Enhancement of a Commercial Pressure Plate Apparatus for Soil Water Retention Curves

Marco Caruso and Cristina Jommi

Abstract. Pressure plates are widely used to measure soil water retention properties of soils in the laboratory with axis-translation technique. Imperfect sealing of the pressure chamber, exchange of water vapour between the soil and the air in the chamber, lack of soil-plate contact, part of the porous plate directly in contact with air in the pressure chamber, and evaporation of water from the ballast tube may lead to incorrect estimation of the water volumes exchanged by the soil. An improved version of a commercial pressure plate apparatus is presented, which proved able to reduce the intrinsic drawbacks of the original design. The system was also equipped with an image-processing based data acquisition system for continuous measurement of exchanged water.

Keywords: axis translation, experimental techniques, matric suction, retention curve.

1 Introduction

Pressure plate apparatus has been widely used as a standard technique for the determination of soil water retention curve (SWRC) since Richards' (1948) proposal. In the original arrangement, pore water is kept at constant atmospheric pressure, allowing drainage, while the gas pressure (typically air pressure) is raised, to apply suction via the axis translation technique. Water retention data are obtained by increasing the suction and measuring the water content at equilibrium.

Marco Caruso
Politecnico di Milano, Milano, Italy
e-mail: `caruso@stru.polimi.it`

Cristina Jommi
Politecnico di Milano, Milano, Italy
e-mail: `cristina.jommi@polimi.it`

A body of literature is devoted to the assessment of the pressure plate data accuracy. Campbell (1988) showed that lack of sample suction equalisation with imposed external pressures is often due to poor contact between the sample and the porous plate. Even under ideal contact, low hydraulic conductivity of the soil can hinder full equalisation. Madsen et al. (1986) highlighted some problems related to equalisation issues at suctions higher than 500 kPa. Cresswell et al. (2008) investigated the accuracy of pressure plate measurements at 0.5 and 1.5 MPa, and stressed on the problems arising from contact loss due to soil shrinkage. Bittelli & Flury (2009) showed differences between the data obtained by a standard pressure plate apparatus, equipped with a 15 bars ceramic, and dew point meter measurements, suggesting the need for further investigation on the experimental techniques.

Gee et al. (2002) studied how sample equilibrium is affected by both soil and ceramic hydraulic conductivity, by means of numerical simulations. They concluded that for coarse grained soils (sands and gravels) long time lapses are necessary for equilibrium to be achieved (days to weeks) because of the very low soil water conductivity at low suctions. Equilibrium can be achieved in a reasonable time interval for finer soils, but only if ceramic plates having relatively high conductivities, greater than 10^{-10} m/s, are mounted in the apparatus. They showed experimental data on sand, silt, and clayey soils obtained with a high entry value (1.5 MPa) ceramic plate, and they concluded that neither loading the samples, nor the use of kaolinite slurry could allow the samples to equilibrate in times up to 10 days. These drawbacks are also shown to depend on samples height, and they can be reduced if thin samples, about 10 mm thick, are tested.

Wang & Benson (2004) put in evidence how pressure plate apparatuses suffer from a few problems due to their mechanical design. Imperfect sealing of the chamber, air leakage through the external part of the plate (especially at high pressures), diffusion of gas through the ceramic plate, air entrapment beneath the ceramic plate lead to poor control of the mass of water in the specimen. The authors tried to limit these drawbacks by means of a new design for the position of the porous plate and by improving the sealing system. Leong et al. (2004) paid attention to air diffusion in the water drainage system, and they suggested a modified apparatus equipped with a "flushing assembly" that enables flushing of air to be performed during the test without closing the air pressure line.

Notwithstanding its well-known drawbacks, pressure plate extractor is a cheap and generally appreciated equipment for the determination of water retention properites of unsaturated soils. A research effort has been made to suggest possible improvements to a commercial equipment, to increase data reliability. The suggested enhancements and experimental verification of the modified apparatus are described in the following.

2 The Modified Pressure Plate Apparatus

The reference apparatus is a commercial Soilmoisture® 1250 volumetric pressure plate extractor. It is claimed to be a high precision extractor, designed so that the outflow section of the instrument gives stable reading (Soilmoisture 2005). When used in conjunction with a "hysteresis attachment", it allows the measurement of the volume of water inflowing or outflowing from the sample at any pressure level. Following literature suggestions, the cell should be equipped with ceramic plates as permeable as possible, and with entry values (AEV) as low as possible, depending on the soil to be tested.

The experimental tests were run on silty sands, hence two ceramic plates with AEVs of 250 kPa and 500 kPa, having hydraulic conductivity of $6.3 \cdot 10^{-9}$ m/s and $1.7 \cdot 10^{-9}$ m/s, respectively, were mounted in two identical pressure plate extractors. A series of preliminary tests carried out with the original commercial testing apparatus showed many of the experimental issues affecting data reliability reported in the previous literature review.

Therefore, various enhancements were performed and tested. The ones which proved to be effective to improve data reliability are briefly described in the following. They consist in the design of a combined contact and counter-evaporation system, in improving hydraulic connections, in modifying the pressure control manifold, and in providing some modifications to the measurement system.

2.1 The Contact System

Preliminary tests run in the laboratory of the Politecnico di Milano (Caruso 2007) had confirmed the problems related to poor contact between the soil specimen and the ceramic plate to be the most influent negative factor affecting the pressure plate experimental success. Therefore, a contact device has been developed to ensure better contact between the soil specimen and the ceramic plate along all test duration.

The system (figure 2) is based on a cave variable-length stainless steel piston driven by a spring mounted inside the cave piston itself. The spring allows constantly pushing the specimen against the pressure plate, regardless any soil shrinkage or swelling. The vertical load, which can be calibrated by choosing the elastic constant of the spring, is transmitted to the specimen as uniformly as possible through to a plate with holes positioned on the top surface of the sample. A high number of holes in the plate are necessary to ensure continuity between pressurised air in the chamber and air in soil pores.

To prevent radial strain due to the even small vertical load applied to the specimen a stainless steel ring was designed to laterally confine the specimen. The stainless steel ring is equipped with a cutter on its top, in order to use it already for sampling tasks. If axial strain occurs, the top loading plate can slide inside the ring without friction. The ring also prevents water outflow from the specimen lateral surface.

The contact system has been designed for testing of 80 mm or 75 mm diameter specimen. The diameter was chosen to allow testing of undisturbed samples from standard site probes. The sample thickness has been chosen to be 15 mm, following previous literature suggestions, and ensuring both reasonable testing times and the accuracy of the water volume measurement system to be sufficiently high compared to the amount of water volume expected to be exchanged by the soil.

2.2 Improving the Measurement Accuracy

The need for accurate measurement of water volume is mandatory, especially when trying to determine the SWRC by means of multi-stage test on a single specimen, consisting in applying a series of increasing pressure steps and waiting until the equilibrium condition are established (i.e. water flow lowers under a predefined tolerance). The specimen water content at the end of each step can be estimated only on the basis of exchanged water measurements, while check on the actual water content can be performed only at the end of the test.

The first hindering effect on measurement may be due to air leakage through the porous ceramic and, as a consequence, into the water measurement circuit. Air leakage can be identified only by visual inspection and, for this reason, all circuit bundle tubes have been replaced with transparent ones. Diffusion of air can be prevented mostly by careful saturation of the porous ceramic before the beginning of the test. It was observed that submerging it in a sealed box filled with de-aired water while applying vacuum can be effective to ensure full saturation of the porous stones chosen for the experimental tests on silty sands. Further details on similar procedures may be found, for instance, in Tarantino & Mongiovì (2002). Careful saturation ensures air diffusion reduction in the first steps of a multi-stage test. Nonetheless, air diffusion was noticed in tests lasting more than two weeks, even if the difference between air and water pressure was maintained below the air entry value of the porous stone. Diffused air can be removed by forcing it to move along the outlet circuit connecting the chamber to the air trap. Afterwards, the air can be eliminated with the aid of a vacuum pump, re-establishing the reference water level in the trap.

Water evaporation from the sample into the extractor cell, occurring until the air in the chamber becomes saturated, should be avoided as much as possible, as this volume exchange cannot be measured. To reduce evaporation in the chamber, an air saturator was placed along the air inlet into the chamber. A possible drawback of this procedure is that moisture may condense due to temperature differences on the free area of the porous stone, which has a diameter of about 120 mm larger than the 80 mm diameter of the specimens. To avoid free moisture flux through the porous plate, which would mix with the water extracted from the soil and hinder the reliability of soil moisture exchange measurement, a stainless steel isolation ring is placed around the specimen covering the free ceramic portion.

The measurement system (figure 2) was enhanced by graduating the horizontal ballast tube every $0.1cm^3$, in order to avoid the need for sucking water in the burette to perform any reading. As a consequence, more frequent readings can be performed continuously, especially immediately after air pressure increments.

To allow for automatic reading of water volume exchanged by the soil sample, an image acquisition system was placed to track the ballast filling status as frequently as desired, with a minimum time interval of 10 s.

The image processing system permits accurate estimate of water fluxes, and allows for reliable determination of hydraulic conductivity as a function of water content by means of a backward analysis based on Richard's equation.

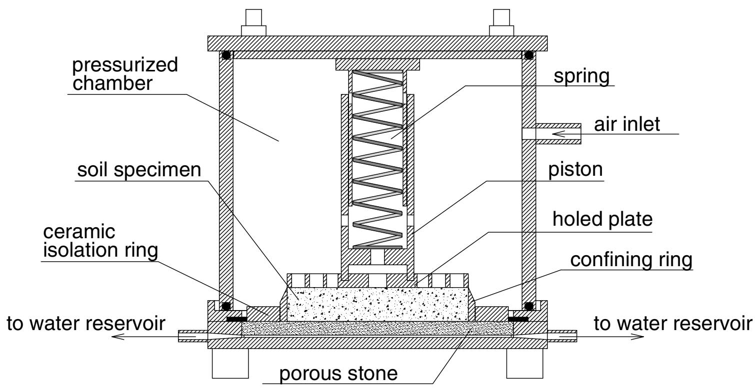

Fig. 1. Schematic representation of the contact and leakage reduction system into the pressurized chamber.

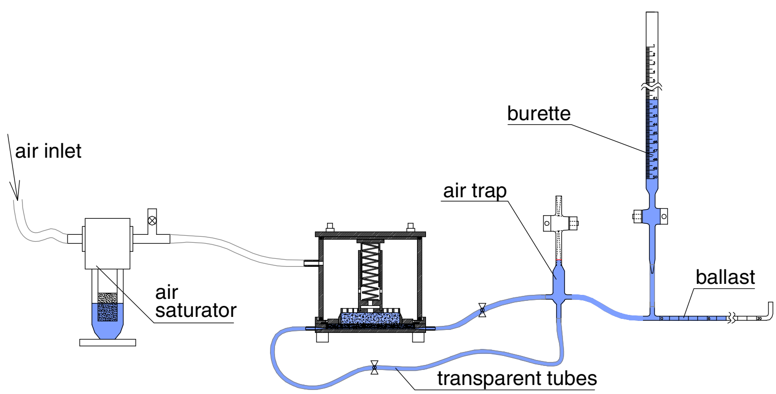

Fig. 2. Schematic representation of the hydraulic connections and water volume measurement system of the modified pressure plate apparatus.

3 Experimental Results

The image-based acquisition system and the hydraulic circuit improvements are permanently installed and used throughout any test. Two set of preliminary tests were conducted to evaluate effectiveness of the enhanced contact system on the SWRC data from a multi-step procedure. The soils used were a silty sand and a clayey silt.

The data (i.e. the exchanged water volumes) were post-processed to obtain the drying branch of the SWRC both following a forward and a backward procedure. In the forward procedure, the initial water content (estimated from direct measurements on the part of the sample discarded from the trimming procedure) is taken as reference value, and the current water volume is calculated by subtracting the observed volume outflow at equilibrium. On the contrary, in the backward procedure the water contents are estimated based on the water content measured at the end of the test by means of oven drying. If no errors occurred during the test, the two procedures should give the same values for the water retention results.

A comparison between the results obtained by means of the original equipment and those obtained in the enhanced apparatus are compared in figure 3 for the clayey silt (table 1). The air-dried soil sieved with a 2 mm sieve was prepared by moist-tamping into cylindrical 80x30 mm specimens at e = 0.63 and Sr = 0.9. Each specimen was then trimmed to the required size, saturated by constant-head flow, and mounted into the pressure plate.

Table 1. Soil properties (AASHTO standard)

%sand	%silt	%clay	Specific gravity	Liquid limit	Plastic limit
18	59	21	2.71	0.34	0.19

The results obtained by forward and backward processing the data coming from the enhanced apparatus tend to overlap, and they differ by an amount which can be disregarded for practical purposes. The same two elaborations of the data coming from the original equipment show differences of more than 30%.

The experimental data obtained with the enhanced apparatus correctly represent the water content exchanges of the soil. On the contrary, measurements which can be done with the original equipment suffer from relevant losses (among which evaporation in the chamber may be considered the most important), which hinder suction control, hence correct description of the soil hydraulic behaviour.

The data obtained with the pressure plate apparatus are also compared in the figure with experimental points previously obtained by means of direct suction measurement with tensiometers (Caruso, 2003). The two data sets are consistent, with tensiometers giving slightly higher suctions for the same water content, as often observed when data sets of the two types are compared one to the other.

In figure 4 the measured water outflows obtained by means of the two setups are compared with each other for the two soils investigated. The comparison confirms the importance of assuring optimal contact between the porous stone and the sample during the test to correctly estimate the water content at equilibrium, for both soils. Besides, the data presented in the figure allow appreciating the influence of contact loss on the time evolution of the results. The original setup does not allow evaluating correctly the flow rates, which limits to a great extent the possibility of deriving reliable information on the hydraulic conductivity of the soils.

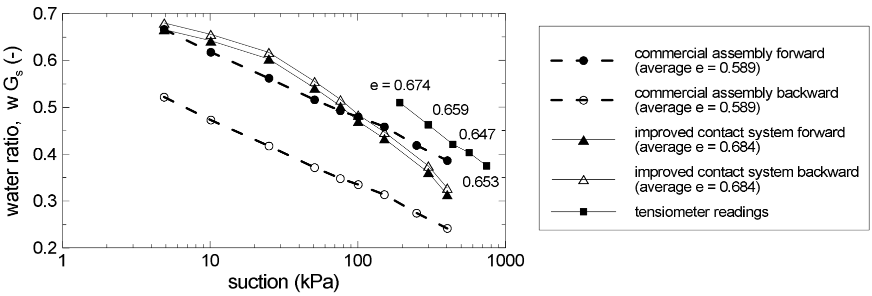

Fig. 3. Data obtained for the drying branch of the SWRC of the clayey silt.

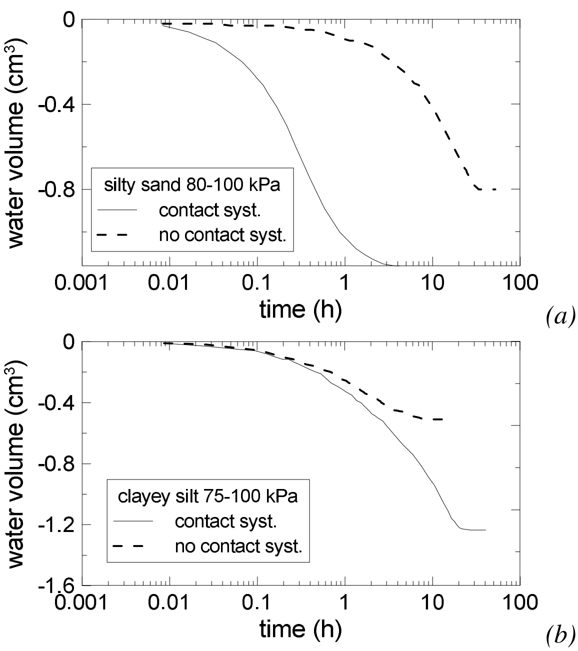

Fig. 4. Pressure increment step analysis (a) 80-100 kPa and (b) 75-100 kPa

4 Conclusions

The relevant effects on data elaboration of some drawbacks of the original design of commercial pressure plate extractors are discussed in the paper. The most important limitations come from air evaporation in the chamber, affecting suction control, air diffusion in the measuring system and imperfect contact between the sample and the porous AEV stone. Although the data obtained with the original equipment could be post-processed to obtain realistic water contents for practical applications relying mostly on the initial water content, the outflow rates exclusively due to soil-water exchanges during each step are lost, and no reliable information can be deduced on the hydraulic conductivity of the soil.

In the paper a few modifications are proposed to enhance the accuracy of the commercial equipment, providing improved contact, limited losses and more reliable data on water outflow and flow rates. The use of a contact spring allows partial control of axial stress, especially for soils having limited deformability.

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