Laboratory Measurement of Soil Hydraulic Functions in A Cycle of Drying and Rewetting

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Abstract—The extended evaporation method and the accompanying HYPROP measuring system allow the simultaneous determination of desorption curves for water retention and hydraulic conductivity in the range between saturation and the permanent wilting point. We used this method to test for possible hysteresis effects. Water was added to the surface of the sample to simulate a precipitation event. The measured values were used to determine the sorption curves of the hydraulic properties throughout the measuring range. There was no need for any further use of technology. The test results are presented for samples of sand, loamy sand and soils developed from volcanic ash. It was shown that hysteresis of the water retention function occurred exclusively in the soil water tension range between saturation and approximately 100 hPa. The hydraulic conductivity was not affected by hysteresis for tensions above 100 hPa. No statement can be made for the hydraulic conductivity regarding lower tensions. [3]

Keywords—extended evaporation method (EEM), HYPROP, hysteresis, water retention curve, unsaturated hydraulic conductivity function.

I. INTRODUCTION

The soil hydraulic functions (the water retention curve and the unsaturated hydraulic conductivity function) are usually derived from laboratory desorption experiments. However, when the soil water content and soil water tension are measured over long periods in the field, this relationship is not unambiguous. [4] recognised early on that the relationship between the water content and soil water tension, also known as the water retention or pF curve, differs in a cycle of drying and rewetting. When the soil water tension is unchanged, the water content is lower upon rewetting (soil water sorption) than was measured during the process of desorption. This is described as hysteresis. Knowledge of the resulting different hydraulic functions is important for the transportation of soil water and solute [11], [26], [9], [1], [10].

Reasons for hysteresis in the relationship between the soil water tension and the soil water content are the so-called “bottle-neck effect”, air pockets, wetting resistance and differences in the contact angle between the water and solid phases during drying and rewetting [11], [9], [8].

Over the last few decades, a large number of methods and devices have been developed and tested in the laboratory [5], [28], [3], [12], [16], [1] and in the field [17], [29], [26]. Based on this, various models were developed to estimate the hysteresis [7], [18], [15], [28], [27], [26], [6].

[26] presented a field method which involved water infiltrating the soil via a cone permeameter. The infiltration was continued until a constant soil water tension set in. The flow was then stopped and the soil drained. The soil water tension and water content values were used to calculate the water retention function with hysteresis. [1] investigated the hysteresis process in the laboratory using soil monoliths. [5] used a hanging water column connected to a ceramic plate to dry and rewet the sample. [16] present an interesting method. They modified the shrinkage measurement device developed by [2]. The sample was dried by means of surface evaporation and rewetted via a ceramic plate placed underneath it. To determine the soil water content, the sample was put on a set of scales. The soil water tension was recorded with an inbuilt tensiometer. [3] use the WP4 dew-point meter to measure hysteresis in the case of very high soil water tensions. At the Institute of Agrophysics in Lublin (Poland), a modified pressure plate extractor was used.

Measuring drying and wetting cycles in the soil using well-known procedures and devices frequently calls for an extensive amount of equipment and time. In addition to this, the results are almost entirely limited to the water retention curve, and the measuring range usually only describes a section of that curve. Below, a simple procedure will be presented allowing soil hydraulic properties – the water retention curve and hydraulic conductivity – to be quantified during drying/rewetting cycles in the range between saturation and the permanent wilting point.
II. MATERIALS AND METHOD

A. Soil material

The investigations were carried out on soil samples of various textures and geneses (Table 1). Altogether, more than 20 samples were analysed, including not only the samples given as an example in Table 1 but also clay samples from the Oder valley area and samples of organic soil material.

B. Extended evaporation method (EEM)

Based on the simplified evaporation method [21] the extended evaporation method (EEM) was developed [22], [23]. This allows the water retention curve and the hydraulic conductivity function of soil samples to be determined simultaneously in the range between saturation and the permanent wilting point. The method has undergone multiple tests to check its simplified assumptions, and been assessed as effective [30], [31], [14]. The UMS company in Munch worked together with a group of developers to develop the corresponding measuring device (HYPROP; HYdraulic PROPerty analyser). It is a commercial device and was successfully introduced into the soil hydraulics community in 2008.

C. Process principle

A soil sample (250 cm$^3$), disturbed or undisturbed, is saturated with water. The sample is attached to the HYPROP assembly (Fig. 1), on which two tensiometers of different lengths (1.25 cm and 3.75 cm) are mounted. At 2.5 cm, the distance between the tensiometers is half the length of the sample. The sample is fastened onto the HYPROP assembly, its base sealed off.

The HYPROP assembly, with the sample attached, is placed on a set of scales, the surface of the sample is subjected to free evaporation, and the tensions and sample mass are recorded at certain time intervals (between 10 minutes and several hours) online, using a computer. The measurement stops when air enters the tensiometer and the tension indicated at the lower tensiometer falls to 0. The sample is detached from the assembly and the remaining moisture is measured by drying it out at 105°C. The values measured for the soil water tension and sample mass are used to calculate the hydraulic properties. The measurement curves feature a large number of measured values. The dry soil mass and sample volume are used to calculate the dry bulk density. The measuring time depends on the evaporation rate and amount of water to be evaporated, falling between 3 and 10 days.

The HYPROP system can also be used to quantify the shrinkage behaviour of soil samples [21]. Comparing the HYPROP results with conventional methods (sandbox, sand-kaolinbox, pressure plate extractor, multi-step outflow method) produced good correspondence both for the water retention curve [24], [20] and for the hydraulic conductivity [19].

D. Measuring the hydraulic properties during rewetting

The saturated soil sample is connected to the HYPROP assembly and measurement begins as described above. During the evaporation process, the soil water tension and sample mass are measured online.

At a certain point in time, $t$, the evaporation process is interrupted by wetting the surface of the sample with free-flowing water. This simulates a precipitation event of the kind that frequently occurs in natural conditions.

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil type</th>
<th>Depth cm</th>
<th>Horizon</th>
<th>Clay %</th>
<th>Silt %</th>
<th>Sand %</th>
<th>DBD Mg m$^{-3}$</th>
<th>SOM g kg$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Müncheberg</td>
<td>Cambic Abeluvisol</td>
<td>90</td>
<td>C</td>
<td>0</td>
<td>3</td>
<td>97</td>
<td>1.63</td>
<td>0</td>
</tr>
<tr>
<td>Hasenholz</td>
<td>Haplic Luvisol</td>
<td>40</td>
<td>Al</td>
<td>9</td>
<td>44</td>
<td>47</td>
<td>1.63</td>
<td>3</td>
</tr>
<tr>
<td>Pelchuquin</td>
<td>Andosol</td>
<td>20</td>
<td>Ap</td>
<td>35</td>
<td>59</td>
<td>6</td>
<td>0.67</td>
<td>230</td>
</tr>
</tbody>
</table>

DBD – dry bulk density; SOM – soil organic matter
Water should preferably be added using a syringe and, ideally, a distributor. Care must be taken to ensure that the sample surface is wetted as evenly as possible.

The amount of water to be added is determined by the user. The user can roughly estimate the target point depending on the amount of water added based on the change in the sample mass during evaporation and the corresponding soil water tensions indicated on the computer monitor. One after the other, the soil water tensions of the upper, then the lower tensiometer drop. The rewetting process is completed when both tensions are of roughly the same value and the downward flow of water changes direction into an upward flow, i.e. the upper tensiometer again displays higher values than the lower one. Together, the water content and mean tension in the sample at this point in time produce the first value on the rewetting curve. After this, the sample can be rewetted a second or third time, or more, always with the possibility to then continue the evaporation experiment. Once the final rewetting has occurred, the evaporation experiment can be continued, e.g. until the tensiometers go out of function.

The values (tensions and sample mass) thus measured are used to calculate the drying and rewetting curves of the water retention and hydraulic conductivity.

III. RESULTS AND DISCUSSION

Figure 2 shows the variation in the soil water tensions over time during a double rewetting cycle on the Müncheberg sand sample. The evaporation process was first interrupted by wetting the sample surface when the tension at the upper tensiometer reached roughly 500 hPa. First, the tension at the upper tensiometer drops. The hydraulic gradients, which now have an extreme downward gradient, mean that after a certain time the lower tensiometer, and eventually the entire sample, are rewetted. When a balance was reached between the two tensiometers (with the upper and lower tensiometers showing roughly the same values), water was repeatedly added. This rewetting was then repeated another four times until the sample was shown to be saturated by the piezometric head. Subsequently, the evaporation process was continued. When the soil water tension at the upper tensiometer reached roughly 1700 hPa, it was again interrupted by wetting the sample surface. After water had been added four times, always waiting for the balance to be reinstated, the soil water tensions in the sample showed saturation.

Figure 2 Tension at the upper and lower tensiometers over time, with evaporation and rewetting; sand sample from Müncheberg site.

Figure 3 Water retention curve, left; hydraulic conductivity, right, over the drying and rewetting cycle; sand sample, Müncheberg
The dynamics of the water retention curve and hydraulic conductivity are shown in Fig. 3. In the case of water retention, the wetting curve initially follows the drying curve. Only at a tension of roughly 100 hPa does it move away from the drying curve, with the water contents remaining lower at the same tension.

The difference in the water content between the drying and wetting curves was around 4 % by volume. If the sample were to be constantly rewetted, the water content would move back towards the initial water content of the drying curve. This is not shown in Fig. 3 but was proven experimentally.

In the case of hydraulic conductivity, no markedly differences could be proven within the range depicted. However, the point should be made that because the tensiometer was not sufficiently precise (only for the hydraulic conductivity), it was only possible to measure hydraulic conductivity values in sand samples from about 100 hPa.

The result that the water retention curves during drying and rewetting only differed in the range between saturation and about 100 hPa was confirmed for all the other samples. Figure 4, for example, shows the results for the loamy sand from Hasenholz and the sample from volcanic ashes from Pelchuquin in Chile.

While it is usually assumed that hysteresis occurs throughout the water content range from saturation to the dry range [11], [26], [3], the results of this study drew a different picture. During the investigations carried out here, hysteresis only occurred in the range between saturation and roughly 100 hPa. This proposition is supported by [5], who was only able to find evidence of hysteresis in organic soils up to 60 hPa. The results gained by [13] and [12] also show that hysteresis of the water retention function mainly takes place in the range below 100 hPa. Subsequent investigations should look into the causes for this inconsistency.

IV. CONCLUSIONS

The extended evaporation method (EEM) allows the simultaneous determination of the water retention curve and hydraulic conductivity in the range between saturation and the permanent wilting point, based on the evaporation process.
Water added to the surface of the sample simulates a precipitation event. The measured values can also be used to find the wetting (sorption) curves for the hydraulic properties throughout the measuring range. This extension to the measurement range allows hysteresis to be quantified effectively, and can be produced using the HYPROP system with no additional technological requirements. Future works should, however, determine why hysteresis only occurs in the tension range between saturation and approximately 100 hPa in these investigations, rather than being a phenomenon throughout the total water content range as usually assumed.

REFERENCES