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IMPROVED HORIZONTAL INSTALLATION OF LARGE SOIL MOISTURE CONTENT SENSORS AND INTERPRETATION OF THEIR READINGS IN TERMS OF PREFERENTIAL FLOW

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Soil moisture content was measured by TDR sensors Aqua-Tel-TDR (Automata, Inc., today McCrometer CONNECT) in a loamy Chernozem on carbonate-rich loess substrate. The sensors, wrapped in slurry made of local soil and water, were installed horizontally into pre-made holes. The bias caused by imperfectly filled gaps between the wall of the hole and the sensor surface was reduced by field calibration. The same gaps made it possible to detect the preferential flow in soil macropores, due to which the reflectometric readings were perceivably higher than analogous readings before percolation events and sometimes higher than the native soil porosity. One typical event is presented. It is envisaged that sensors of this type can be used for semi-quantitative estimation of the preferential flux density, e.g. with the help of dual or multiple porous medium models or the momentum dissipation theory.

KEY WORDS: Time-Domain Reflectometry (TDR), Bias Reduction, Macropores, Rain, Snowmelt, Irrigation.

František Doležal, Svatopluk Matula, João Manuel Moreira Barradas: ZLEPŠENÁ VODOROVNÁ INSTALACE VELKÝCH ČIDEL PŮDNÍ VLHKOSTI A INTERPRETACE JEJICH ČTENÍ VE SMYSLU PREFERENČNÍHO PROUDĚNÍ. J. Hydrol. Hydromech., *60*, 2012, 4; 16 lit., 3 obr.

Vlhkost hlinité černozemní půdy na karbonátovém sprašovém substrátu byla měřena metodou TDR čidly Aqua-Tel-TDR (Automata, Inc., dnes McCrometer CONNECT). Čidla, obalená před osazením pastou z místní zeminy a vody, byla instalována vodorovně do předvrtaných otvorů. Systematická chyba způsobená nedokonale zaplněnými mezerami mezi čidlem a stěnou otvoru byla zmenšena terénní kalibrací. Tytéž mezery umožnily indikovat preferenční proudění v půdních makropórech, díky němuž byla reflektometrická měření citelně vyšší než analogické hodnoty před průsakovou epizodou a někdy i vyšší než pórovitost původní půdy. Je demonstrována jedna typická epizoda. Lze předpokládat, že čidla tohoto typu mohou být použita k semikvantitativnímu odhadu hustoty preferenčního toku, např. za pomoci modelů dvojného nebo vícenásobného pórovitého prostředí nebo teorie rozptylu hybnosti.

KLÍČOVÁ SLOVA: reflektometrie v časové oblasti (TDR), redukce systematické chyby, makropóry, déšť, tání sněhu, závlaha.

Introduction

Clothier et al. (2008) demonstrated the importance of preferential flow in soils for ecosystem services. An overview of the methods of study of the preferential flow was recently published by *Allaire* et al. (2009). It is rarely possible to measure the preferential flux density directly and continuously in the field. One possible option is to use a network of sensors for continuous monitoring of the variability of water occurrence in the soil. This variability is, among other factors, caused by the preferential flow. *Allaire* et al. (2009) state that it may be advantageous to place numerous sensors horizontally and at small spatial intervals. The sensors that allow continuous monitoring at high temporal frequency can detect short-duration preferential flow events. The preferential flux density at different depths can be estimated from these measurements using, e.g., the momentum dissipation theory (e.g. *German* et al., 1997), if the flux density at the surface is known. This was done, for example, by *Alaoui* et al. (1997). The present paper suggests a way of qualitative and, possibly, semi-quantitative detection of the preferential flux for which a single moisture content sensor is needed. It is the flow in planar features, such as cracks, or in a dense and continuous system of inter-aggregate pores, that is detectable in this way. A preliminary report was presented by *Doležal* and *Matula* (2011).

Today's most widespread, so-called electromagnetic soil moisture sensors make use of the difference in permittivities between water and the other soil components. They are extremely sensitive to the presence of gaps or disturbed zones between the sensor and the natural soil. It is recommended to their users (e.g., by *Loiskandl* et al., 2010) not to rely on universal (factory) calibration curves but calibrate individual sensors for their own conditions. The literature is full of reports about discrepancies between the calibration curves obtained by the users and those supplied by the manufacturer (e.g. *Paltineanu*, *Muñoz*, 2010). *Loiskandl* et al. (2010) concede that they "have personal experience of being consulted to explain obviously wrong readings" of electromagnetic sensors. The time-domain reflectometry (TDR) is a standard electromagnetic method (e.g., *Noborio*, 2001). The Aqua-Tel-TDR sensors, supplied by Automata, Inc. (now McCrometer CONNECT), are designed for practical operation in irrigated agriculture and are relatively large and robust. *Adamsen* and *Hunsaker* (2000) found out that these sensors, as well as two other types of TDR sensors, do not provide sufficiently accurate data at soil moisture contents next to saturation. *Zhao* et al. (2006), too, report a large variability of Aqua-Tel-TDR measurement near to saturation.

The results reported here were obtained during a study focused on soil water regime under agricultural crops. Later it was recognised that the readings of sensors may provide an insight into preferential percolation through structured soils. The phenomenon that from the point of view of the original purpose of the study was an artefact appeared to be more interesting than the original purpose itself. The objective of this paper is to draw attention to this phenomenon.

Methods and materials

The research has been conducted on the Demonstration and Experimental Grounds in Prague – Suchdol (50°8'N, 14°23'E, 286 m a.s.l.) under moderately warm and moderately dry climate with prevailing mild winters. Average annual temperature and precipitation are 9.1 °C and 495 mm, respectively (*Černý* et al., 2012). The plot studied is flat and its slope is negligible. The soil is a loamy carbonate Chernozem on loess. The fine earth contains 22–32.5 % sand (0.05 to 2 mm), 39.5–54 % silt (0.002 to 0.05 mm) and 22–28 % clay (below 0.002 mm) (*Krkavcová*, 2010, unpublished). There is virtually no textural difference between topsoil and subsoil. The structure is polyhedric-crumby in the A horizon and polyhedric-prismatic in the loessial C horizon. The boundary between A and C horizons lies at about 35 cm (under grass) and 60 cm (under maize). The transitional A/C horizon is about 10 cm thick. The soil has a moderate capacity to swell and shrink. The saturated hydraulic conductivity (100 cm^3 cores) varies between $1×10^{-7}$ and $7×10^{-5}$ m s^{-1}. The total porosity varies between 0.40 (plough sole) and 0.54 (topsoil) m^3 m^{-3}. Its mean value is 0.457 m^3 m^{-3} (0–100 cm). The average water retention curve (*Kozáková*, 1994, unpublished) can be approximated by the van *Genuchten* (1980) equation with the saturated moisture content θ_s = 0.47 m^3 m^{-3}, the residual one θ_r = = 0.07 m^3 m^{-3}, the capillary rise parameter α = 6.0 m^{-1} and the shape factor n = 1.152. The soil had been ploughed for several centuries. Grass was sown in spring 2009 and is maintained as a short lawn. The maize parcel belongs to a long-term stationary experiment, started in 1992 (*Černý* et al., 2012). The sites were not irrigated.

Precipitation was observed on the site. Three soil moisture sensors Aqua-Tel-TDR were installed under grass (at 10, 20 and 30 cm depth) and other three under maize (at 15, 30 and 50 cm depth). The sensors are cylindrical, about 700 mm long, with a diameter 20 to 25 mm. The sensing TDR elements (457 mm long) and the electronics are encapsulated within the sensor body (Fig. 1). The sensors are sensitive to the distance 10 to 50 mm from their surface, larger when the soil is moister. The sensors' manufacturer (*McCrometer CONNECT*, 2012) admits the problem of gaps around the sensors. Vertical installation is preferred; the manufacturer recommends either to partially fill the borehole with soil slurry and immerse the sensor into it or to bring the soil into an intimate contact with the sensor by hammering rods into the ground in parallel with the sensor. If horizontal or slanting installations are desired, the user is advised to lay the sensors in open trenches, backfilled afterwards. We placed the sensors horizontally in order to improve the vertical resolution and to avoid sensors' sticking out. As the permeable backfill might prohibitively favour the percolation of water towards the sensors, we avoided the installation in backfilled trenches. The hammering of rods in parallel with the probes might result in an excessive loosening of the soil. Hence, the sensors were inserted into horizontal boreholes from temporary installation pits. The soil above the sensors remained undisturbed. The borehole diameter (25–27 mm) was made slightly larger than that of the sensor. The sensors were wrapped with slurry of native soil (later of fine earth below 1 mm) before the insertion. The slurry had a very soft plastic consistency below the liquid limit.

The bias was reduced by field calibration. Soil was sampled in triplicate with a gouge auger at the depths of the sensors and at horizontal distances from the sensors (50 to 240 cm) large enough not to affect sensors' readings and small enough to expect on average the same moisture content of the native soil. Repeated samplings were made at different horizontal positions so that no spot was sampled twice. The moisture content of the samples was determined by weighing and drying and multiplied by the dry bulk density of undisturbed 100 cm^3 cores, taken in triplicate at particular depths during the digging of the installation pits.

Results and discussion

Calibration

Results of calibration are mentioned only briefly and will be published separately. The rapid percolation events and their immediate aftermaths were disregarded. For the rest of the data, the standard deviation of soil moisture contents obtained by sampling for a particular depth and a particular crop was not significantly different from that of the parallel reflectometric readings. However, the mean moisture content obtained by sampling was significantly different from the mean uncalibrated TDR-measured moisture content at the same depth and under the same crop. These differences were different for different sensors. We corrected the TDR readings by adding to them an offset, equal to the average difference between the mean moisture content obtained by sampling at a particular depth under a particular crop and the mean uncalibrated TDR reading of the corresponding sensor.

Indication of rapid percolation events

The passage of gravitational water around the sensors and its possible accumulation on the tops of the sensors was clearly indicated by the sudden increase of the TDR-measured moisture content, frequently up to the average porosity of the undisturbed natural soil (0.457 m^3 m^{-3}) or above it. Sudden upswings of the TDR-measured soil moisture content not exceeding the porosity were observed by other authors (e.g. *Morris* and *Mooney*, 2004, their Fig. 3; *Clothier* et al., 2008, their Figs. 4 and 5). *Alaoui* et al. (1997) do not mention the particle density of their soil, but one can reasonably suspect that the peaks of their TDR readings surpass the soil porosity (cf. the left upper corner of their Fig. 2).

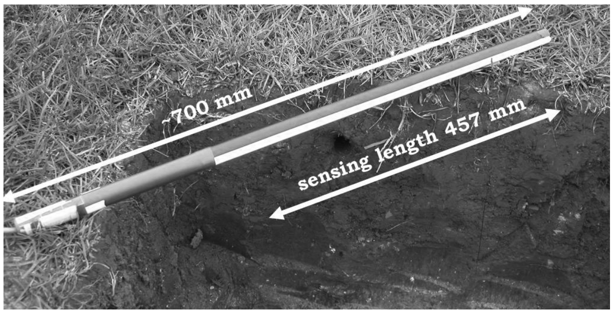

Fig. 1. Overall view of the Aqua-Tel-TDR soil moisture sensor.

Fig. 2 shows the corrected TDR-measured moisture contents during a typical percolation event. It covers a period with two ample rainstorms, the first composed of two and the second one of three partial events. The rainfall sum over the period depicted was 42.2 mm. The initial moisture content was relatively low (around 0.30 m^3 m^{-3}) at all depths and under both crops. The response to the first rain can be seen at 10 and 20 cm under grass; the temporary accumulation of water above the sensor is only manifested at 10 cm. The second rain made the TDR-data increase everywhere except for 50 cm under maize. The accumulation of water is indicated at all depths under grass, while the increase of soil moisture under maize, even though rapid and clearly visible, need not indicate water accumulation. Temporariness of the accumulation of water on the tops of the sensors is confirmed by the rapid fall of reflectometric values after the cessation of the rain in all five partial events at 10 cm under grass and in the first partial event of the second rain at 20 and 30 cm under grass.

Macropores and their functioning

The distinct reaction of TDR sensors to percolation events (especially at shallow depths under grass) and the TDR-measured values (after the offset correction) higher than the porosity of the natural soil can be explained as follows. First, a long sensor installed horizontally almost certainly cuts several preferential flow paths, prevailingly vertical, in planar and inter-aggregate pores. Therefore, the percolation is indicated virtually always when it occurs. Second, the non-negligible diameter (20–25 mm) of the sensors offers an opportunity for water to accumulate on the top of them. It may take several hours before this accumulation drains away along the sides of the sensor. The water retained on the top of the probe and elsewhere around it has a short-lasting privileged opportunity to be absorbed by the soil matrix, which may keep the signal increased over few days (Fig. 2). The third factor that paradoxically qualifies the Aqua-Tel-TDR sensors as indicators of preferential flow is their essential incapability of being installed tightly in pre-drilled constant-diameter holes. The slurry cannot perfectly refill the gaps around the sensor. Moreover, it dewaters and shrinks. This gives rise to a system of artificial macropores around each sensor, connected with the macropores of the natural soil. These artificial macropores were confirmed by visual inspection (Fig. 3) and may have, together with the accumulation of water above the sensors, contributed to the large variability of Aqua-Tel-TDR readings near saturation reported by *Adamsen* and *Hunsaker* (2000) and *Zhao* et al. (2006). The reaction of the TDR-values to rainstorms is stronger under grass than under maize. This is due to larger depths of sensors' placement under maize, but also due to the grass turf itself with its many biopores and inter-aggregate pores. The absence of tillage may have also helped preserve soil cracks in the topsoil under grass in a more conductive state.

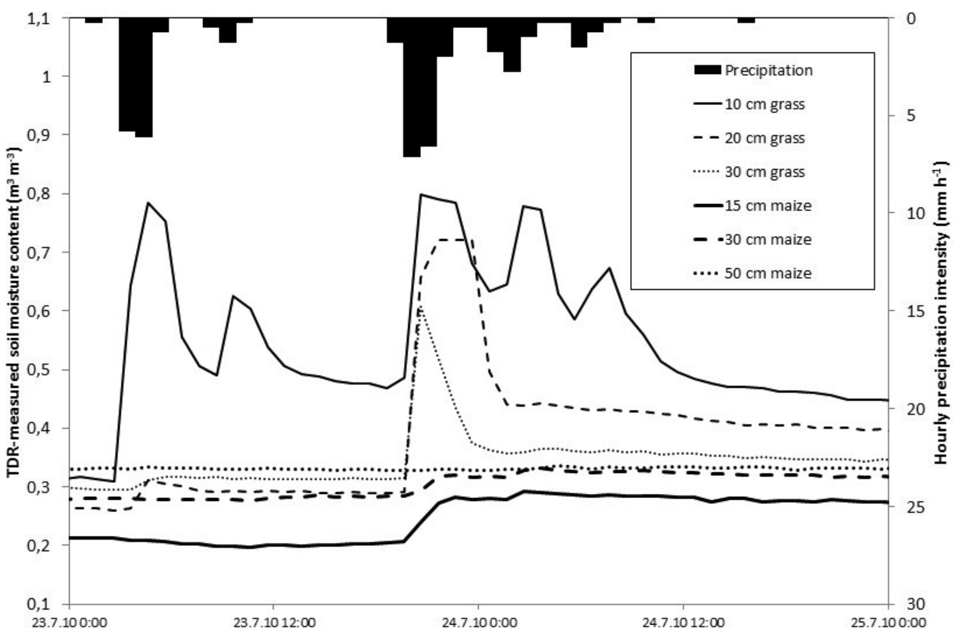

Fig. 2. Volumetric soil moisture contents (measured by TDR and offset-corrected) and hourly precipitation rates over the period of 23 – 24 July 2010.

Conclusions

The phenomena observed in this paper deserve to be studied in order to improve the design of sensors. These very artefacts also indicate the occurrence of preferential flow. Their magnitude is related in some way to the preferential flux density. The latter can be therefore semi-quantified with help of them, e.g. using dual permeability models (*Vogel* et al., 2000), with some soil parameters known a priori and the rest obtained by inverse simulation. A two-dimensional simulation would help us to understand the actual dynamics of water in the soil profile with an assembly of sensors. If all soil parameters were correctly set and the processes were reliably measured, then even the unknown upper boundary condition (in both the matrix domain and the preferential one) might be found by optimisation. The corresponding fluxes at any depth within the region scanned by the sensors could be then obtained by direct simulations. Another option is to apply the theories similar to that by *Germann* et al. (1997; see also *Alaoui* et al., 1997), as long as the geometry of the macropores is known.

The final goal would be continous sensing of the actual preferential flux at a given depth and indication of the instant when the flux takes place. The mere dye tracing, as well as most other methods reviewed by *Allaire* et al. (2009), could hardly fulfil this task. The preferential flow can also be indicated by soil water potential sensors, such as tensiometers or porous matrix sensors (e.g., *Finsterle* and *Faybishenko*, 1999), which are, however, rarely installed horizontally and are not long enough to safely hit the vertical flow paths. The amplification due to water accumulated in the gaps and on the tops of the potential sensors is absent and most types of them swing up to zero readings when hit by preferential flow, irrespective of the magnitude of the preferential flux. A detailed discussion is outside the scope of this paper.

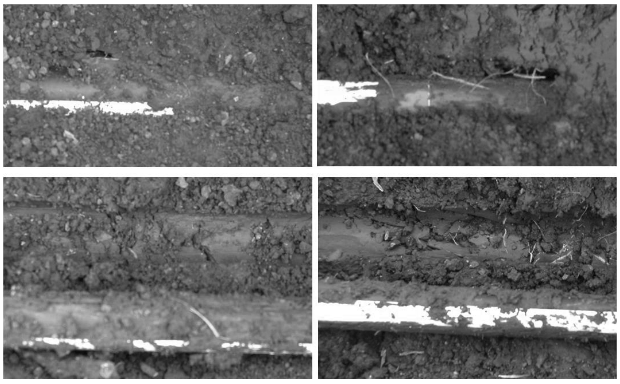

Fig. 3. Artificial macropores in the soil around the Aqua-Tel-TDR sensors, seen from above before (the upper pictures) and after (the lower pictures) the sensor removal, 23 October 2010.

Except for the days of percolation events and few days afterwards, the sensors studied do measure soil moisture content in a way that is at least qualitatively acceptable. They may be slightly biased towards higher moisture contents because of leftovers of the preferential water, either excessively absorbed by the matrix or retained in macropores. It seems probable that not only the large encapsulated TDR sensors, but many other electromagnetic sensors are prone to overestimating soil moisture content. The gaps between the TDR sensing rods (6 mm in diameter) and the surrounding soil have been reported by *Alaoui* et al. (1997) and may be a more general phenomenon. This would be of practical importance in irrigation management (notwithstanding the fact that some irrigation sensors are placed in disturbed soils, which adds other artefacts to the problem). The stopping of irrigation as soon as the sensors indicate high enough soil moisture may be precocious, because the actual soil moisture content may be considerably lower than the one signalled. At least some electromagnetic sensors do not measure "in real time" but with a delay, needed for the gravitational water to drain away from their vicinity. It is a challenge to estimate the magnitude of this delay.

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