Percolation in macropores and performance of large time-domain reflectometry sensors

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ABSTRACT

The large-diameter time-domain reflectometry soil water sensors placed horizontally in a structured loamy soil are very sensitive to rapid preferential percolation events. Their readings on these occasions rise considerably, often becoming higher than the native soil's porosity. The effect is caused by gaps between the native soil and the sensors. The geometry of the gaps, even if filled with soil slurry at installation, is not exactly reproducible, which leads to sensor-to-sensor variability of readings. Field calibration in percolation-free periods lead to non-unique trajectories rather than monotonous calibration curves, which can be commented in terms of soil heterogeneity and the dual porosity theory. Data of two typical percolation events are presented. Sensors of this type can be used for detection of preferential flux.

Keywords: TDR; soil water; installation; calibration; preferential flow

The spatial reach of sensing of time-domain reflectometry (TDR) and other electromagnetic soil water sensors is small. Any empty space between the sensor and the soil to be sensed adds bias to the measurement. Adamsen and Hunsaker (2000) and Zhao et al. (2006) found that the Aqua-Tel-TDR and two other TDR sensors did not measure accurately when the soil was near to saturation. The latter authors found a roughly linear relation between the actual soil water content (a dump site material or quartz sand) and the TDR-value derived from the factory calibration line.

The installation described in this paper was designed to monitor soil water dynamics under grass and maize. However, we found that the TDR sensors show unrealistically high values during and after intensive rain and snowmelt events. We explain this phenomenon as a consequence of preferential flow (Clothier et al. 2008, Allaire et al. 2009) through the macroporous unsaturated soil. The objective of this paper is to describe these observations, outline the ways in which they could be interpreted and exploited and to explore their consequences for field calibration and performance of soil water content meters.

MATERIAL AND METHODS

The measurements were carried out in Prague-Suchdol, Czech Republic (50°8'N, 14°23'E, 286 m a.s.l.), where the climate is moderately warm and moderately dry with prevailingly mild winters. The average annual precipitation and temperature are 495 mm and 9.1°C, respectively (Černý et al. 2012). The terrain is flat. The soil is a loamy carbonate Chernozem on aeolic loessial substrate. The fine earth contains 22–28% clay, 39.5–54% silt and 22–32.5% sand. The soil has some capacity to swell and shrink. Its structure is polyhedric to crumby in the topsoil and polyhedric/prismatic in the subsoil. During dry spells, cracks about 1 to 3 mm wide appear at the surface 15 to 20 cm apart. The total porosity varies between 0.54 (topsoil) and 0.40 (plough sole) m^3/m^3, with the average 0.457 m^3/m^3. The field capacity indicator (so-called 'maximum capillary water capacity') varies between 0.30 and 0.35 m^3/m^3. The total organic carbon content in the topsoil is about 2.5% of dry matter (Nedvěd et al. 2008). The land was used as arable. Grass (short lawn) was sown on a part of it in spring 2009. The maize parcel belongs to a

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long-term stationary experiment, started in 1992 (Černý et al. 2012). The field is neither irrigated nor tile-drained.

Weather was measured on the site. Three soil water content sensors Aqua-Tel-TDR (McCrometer CONNECT, USA) were installed under grass (at 10, 20 and 30 cm) and the other three under maize (at 15, 30 and 50 cm), with the TDR waveguides (457 mm long) and primary electronics enclosed in plastic tubes about 700 mm long with outer diameters mostly 20 mm, on few places up to 25 mm. The sensor surrounded by air feels water at distances less than 10 mm from its surface. When it is surrounded by water, its sensitivity to a low-permittivity environment (e.g., air) extends to about 50 mm.

In order not to obstruct field operations on the site by above-ground parts of the sensors and to achieve higher vertical resolution, we installed the sensors into horizontal pre-drilled holes with diameters (25–27 mm) slightly larger than those of the sensors. The sensors were wrapped with soft plastic slurry made from undisturbed local soil or fine earth, in order to refill the gaps between them and the native soil. The data were read every hour.

For the purpose of field calibration, disturbed soil samples were taken with a gouge auger at the depths of the sensors and at safe horizontal distances (50–240 cm) from them. The soil water content of the samples was determined by weighing and drying and then converted to volumetric base, using dry bulk density from undisturbed cores taken in triplicates at the beginning of the study. Care was taken not to include the data affected by percolation events.

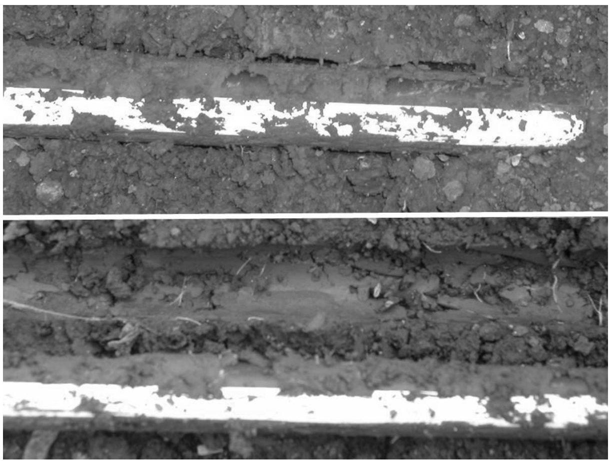

Figure 1. Examples of artificial macropores around the Aqua-Tel-TDR sensor before (the upper picture) and after (the lower picture) the sensor removal, 23rd October 2010

RESULTS AND DISCUSSION

Gaps and macropores around sensors. The incomplete filling of the space around the sensor with the slurry, as well as the subsequent shrinking of the slurry when its water content equilibrated with that of the native soil, left behind a network of artificial macropores around each sensor, connected with the macropores of the natural soil. Their presence and connectedness were confirmed by visual inspection in autumn 2010, when the upper two sensors under maize were uninstalled (Figure 1).

Calibration. The field calibration points for particular sensors grouped along complicated non-monotonous trajectories. For the same crop, these trajectories were similar, which can be associated with horizontal heterogeneity of the soil and its gouge-sampled water content pattern. The long TDR sensors may have sensed the preferential domain water and the soil matrix water on average in the same extent, while the small gouge samples may have missed the droplets of preferential water and the moist spots of soil matrix left behind them.

The laboratory calibration of another Aqua-Tel-TDR sensor in quartz sand (not described here in detail) resulted in a virtually linear calibration equation:

$$\theta_{sampling} = 0.654 \times \theta_{TDR} - 0.043 \qquad (1)$$

Where: $\theta_{sampling}$ – volumetric soil water content (m^3/m^3) obtained by sampling, while θ_{TDR} – non-calibrated output of the TDR sensor in units of volumetric water content (m^3/m^3).

It follows from Table 1 that the average soil water contents obtained by sampling were significantly different from the corresponding mean values obtained by TDR. On the contrary, the standard

Table 1. Field calibration means and offsets

Sensor	Crop	Depth (cm)	$x(G)$	$x(T)$	offset(1.000)
			(m^3/m^3)		
1	grass	10	0.279279	0.408457	–0.12918
2	grass	20	0.273734	0.553436	–0.2797
3	grass	30	0.28746	0.355783	–0.06832
4	maize	15	0.268199	0.577963	–0.30976
5	maize	30	0.308409	0.593799	–0.28539
6	maize	50	0.299749	0.567244	–0.26749

G – water contents from sampling; T – water contents from TDR, uncalibrated; x – sample mean; offset(1.000) – see equation (2)

Table 2. Field calibration variances and their testing

Sensor	Crop	Depth (cm)	$s^2(G)$ (m^6/m^6)	$s^2(T)$ (m^6/m^6)	df	$F_{(G,T)}$	$F_{(0.05)}$
1	grass	10	0.002584	0.006360	6	2.461	4.284
2	grass	20	0.002019	0.001023	7	1.973	3.787
3	grass	30	0.001762	0.001033	5	1.706	5.050
4	maize	15	0.000782	0.002428	4	3.107	6.388
5	maize	30	0.001041	0.001596	4	1.533	6.388
6	maize	50	0.000753	0.001986	7	2.637	3.787

G – water contents from sampling; T – water contents from TDR, uncalibrated; s^2 – sample variance; df – degrees of freedom; $F_{(G,T)} = \max(s^2(G), s^2(T))/\min(s^2(G), s^2(T))$; $F_{(0.05)}$ – F-quantile exceeded in 5% of cases

deviations of data obtained by sampling were not significantly different from those of parallel TDR readings (Table 2). This statement was checked with a standard F-test (Table 2). Therefore, it seems most adequate to relate the soil water contents from field samplings to the TDR measurements with a unity-slope straight line:

$$\theta_{sampling} = 1.000 \times \theta_{TDR} + \text{offset}(1.000) \qquad (2)$$

rather than (1). In (2), offset(1.000) is a difference (m^3/m^3) between the mean water content obtained by sampling at a particular depth under a particular crop and the mean non-calibrated water content obtained from the corresponding TDR sensor.

Rapid percolation events. Figures 2 and 3 display typical variation in time of the soil water contents obtained by TDR and corrected using (2). The passage of easily drainable water through large pores was indicated by a sudden increase of the TDR-measured water content. In some cases, the latter exceeded considerably the average porosity of the undisturbed natural soil (0.457 m^3/m^3). This can be explained by temporary accumulation of water on the top of and around the sensor. The water could come into intimate contact with the sensor surface in a much larger extent than if there were no gaps and artificial macropores. This several-hours lasting presence of water in the artificial macropores may have also increased the water content of the surrounding soil matrix, making thus the sensors' readings elevated over a longer time.

Figure 2 presents a four-day period with three rainstorms, the second composed of two partial events. It was preceded by other ample rains, which made the initial soil water content relatively high at 10 cm (about 0.46 m^3/m^3) and 20 cm

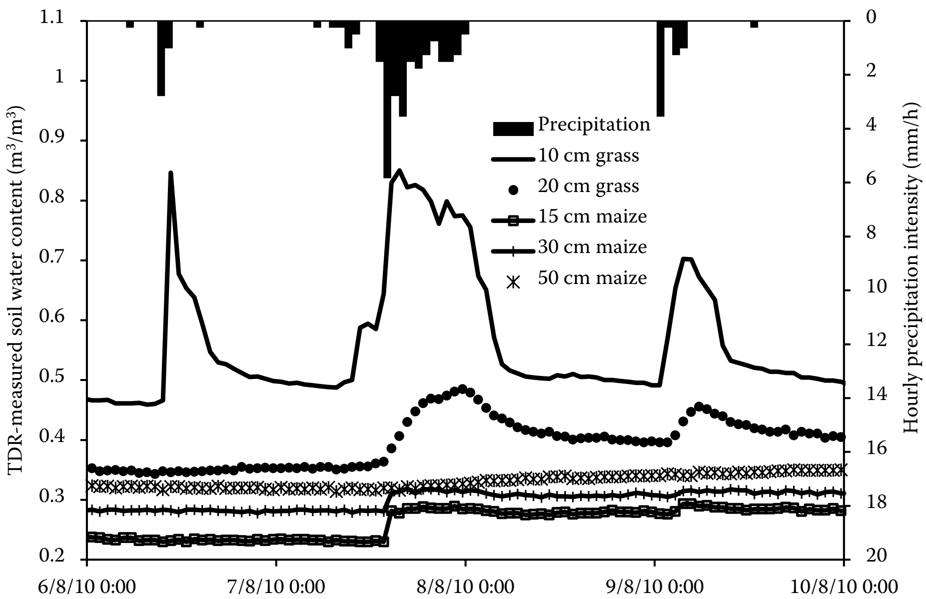

Figure 2. Volumetric soil water contents (measured by TDR and modified using equation (2)) and hourly precipitation rates over the period of rain precipitation on 6–9th August 2010

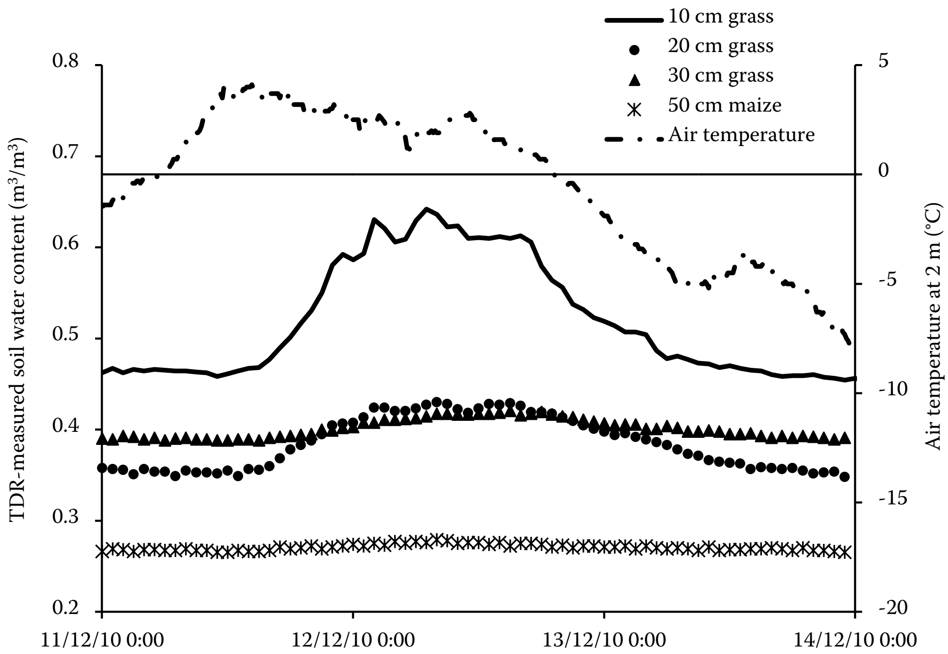

Figure 3. Volumetric soil water contents (measured by TDR and modified using equation (2)) and air temperature over the period of snowmelt on 11–13rd December 2010

(about 0.35 m^3/m^3) under grass but relatively low elsewhere. The rainfall sum over the period was 36.8 mm. The sensor at 30 cm under grass was out of order. All three rain events caused a sudden and high-amplitude increase in the TDR-readings at 10 cm under grass, while the second and third event produced a similar increase also at 20 cm under grass and 15 cm under maize. The second event was also perceived at 30 cm under maize. The reaction at 50 cm under maize was slow. The temporary accumulation of water around the sensor is signalled at 10 cm under grass, but it probably also occurred at 20 cm under grass, as indicated by the rapid fall of TDR values immediately after the cessation of the rain in the end of the second and third event.

Figures 3 shows an isolated three-day snowmelt event due to increased air temperature. The snowpack height was 20 cm at the start and 6 cm at the end. The soil temperature at 10 cm oscillated around zero. The soil was frozen to 2 to 3 cm but was not impermeable. The precipitation sum over the period was only 1.3 mm (not depicted). The sensors under maize at 15 and 30 cm had been taken away at that time, while the sensor at 50 cm remained in place. The maize plot was ploughed and left in rough furrow. The initial soil water content (except for 50 cm after maize) was relatively high. The increase of the TDR-values due to snowmelt was perceived by all four sensors, but the accumulation of water around the sensor was only significant at 10 cm under grass. The release of liquid water from the snowpack was gradual; the resulting soil water content hydrograph had a quasi-symmetric bell-like shape.

Conclusions. The long horizontal sensors are more sensitive to vertical percolation events than the vertically or otherwise oriented sensors, because the probability of intersection between a horizontal linear sensor and virtually vertical planar flow paths (cracks or inter-aggregate pores) is high. The intersection of short and/or vertical sensors with the preferential flow paths would be less probable. The non-negligible diameter (20–25 mm) of the sensors enabled water to accumulate on the top of and around them whenever its influx from above was high. This effect would be less pronounced for TDR sensors with thin wires pushed in the soil. These mechanisms may have contributed to the large variability of Aqua-Tel-TDR readings near saturation (Adamsen and Hunsaker 2000, Zhao et al. 2006).

The field calibration of large encapsulated TDR-sensors in macroporous soils does not necessarily lead to monotonous calibration curves. This fact is intrinsically associated with the nature of the water movement and retention is such soils. Similar 'bad' experience with the field calibration of electromagnetic sensors is reported by Kinzli et al. (2012), who prefer laboratory calibration to the field one. We disagree with them, as long as the final purpose is the field measurement, because the field techniques of sensor installation can hardly be mimicked in the laboratory, especially when the sensors are large and the soil is structured.

The phenomena described can be exploited to indicate the preferential gravitational flow. Their magnitude is very probably related to its flux density. There is therefore a chance that these measurements will be apt to quantification. Over rainless periods and periods without snowmelt, the sensors studied may reveal a slight bias towards higher soil water contents because of leftovers of gravitational water accumulations.

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