

Recent Progress in Measuring Soil Hydraulic Properties

U. Schindler, G. von Unold, W. Durner, and L. Mueller

Abstract—Knowledge of soil hydraulic properties- water retention curve and unsaturated hydraulic conductivity- is required for soil water modelling and various soil hydrological studies. Measurements with the classical methods are time consuming, the equipment is costly and measured results are affected by uncertainties. The evaporation method is frequently used for the simultaneous determination of hydraulic functions of unsaturated soil samples, i.e., the water retention curve and hydraulic conductivity function. Due to limited range of common tensiometers, all methodological variations of the evaporation method suffered from the limitation that the hydraulic functions can only be determined to maximum 70 kPa. The extended evaporation method (EEM) overcomes this restriction. Using new cavitation tensiometers and applying the air-entry pressure of the tensiometer's porous ceramic cup as final tension value allow the quantification of both hydraulic functions close to the wilting point. Additionally, soil shrinkage dynamics as well as soil water hysteresis can be quantified. The experimental setup followed the system HYPROP which is a commercial device with vertical aligned tensiometers that is optimized to perform evaporation measurements. The HYPROP software ([HTTP://WWW.UMS-MUC.DE](http://www.ums-muc.de), 2012) was developed for data recording, calculation, evaluation, fitting and export of the hydrological data. A methodological comparison of soil hydraulic functions obtained from classical methods and the extended evaporation method showed a good agreement between the results. Systematic deviations were not found.

Index Terms—extended evaporation method (EEM), HYPROP, soil hydraulic functions, water retention curve and hydraulic conductivity function.

I. INTRODUCTION

Classical determination of soil hydraulic properties – water retention curve and unsaturated hydraulic conductivity characteristics – has been carried out using various methods and procedures. In the low tension range, between 0 and 50 kPa, the sand and sand/kaolin boxes [4] are commonly used. For higher tensions (100-1500 kPa), the pressure plate extractor is applied [5]. For quantifying the unsaturated hydraulic conductivity, the one-step [13] and especially the multistep outflow method [10], [7], [6] is widely in use. Most of these methods and devices are very old, the devices are expensive, the measurement is time consuming and the results are influenced by high uncertainties.

The evaporation method [30], [2], [21], [12], [18], [9], [29], [3], [26] allows the simultaneous determination of both, the water retention curve and the hydraulic conductivity function. Measurement time and expense of the equipment are strongly reduced compared to the classical methods. However, all variations of the evaporation method suffer from one limitation, namely the measurement limit of the tensiometers in use of about 70 kPa.

The extended evaporation method (EEM) described by [22], [23] overcomes this limitation. Using new cavitation tensiometers and applying the air entry value of the tensiometer's ceramic cup allow extending the range close to the wilting point. Following the EEM method, the measurement device (HYPROP (HYdraulic PROProperty Analyzer), and the measurement procedure are described, and measurement results are presented. Additionally, soil shrinkage dynamics and soil water hysteresis can be quantified. Results of a comparison between classical and evaporation measurements are presented.

II. THE EVAPORATION METHOD

The HYPROP[®] device (HYdraulic PROProperty analyzer, [28], Fig. 1) was used as a basis for the experiments. HYPROP provides measurements of the water retention curve and the hydraulic conductivity function using the extended evaporation method (EEM) in the tension range between saturation and close to the wilting point [22], [23].

Procedure: The measurements can be performed either at undisturbed or disturbed soil samples. The samples are taken in stainless steel cylinders 8 cm in diameter and 5 cm high. The soil cores are slowly saturated by placing them in a pan of water. The tensiometers are inserted and the core sealed at the bottom by clamping the cylinder with the assembly. The assembly with the core is placed on weighing scales and the soil surface is exposed to free evaporation. The measurement cycle is started. Tension (Ψ) and sample mass (m) are recorded at consecutive times. This is organized by the tensioVIEW software -(<http://www.ums-muc.de>, 2012). The HYPROP-Fit software was developed for the calculation, evaluation, fitting and export of the hydraulic functions (<http://www.ums-muc.de> (2012)). Fig. 1 shows the experimental setup of the HYPROP device.

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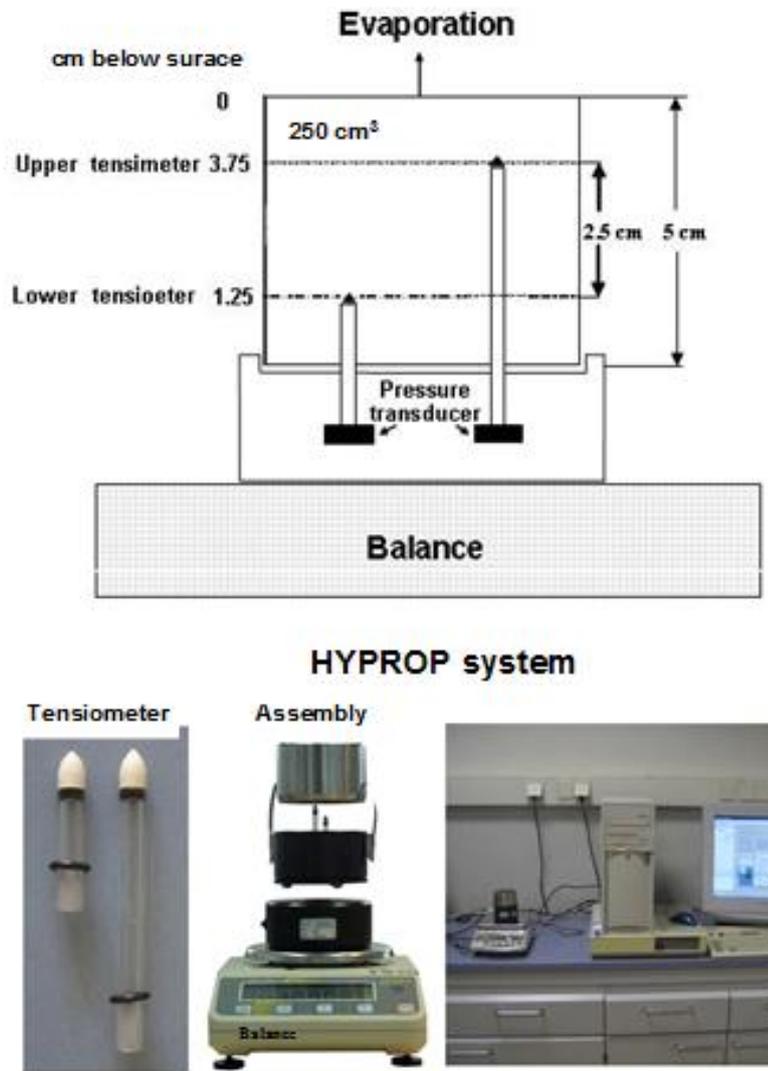


Fig. 1 Schematic illustration of the evaporation experiment and photo of the HYPROP system.

The hydraulic gradient is calculated on the basis of the tension recorded during the time interval. The water flux is derived from the associated soil water volume difference. Single points of the water retention curve are calculated on the basis of the water loss per volume of the sample at time t_i and are related to the mean tension in the sample at this time. The unsaturated hydraulic conductivity (K) is calculated according to the Darcy-Buckingham law (Equation 1).

$$K(\Psi_{mean}) = \frac{\Delta m}{aA\rho_{H_2O} \Delta t i_m}$$

where: Ψ_{mean} is the mean tension over the upper tensiometer at position z_1 (3.75 cm above the bottom of the sample) and the lower tensiometer at position z_2 (1.25 cm above the bottom), geometrically averaged over a time interval of $\Delta t_j = t_{i+1} - t_i$, with $i = 1 \dots n$, $j = 1 \dots n-1$; Δm is the sample mass difference in the time interval (assumed to be equal to the total evaporated water volume ΔV_{H_2O} of the whole sample in the interval); ρ_{H_2O} is the density of water and is assumed to be 1 g cm^{-3} ; a is the flux factor (in the case of rigid soils $a = 2$); A is the cross sectional area of the sample

and i_m is the hydraulic gradient averaged over the time interval.

Data points of the water retention curve are pairs of mean tension at time t_i and t_{i+1} for $i = 1 \dots n$ and the corresponding volumetric water content. Generally, the soil is assumed to be rigid. An EEM data set of a single sample consists of plenty user-defined water retention and hydraulic conductivity data pairs. At the end of the measurement cycle, the residual amount of storage water is derived from the water loss upon oven drying ($105 \text{ }^\circ\text{C}$), and the initial water content is calculated. The dry bulk density is derived from the dry soil mass.

III. EXTENDING THE MEASUREMENT RANGE

The dynamics of a tensiometric measurement in a drying soil can be divided in three distinct stages (Fig. 2). In the first stage, the measured tension reflects the real matric potential of the surrounding soil. The second stage is the vapor pressure stage. The tensiometers are out of function. The tensiometer readings in this stage are no longer representative of the soil water matric potential. The third and final stage can be called “air-entry stage”. It occurs when

the tension in the surrounding soil exceeds the air-entry pressure of the ceramic material. The largest continuous pore of the ceramic drains and air enters from the soil into the tensiometer. At this moment, the measured tension collapses towards zero, which is easily visible in the tensiometer

reading. The basic idea for extending the measurement range is to use the ceramic's air-entry pressure (A_e) at the well-defined moment of the tension collapse, i.e., at the initiation of stage three, as additional measurement of the soil's matric potential (Fig. 2).

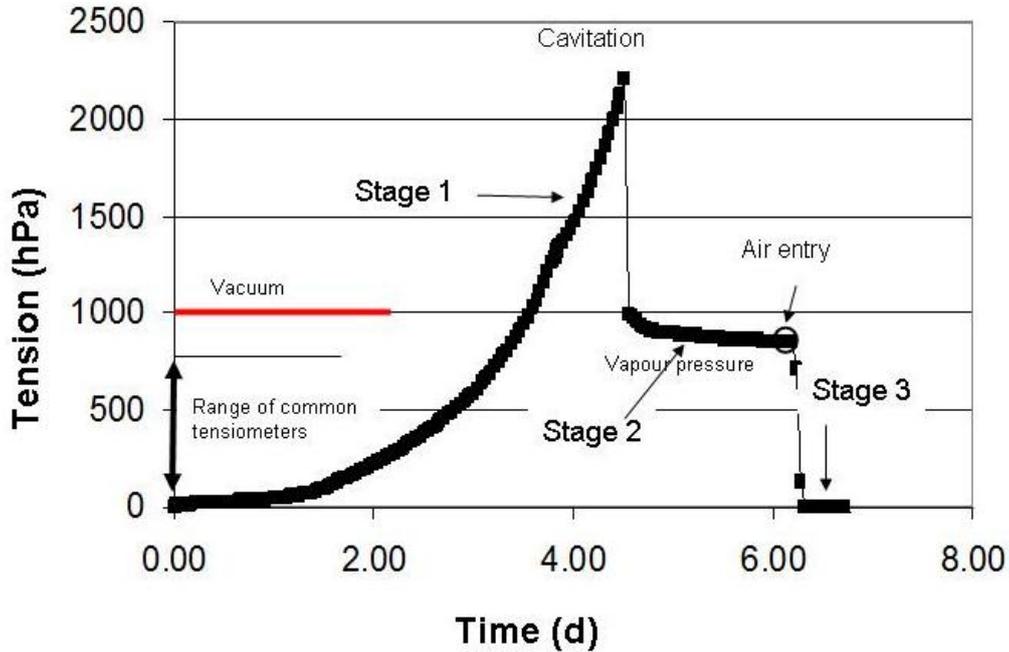


Fig. 2 Tension dynamics.

Any smooth function with higher-order continuity, such as polynomial functions or Hermitian spline interpolation, can be used for interpolation between tension values of stage 1 and the final tension at stage three, the air-entry value (Fig. 3, [23]). Using this procedure we are able to quantify the

hydraulic functions in the range between saturation and close to the permanent wilting point (Fig. 4). The comparison between classical methods and EEM produced a good agreement for the water retention function [24], [20] as well as the hydraulic conductivity [19].

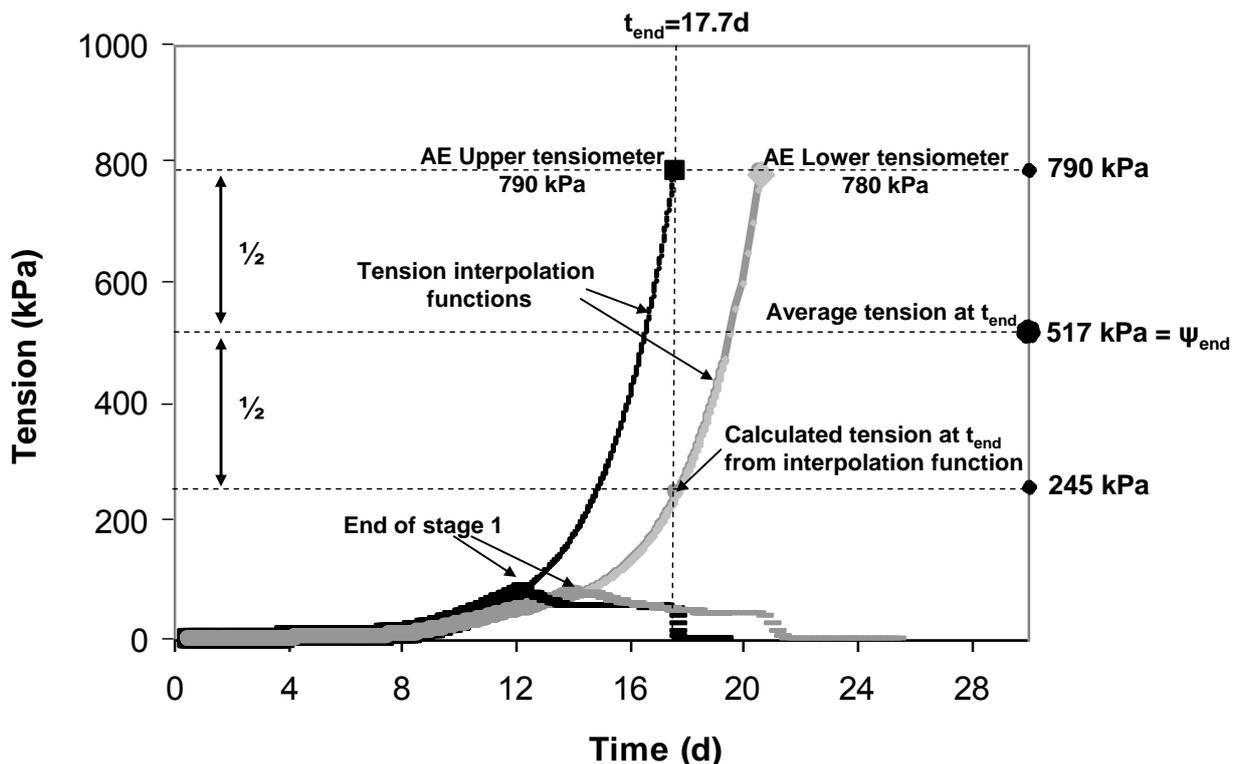


Fig. 3 Principle of tension interpolation, AE- air-entry pressure.

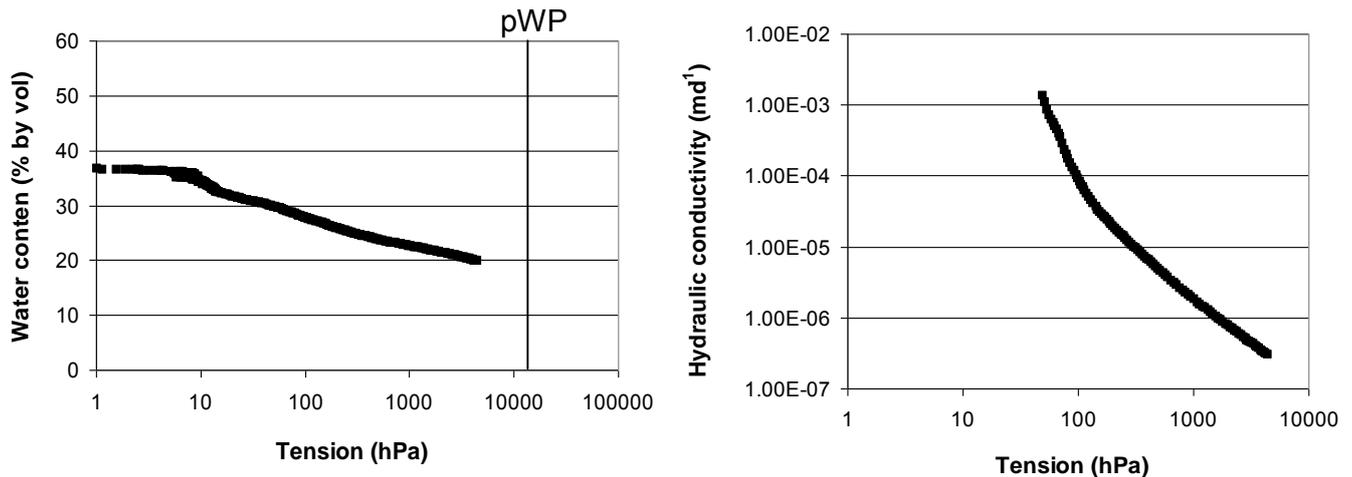


Fig. 4 Water retention curve (left), hydraulic conductivity function (right), sandy loam, Dedelow, Germany.

IV. SHRINKAGE MEASUREMENT

In general, soils and their pore size systems are assumed to be rigid during the loss of water on drying. This is different from reality for many soils, especially for soils with high quantities of clay or organic matter. As the result of shrinking, the bulk density, the porosity and the pore size distribution of these soils change. For quantifying the hydraulic functions under consideration of shrinkage, the HYPROP[®] evaporative device was combined with a circumference meter [25]. A preliminary investigation confirmed that the sample diameter decreased linearly during evaporation from the bottom to the top. To sum up, recording the perimeter change in the middle position of the sample during drying-out together with the corresponding tension and water content was sufficient to determine (i) the increasing dry bulk density and (ii) the hydraulic functions under consideration of shrinkage in the range between saturation and close to the permanent wilting point. In order to make these measurements, the steel cylinder was removed and the sample was coated with a rubber membrane impermeable for water and air.

Measurements were carried out on 25 samples different in texture and origin. The maximum shrinkage (35.4 % by vol. between saturation and 5000 hPa) was measured in the

peat samples. The minimum shrinkage was quantified with 2.8 % by vol. for the Chilean silty loam samples. Taking soil water content measurements on shrinking soils in the field can lead to an underestimation of soil water content differences if the changing dry bulk density is not considered. However, the degree of misinterpretation depends strongly on the soil and its shrinkage activity and ranges from negligible to strong. The unsaturated hydraulic conductivity function was only slightly influenced by shrinkage.

The advantages of the presented method are: (i) the water retention curve and the hydraulic conductivity function can be determined simultaneously, taking into consideration shrinkage, with a high resolution over the whole range from wet to dry, (ii) the method and device are simple and robust to use, (iii) little time is required for measurement, between 3 and 10 days, (iv) the functions are described over the whole tension range, using numerous user-defined data points, (v) the evaluation of the soil water content measurement in shrinking soils is improved and (vi) common data models can be fitted to the hydraulic data as well as to the shrinkage data. Fig. 5 shows exemplarily the change of the water retention curve within the shrinkage dynamics of a clay sample.

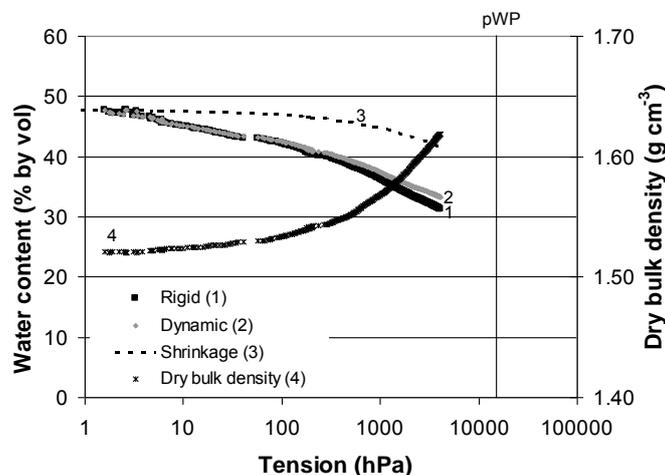


Fig. 5 Water retention function of a loamy clay sample, Seelow, Oder valley, Germany, line 1: rigid soil, line 2: dynamic soil water retention curve under consideration of increasing dry bulk density, line 3: shrinkage, line 4: dry bulk density (DBD).

IV. HYSTERESIS OF THE HYDRAULIC FUNCTIONS

Generally soil hydraulic functions are measured during desorption in the laboratory. Sorption and desorption processes, however, alternate in the field. Tension and water content measurements in the field do not show a clear relationship. [8] has long recognized that the water retention curve during desorption differs from the curve when the soil is rewetted. The water content is smaller when the soil is rewetted. We call this phenomena Hysteresis. The knowledge of the different hydraulic functions between desorption and sorption is important for the soil water and solute transport [17], [27], [1], [16]. Practicable methods and devices for the quantification of hysteresis are missing but required. Here we show the possibility to measure hysteresis with the HYPROP system. No additional technical effort is required.

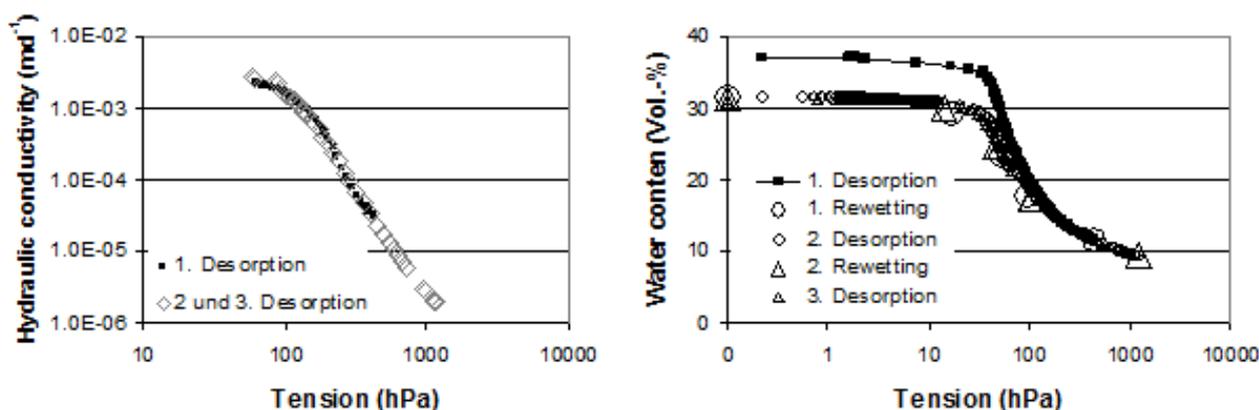


Fig. 6 Water retention curve, right and hydraulic conductivity function, left, during the cycle of desorption and sorption, sand sample, Muencheberg, Germany.

IV. CONCLUSIONS

The Extended Evaporation Method (EEM) and the HYPROP device allow the simultaneous determination of the soil hydraulic functions in the range between saturation and close to the wilting point. The results agreed well with those of classical methods. Additionally the soil shrinkage and hysteresis can be quantified.

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