Tagungsbeitrag zu: Jahrestagung der DBG 2011
Titel der Tagung:
Böden verstehen-Böden nutzen-Böden fit machen
Veranstalter:
Kommission I der DBG, 5.09.2011, Berlin
Berichte der DBG (nicht begutachtete online Publikation)
http://www.dbges.de

3D infiltration dynamics in an initially dry sandy soil: interactive soil hydraulic-geophysical interpretation

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Abstract

To assess water transport dynamics in a poorly structured homogeneous sandy soil, labour-intensive TDR and tensiometer measurements were conducted during a double tracer ponding experiment. Water transport was also observed by 3D-ERT measurements. The excavated soil profile showed a cone-shaped infiltration zone with depth, contrary to an expected tracer pattern in sand. Water content changes showed highest water contents at the wetting front, referred to as saturation overshoot. This non-monotonic pattern is likely to have been caused by reduced wettability of the soil material, which reduces capillary forces during the infiltration. Independent ERT-data showed the same infiltration pattern during ponding, but could not detect the saturation profile due to gradient smoothing during the inversion process.

key words: infiltration, saturation overshoot, tracer, wettability, ERT

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Introduction

Quantifying the transport dynamics of water and solutes is essential for predicting soil water balance, pollution by agrochemicals and management of irrigation systems.

Common soil physical methods are labour-intensive. 3D-Electrical Resistivity Tomography (ERT) can dynamically capture resistivity changes during water transport processes. To investigate under which conditions ERT can serve as a proxy for standard methods is the main issue. Therefore, infiltration experiments in a poor-structured, sandy podzol soil near Hannover, Northern Germany, are carried out. On such sites, transport can be highly dynamic.

Materials and Methods

Two ponding tracer experiments were conducted on the same site to observe infiltration dynamics. For the test site, a poorly structured homogeneous sand profile in Northern Germany was chosen. In both experiments a tracer solution of KBr (3g L^{-1}) and „Brillant Blue“ (5g L^{-1}) was applied with a

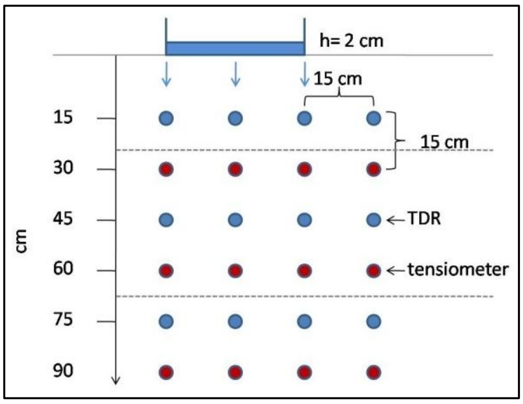

Fig.1: Arrangement of TDR and tensiometer sensors installed in the soil profile during the ponding experiment.

constant ponding height of h = 2 cm. 35 L in 30 min infiltrated into the soil under quasi-saturated conditions.

First, infiltration was observed by measuring water content and matric potential (Fig. 1). In a second experiment, dynamic evolution of electrical potential was measured to capture specific resistivity changes during infiltration (Fig. 2).

Additionally, besides basic soil physical parameters the effect of reduced wettability was determined measuring contact angles with the modified sessile drop method according to Bachmann et al. (2003).

TDR and Tensiometer measurements

12 TDR probes and 12 tensiometers were vertically installed in the soil profile in a regular 15 cm grid under the ponding ring. Data had been collected with a high temporal resolution to detect water content and matric potential changes for 2 hours.

After the end of the ponding experiment a vertical trench through the infiltration area was dug out and the stained profile was photographed.

Geophysical measurements

6 vertical sensors, each equipped with 25 electrodes, were arranged in equal distance around ponding center up to 130 cm depth. 263 measurements were conducted in each of the 7 measurement cycles with two cycles before the infiltration started.

Fig.2: Arrangement of geoelectrical vertical probes around the ponding center during the experiment.

Results

Water content changes

After excavation of a vertical soil trench through the central ponding area an unexpected infiltration pattern was visible (Fig.4). The tracer pattern was cone-shaped with sharp contrasts between the dye-stained soil and the uncolored soil.

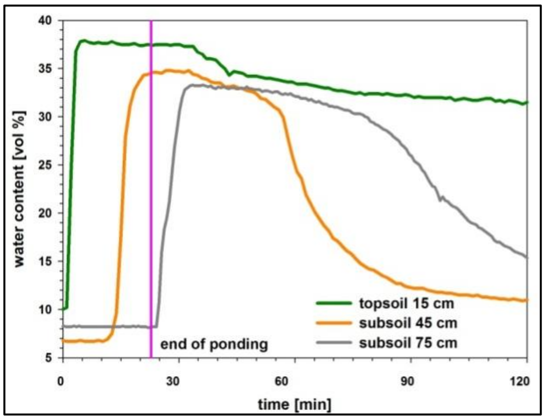

Fig.3: Water content changes during the experiment centrally under the ponding area in 15, 45 and 75 cm depth.

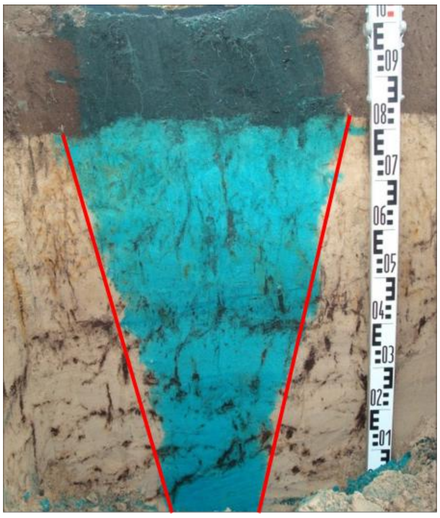

Fig. 4: Tracer pattern of central soil trench 4 hours after end of experiment.

The tracer front resulted in one macro-finger indicating gravity-driven flow during the ponding.

Measured TDR-water content measurements exhibited saturation overshoot in the vertical direction under the ponding area with highest water contents at the wetting front and lower water contents behind the front. The topsoil (15 cm depth) showed a different hydraulic behavior due to different texture and organic matter content. The decrease in water content in 45 cm depth was more pronounced than in 75 cm depth. The deeper subsoil (75 cm depth) showed a lower decrease of water content after the end of ponding.

ERT results

After data inversion with the inversion program BERT (Boundless Electrical Resistivity Tomography, T.Günther 2006). Resistivity changes were inverted as the relation of resistivity at measuring time to resistivity before infiltration started. Fig. 5 depicts the resistivity ratios as a 3D graphic at the final measuring time. The infiltrating water plume is illustrated as a sharp resistivity contrast with a low ratio in the center and higher ratios at the borders. The central area with a low resistivity ratio has a cone-shape structure like the blue stained parts of the excavated soil profile in Fig. 4.

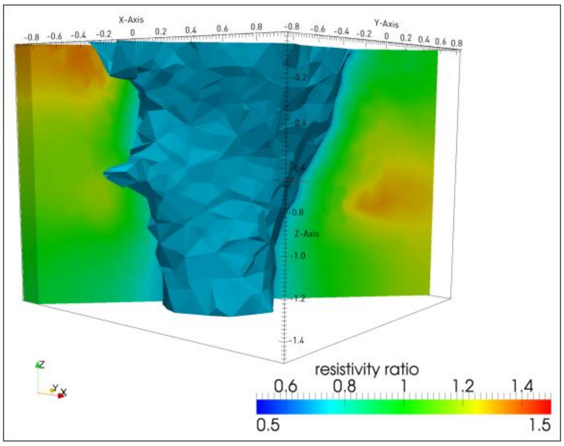

Fig.5: Resistivity ratios after data inversion for the final measuring time during the ponding experiment. The blue plume indicates the infiltrating water.

Contact Angles

Measured contact angles are shown for different soil depth (Fig. 6). With depth contact angles increased. It is striking, that the contact angle decrease due to spreading of the drop is more pronounced in the topsoil. In 125 cm the CA is stable within the measuring time of 5 s, although CAs are still subcritical under 90°. The higher persistence of the subcritical water repellency might have caused the slower decrease of water contents in the deeper subsoil. In the deeper subsoil the breakdown of the persistency of water repellency takes longer due to contact time of soil and water.

The contact angle affects the relation of gravity-driven and capillary driven flow components during infiltration.

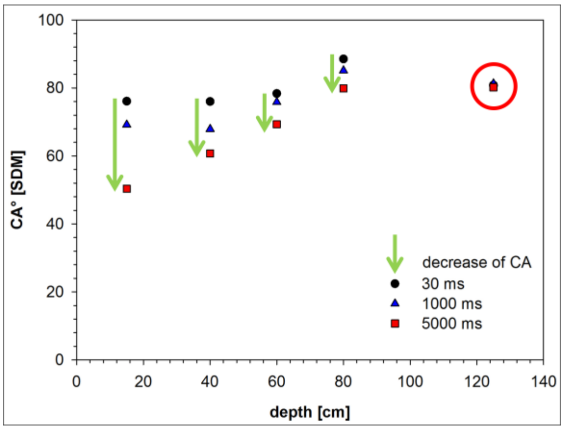

Fig.6: Change of contact angles within measuring time with the SDM method.

Conclusions

We showed non-monotonic saturation overshoot behavior during a ponding experiment in sandy soil in Northern Germany. The infiltrating wetting front did not follow a regular pattern with gradual decreasing moisture content towards the wetting front. In contrast to this, moisture content was highest at the wetting front and decreased behind it. Such saturation profiles have already been observed during fingered flow in laboratory experiments, but extent of these fingers where much smaller as shown by our "macro-finger" experiment. Saturation overshoot under natural conditions was until now only measured by Nimmo et al. (2009) during a ponding experiment in the Mojave Desert. He measured saturation overshoot in the vertical direction.

We also showed that the breakdown of the subcritical water repellency was more pronounced in the topsoil than in the subsoil. In the deeper subsoil stable contact angles could be measured.

Because a reduced wettability affects the capillary forces-gravity forces-relation during infiltration in reducing capillarity, a cone-shaped infiltrating tracer plume could develop.

While measuring with ERT, this tracer pattern could also be detected in the inverted ERT dataset at the final measurement time visible in Fig. 5. However, because the steep gradients between the initially dry soil material and the highly electrical conductive tracer fluid, it is hardly possible to detect the anomalous saturation overshoot pattern with this geoelectrical method. The data inversion automatically smoothes steep resistivity gradients. Consequently, lowest resistivity changes (here in the form of resistivity ratio between resistivity before infiltration and last time step) are located at the "edges" of the tracer plume.

But although inversion process does not allow a real quantification of the non-monotonic moisture distribution, it shows the possibility of tracing infiltrating water under highly dynamic transport situation in measuring in a high temporal and spatial resolution.

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