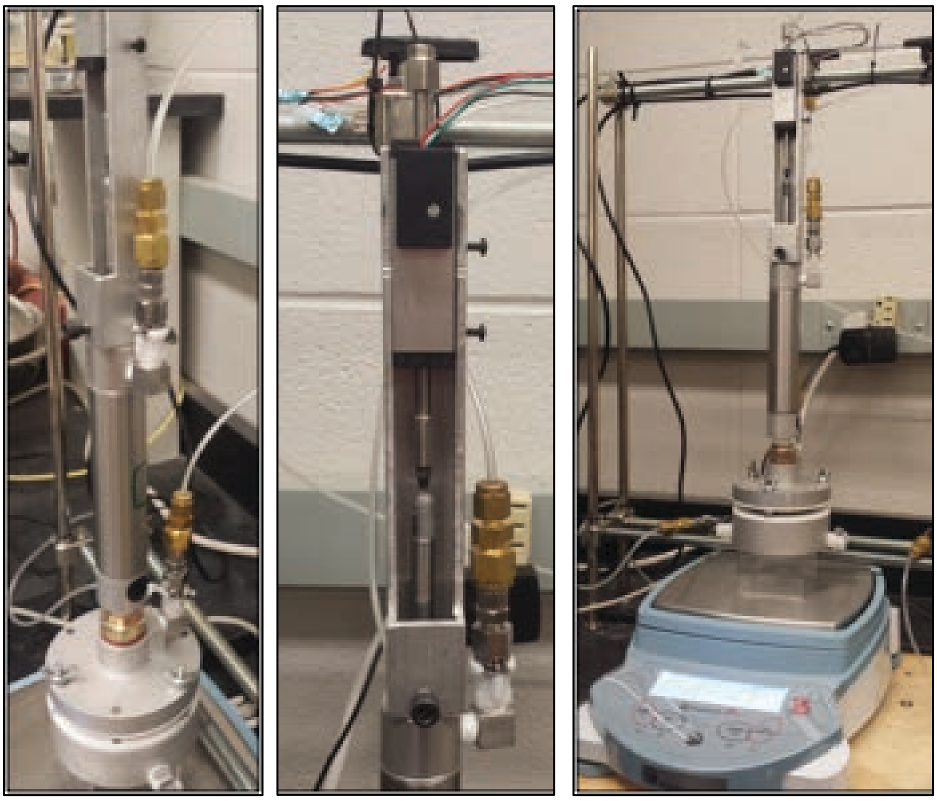

Figure 6. View of the piston and air connections (a); detail of the bracket and LVDT (b); and complete chamber mounted over the scale (c).

Very flexible tubing is used for all air and water connections in order to avoid affecting the weight readings, which could result from the deformation of the tubes. In this set up the capillary tubes, are installed together with the scale in order to provide a source of water for the sample, to keep a redundancy of the measurements, and for the first set of test to observe the scatter and reliability of the scale.

2.5. Testing procedure

The chamber and the supporting system are assembled as follows: 1. Water is placed in the base and flushed with the pump to minimize the presence of the air below the ceramic disc. 2. The intermediate o-ring and brass ring with the sample are placed in the chamber. 3. The plastic disc is placed over the sample. 4. The top and bottom o-ring holders and cap are placed and tightened with screws. 5. The piston rod is carefully handed down until it barely touches the upper disc. 6. The compressed air line is connected. 7. The chamber is carefully placed over the scale. 8. The LVDT is set on the bracket. 8. Air is connected to the chamber and piston. 9. The DAQ system is initiated, 10. Tubes on the sides of the base are connected. 11. Pressure is applied into the chamber and to the piston and water exchange begins. Chamber base, outflow capillary tube and air trap must be aligned vertically to result in the same total head.

In tests following a wetting path, the air pressure is reduced after each stage. Once the initial maximum pressure is applied and water tubing connected, the equalization process begins. The flushing system should be kept running at all times. Each stage is run until no change in water content is observed. This can be represented by plotting weight vs Log(t). Once equilibrium has been reached at the end of the last stage, the chamber should be disassembled. Final sample weight and height are recorded, and gravimetric water content is measured by oven drying the sample. If the last stage does not correspond to a zero suction state, the sample must be removed from the chamber as fast as possible to avoid any changes in water content from the base.

3. Typical results

The new testing device allows the determination of the hydro-mechanical behavior of the soil using a single soil sample. By testing a soil at different initial conditions it is possible to determine the soil water retention surface (SWRS). Still, it should be emphasized that the results will only reproduce a portion of the SWRS. The current testing set up, allows suctions variations of up to 500kPa (5 bar).

3.1. Material, testing program and sample preparation

In order to illustrate the capabilities of the new device, a testing program was conducted using soil from a batch of a low plasticity Clay (CL) obtained from the Rocky Mountain Arsenal (RMA) alternative cover. This soil is at the limit of fine grain or coarse grain soil since clay fraction is 50.5% without particles above sieve #4; Atterberg's limits are LL=32, PL=12 and specific gravity is G_s=2.77. The maximum dry density ($\rho_{d.max}$) is 1.84g/cm^3 (Standard Proctor compaction effort), and optimum water content is w_{opt}=14.5%. Saturated hydraulic conductivity for these conditions is approximately 8.5 10^{-6} cm/sec.

The results from test in this paper were obtained using samples compacted at 80% relative compaction, and at w_{opt}. A summary of the soil characteristics for samples as compacted is presented in Table 1. The time necessary to reach equilibrium for each stage, which varies with sample height, is typically about 12 to 72 hours depending of the stage, for 1.0cm sample height compacted in two lifts of 0.50cm.

Table 1. Initial conditions of compacted samples – Multiple stages test

Test #	Height H [cm]	Water content wc [%]	Dry unit weight γ_d [g/cm^3]	Relative Compaction [%]	Void ratio e_c [-]*	Void ratio e_o [-]**
W3	1.001	14.5	1.475	80.06	0.878	0.813
W4	1.001	14.5	1.471	79.87	0.883	0.871
W5	0.998	14.5	1.472	79.93	0.886	0.886
W6	1.008	14.5	1.457	79.11	0.901	0.899

* as compacted, **after load was applied, before starting the test.

These first tests were run under a minimum load that results in a constant pressure of about 1kPa. It can be seen that the change in void ratio due to the application of the vertical load had a low influence on the initial void ratio at the beginning of the test.

3.2. Results of hydro-mechanical path for SWRS

The results for multistage tests were obtained using the data collected at the end of the various stages. The obtained results include: matric suction (ψ), volumetric water content (θ), unit weight (γ) and void ratio (e). Using this data it is possible to define a representation of the hydro mechanical path of the test in the [ψ,θ,e] space. **Figure 7** shows the results of four wetting tests run with RMA Clay samples prepares at the conditions specified above in **Table 1** for tests W3, W4, W5 and W6. Each point represents the equilibrium state when the matric suction was imposed using the compressed air line.

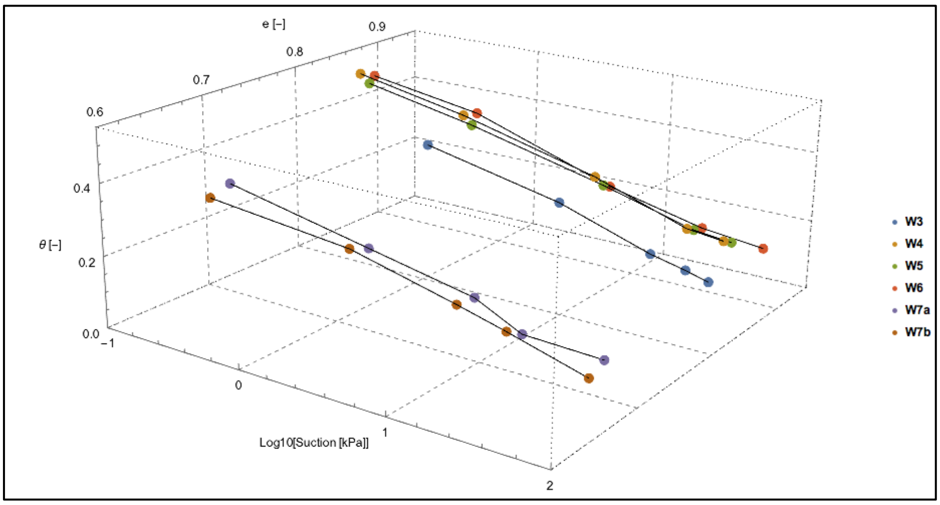

Figure 7. Multiple stages on wetting hydro-mechanical path.

It can be seen that all tests follow similar trends. They have low changes in volumetric water content and void ratio above for matric suction values above 30kPa, while for lower values of suction the water content increases rapidly. Also, main changes in void ratio occur at low suctions, even though in this case there is no an expansive behavior like when testing high plasticity clays. No platoon was observed on water content values at low suctions when representing the results in terms of these three variables. Consequently not being possible to define a value of suction as air entry pressure (ψ_{aep}).

Projections of each of the three planes are obtained in order to observe the coupled evolution of each pair of variables. A typical representation of the SWRC (e.g. θ vs ψ) is shown in **Figure 8** (a). This SWRC would typically be reported as that corresponding to the initial void ratio of the sample. **Figure 8** (b) illustrates the increase in void ratio with increasing water content in the sample. Finally, **Figure 9** shows the changes in void ratio during the test with decreasing suction.

Compaction conditions as well as the magnitude of the applied normal load affects results by modifying the initial void ratio of the soil sample. The tests were initially run under constant vertical stress ranging from 0.85 to 1.00 kPa. This comparatively low normal stress reduced the initial void ratio of the compacted samples. The void ratio of each sample in the first stage of the tests represented in **Figure 8** (b) and **Figure 9** is lower than the one reported in Table 1 corresponding to the compacted condition. These initial lower values were identified as e_o.

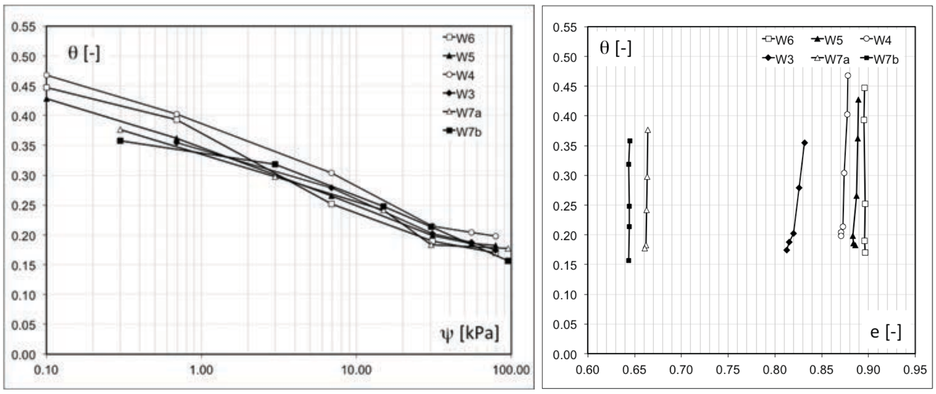

Figure 8. (a) Soil-water retention curve (θ-ψ), (b) θ-e relationship.

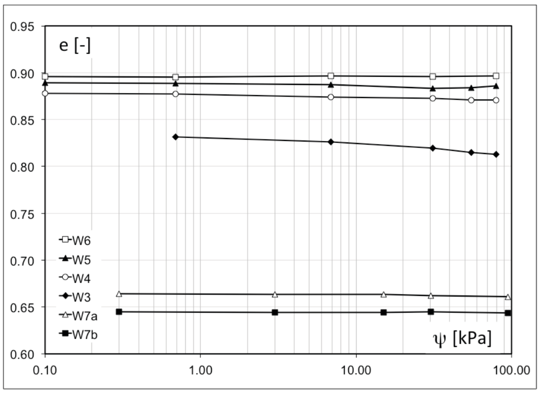

Figure 9. Changes in void ratio with suction (e-ψ).

The RMA soil did not show an expansion behavior, but its small changes in height during the tests was useful to demonstrate the capabilities of the equipment and the evolution of the sample unsaturated behavior in a three variable space. In order to generate a SWRS, several tests should be carried in order to a broaden range of void ratios to be covered by the test results. In this particular case, the objective of the presented series of test results aimed at evaluating the repeatability and accuracy of the results obtained using the new equipment, rather than defining a SWRS.

3.3. Typical results from transient response

The new device allows continuous monitoring of the sample weight throughout each testing stage. **Figure 10** (a) show the changes in gravimetric water content with time, after the air pressure has been applied. The implementation of the scale and a DAQ system has some additional features in comparison to use the capillary tubes. It is easier to increase the number of data points to show the transient response, and the advective-diffusive phenomenon can be seen more clearly.

Figure 10 (b) shows the initial and final point of each stage in terms of water content and void ratio. In this wetting tests air pressure decreases from 80 to 0.1 kPa. It can be seen that even for very low suctions, the water content does not reach the zero air void line (ZAV), corresponding to a degree of saturation of one, (w_c = e / G_s).

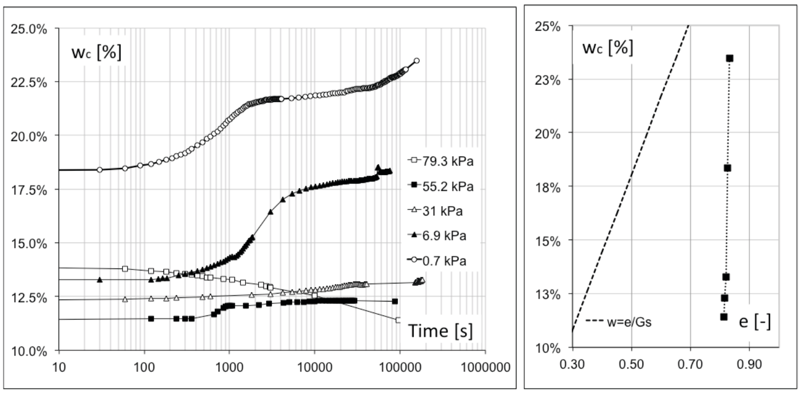

Figure 10. (a) Evolution of gravimetric water content with time, (b) relationship between water content and void ratio at the end of each stage.

Even though it possible to minimize the sources of evaporation and leakage, for example by implementing a system of valves to close and open the flushing system periodically, the continuous monitoring of the weight of the sample eliminates any influence these errors. In **Figure 11** (a) a comparison was made as example showing the results obtained using the scale and the capillary tubes at the same time. It can be seen that the scale shows a more gradual transition, and for long times, if evaporation and/or leakage occurs it only affects the tubes readings.

When compressed air is applied to the sample, it also diffuses over time through the ceramic disc and can build up as bubbles underneath the disc. The flushing system and air trap allows the bubbles to be removed from the system. In **Figure 11** (b) is shown the effect of air being expelled from the base over the transient response. When air bubbles are removed a sudden jump in the readings of the scale can be seen due to the sudden entry of water displacing the bubble, then it is followed by a decrease in the weight reaching a new equilibrium point. Continuous operation of the flushing system reduces jumps and avoids air to get trapped in the system.

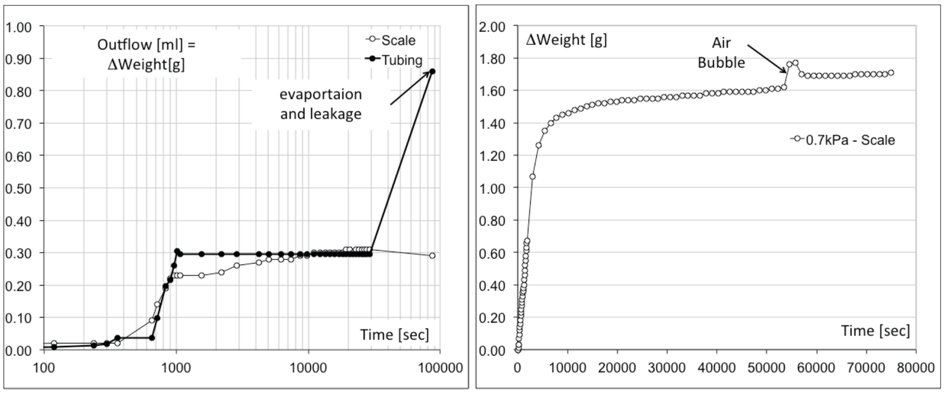

Figure 11. (a) Comparison of measurement systems. (b) Dynamic response of the scale due to air bubbles.

4. Conclusions

A new pressure chamber was developed with the objective of obtaining continuous measurement of void ratio, matric suction, and water content along wetting paths. This allows the determination of the soil-water retention surface (SWRS) that characterizes a soil. The basis for this equipment is the technology of pressure plate extractor, as described in the standardized tests. The features and testing procedure are presented in detail in the paper. Advantages and disadvantages of using different approaches on measuring water content, vertical changes and limitations on testing wetting paths are discussed. The implementation of the scale allows a better description of the advective-diffusive transport phenomenon, and it minimizes the errors associated to leakage and evaporation. The use of an air piston enables to apply an independent vertical normal stress and to monitor the volumetric changes in the sample continuously together with the changes in water content.

The new device not only follows the hydro-mechanical path of the sample, but it also allows the measurement of the water retention characteristics on the same sample and internal soil-structure. Typical results, from a series of test run on a low plasticity Clay (RMA soil) are presented in order to demonstrate the capabilities of the equipment. The test results show good repeatability and accuracy. Overall, the new device was found to successfully determine the three variables needed for determination of the SWRS of soils.

5. Acknowledgments

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