DETERMINATION OF THE WETTING FRONT IN DRIP IRRIGATION USING TDR MULTI-WIRE PROBE

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The adequate estimation of wetting front is fundamental to determine the number of drippers per plant and its location below the plant canopy in drip irrigation. Measurements of wetting front dimensions are usually made by opening trenches, which is a time-consuming method and sometimes imprecise. The recent scientific developments create the possibility to monitor the soil moisture content using electronics sensors. The objective of this research is to study the possibility to use TDR Multi-wire probes (Time Domain Reflectometry) with electrical impedance discontinuities in the determination of the wetting front dimensions in drip irrigation application. The experiment was divided in two parts. In the first one, it was studied the laboratory performance of two Multi-wire probe configurations and evaluated the probes reliability to monitor the water content variation in a porous media profile. The second part was conducted in a 250 L bucket and the water dynamic process was monitored during 48 h, after 5 mm of water application using a drip system. The results showed the viability to estimate the wetting front using TDR equipment coupled the Multi-wire probes with electrical impedance discontinuities.

INTRODUCTION

The knowledge of the wetted front design in the soil profile is important to optimize the drip irrigation management in agriculture. The drip irrigation is characterized by application of small water amounts in high frequency and directly in the root zone. This type of application keeps the water content near to field capacity in a partly soil volume, well known as wetting front. The knowledge of the wetting front location is important, because besides the water, its concentrate the applied products through the irrigation water, such as fertilizers, fungicides, nematicides, etc. The adequate estimation of the wetting front dimensions is fundamental to determine the number of drippers per plant and its location under the plant canopy. Measures of wetted front dimensions are usually made opening trenches where the water is applied. Another method to monitor the soil moisture content is by electronics means, such as specific sensors.

The TDR technique for measuring water content and electrical conductivity of the soil solution is becoming increasingly popular. Its outstanding advantages are accuracy, speed, reproducibility, good theoretical basis, a well-defined and selected sampled volume, and the fact that water content and salinity are measured in exactly the same volume. The method bases on the sensitive effect of the soil water content in the microwaves pulses propagation speed in conductive cables in soil, caused by the large differences in the relative dielectric permittivities of water (81), air (1), and soil particles (3-5). It is necessary, basically, a cable test and a sensor with metallic rods tied by coaxial cable.

In TDR, the propagation velocity of a high-frequency electromagnetic signal is determined by:

\[ v = \frac{c}{\sqrt{\varepsilon_b}} \]

Where \( v \) is the propagation velocity, \( c \) is the propagation velocity of electrical signals in vacuum or free space (3x10^8 m/s), and \( \varepsilon_b \) is the apparent dielectric constant of the soil. In the application of TDR to soil water measurement, a fast rise-time voltage pulse travels in the soil guided by a transmission line or wave guide of length, \( L \), and the pulse reflects back from the end. By determining the travel time, \( t \), of the pulse sent throughout the transmission line, is possible to obtain the velocity during the two-way travel as \( v = 2L/t \). Combining the two mathematical expressions the apparent dielectric constant of the measured soil can be calculated by:

\[ \varepsilon_b = (ct/2L) \]

The most recent researches with the TDR technology show a tendency in the direction of understanding the technique better and improving the probes configuration.
There is considerable flexibility in the probes design, which allows the measurement of water content. A wide variety of TDR probes or transmission lines have been developed and evaluated, both experimentally and theoretically. The initial TDR laboratory measurements were made in coaxial transmission lines (Topp et al., 1980). For field application it was necessary to use a configuration that would allow to monitor the exchange of the soil water content near of the probe, this was not possible using coaxial probe. The parallel-wire transmission line was adopted and used successfully in field (Topp & Davis, 1985). Multi-wire soil probes, which emulate coaxial transmission lines (Zegelin et al., 1989), were designed. They observed that signals from the new probes allowed more reliable and accurate volumetric water content and dielectric constant measurements.

The continuous-rod probes are comprised of two or three parallel metal rods completely surrounded by the medium to be measured, when horizontally installed, are ideally to monitor the water content in a soil profile in laboratory. However, the installation of horizontal continuous-rod probes in the field requires either excavation outside the domain of interest and long rods to avoid disturbance of the medium of interest, or repacking of the soil around buried probes. These requirements make horizontal continuous-rod probes unsuitable for many field applications.

The tendency to use the technique of TDR to measure the soil water content is relatively new in Brazil. Helping the diffusion of the technique, the objective of this research is to study the possibility to use TDR Multi-wire probes with electrical impedance discontinuities in the determination of the wetting front dimensions in drip irrigation application.

MATERIALS AND METHODS

Experiments were conducted in the Hydraulic, Irrigation and Drainage Laboratory of the Agricultural Engineering College (State University of Campinas/Unicamp). The experiment was divided in two parts. In the first one, it was studied the laboratory performance of two Multi-wire probe configurations and evaluated the probes reliability to monitor the water content variation in a porous media profile. The second part was conducted in a 250 L bucket and the water dynamic process was monitored during 48 h, after 5 mm of water application using a drip system. All measurements were made with a Trase System I (Soilmoisture Equipment Corp., Santa Barbara, CA) equipped with a multiplexer (Trase Multiplexer model 6020B5). The TDR signal analysis was done manually by equipment display. ε₈ readings were monitored in the tests.

Part 1

Performance of the Multi-wire probes with electrical impedance discontinuities

The objective of this test was evaluated in laboratory the performance of two Multi-wire probes with 0.10 and 0.20 m segmentations, denominated Probe 1 and 2, respectively. The probes used were designed to monitor the soil water content profile using a series of rod diameter changes. Each change in the rod diameter causes a change in the impedance of the probe, resulting in a characteristic reflection on the waveform. The travel time between these reflections defines the water contents in the regions between each discontinuity.

The probes have 4 stems with 0.675 m of length. The Probes 1 and 2 were divided in 7 and 4 segments, respectively. In both probes it was not considered the reading of the last segment because probes with high impedances without a balun installed result in end reflections with small amplitudes, thus making it difficult to analyze the waveforms. The final stems were made with a sharp segment (0.075 m) to facilitate the penetration in the soil. The probes have an expected reading depth of 0.60 m. The design probes are showed in Figure 1 (Souza et al., 1999). Probes were manufactured in brass, except the intermediary spaces of smaller diameter, which are made of stainless steel.

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1 Reference to registered mark does not constitute endorsement for the authors.
The probes were placed separately in a plastic cylinder box of 0.25 m of diameter and 0.90 m of length filled with distilled water to determine the probes characteristic impedance.

The characteristic impedance \( Z_0, \Omega \) value is used to evaluate the performance of TDR probe. The impedance of a transmission line (i.e., a probe) is a function of the geometry of the line (spacing and diameter of rods) in addition to the dielectric constant of the medium in which the probe is installed. Difference in probe impedance is due to different diameters or rods spacing. So, different reflections in TDR waveforms can detect from the interfaces which different diameters or spacing of the rods are combined. Different combinations could result in probes with high impedance that consequently result in final reflections with small amplitudes, thus making it difficult to analyze the waveforms. The impedance for a coaxial probe type transmission line can be approximated using (1) (Zegelin et al., 1989):

\[
Z_0 = 60\sqrt{\varepsilon_b \ln(b/a)}
\]  
(1)

Where \( \varepsilon_b \) is the dielectric constant of a material surrounding the transmission line, \( a \) and \( b \) are the diameter of the inner and outer conductors, respectively. Alternatively, \( Z_0 \) can be measured by determining the line's reflection coefficient \( \rho_{ref} \) when the line is filled with an uniform and dielectric material with dielectric constant \( \varepsilon_b \) (Zegelin et al., 1989).

\[
Z_0 = Z_u \sqrt{\varepsilon_{b,ref} (1 + \rho_{ref} / 1 - \rho_{ref})}
\]  
(2)

\[
\rho_{ref} = \left( \frac{V_1}{V_2} \right) - 1
\]  
(3)

Where:
\( Z_u = \) TDR Load Impedance = 50 Ω.
\( V_1 = \) local minimum voltage. (Obtained from the waveform)
\( V_0 = \) initial voltage. (Obtained from the waveform)

The \( Z_0 \) values were estimated from (1) and (2) equations for the developed Multi-wire probes with electrical impedance discontinuities.

**Evaluation the probes reliability to monitor the water content variation in a porous media profile**

The evaluation was accomplished in thick sand; thereby the constructive effect of the probes was evaluated isolating the possible effects of the soil. The air-dried sand was packed in two plastic cylinder boxes of 0.25 m of diameter and 0.90 m of length, with bulk density of 1,650 kg/m³. After the installation of the probes (Probe 1 and 2) it was applied 1 L of water on
the surface of the sand by a dripper with 4 emission points (8 L/h). The Topp calibration equation was used to calculate volumetric water content, \( \theta \) (Topp et al., 1980). The water dynamics process in the sand was monitored during 8 h.

**Part 2**

**Evaluation of the Multi-wire probe in the determination of the wetting front in drip irrigation**

It was studied in this work the possibility to use Multi-wire TDR probes with electrical impedance discontinuities to determine the wetting front development under drip irrigation. The evaluation was accomplished in Dusky Red Latosol soil type. The soil air-dried was packed in two plastic cylinder box of 0.60 m of diameter and 0.90 m of length, with soil physical properties: initial water content \((\text{m}^3/\text{m}^3)\), total porosity (%) e bulk density equal 0.10, 53 and 1,200, respectively. In these recipients 10 Multi-wire probes (similar Probe 2) were placed for wetted front determination. The probe choice was based on the laboratory results that indicated the reliability of the probe configuration to describe the profile soil in larger depth than 0.40 m. The 10 probes were distributed symmetrically in 4 directions with spacing of 0.08 m (Figure 2), starting from emitter, which is placed in the center of the cylinder. It was evaluated the wetting front evolution for an application depth of 15 mm, monitoring during 6 days under the discharge rate of 2 and 4 L/h.

The applied depth was divided in 3 irrigations with 2 days of intervals, in order to analyze the necessity to estimate the wetting front using 2 or more consecutive irrigations. The evaporation effect was reduced using a plastic film on recipient during the evolution of the wetting front. The used calibration equation was estimated in field condition and is equal to

\[
\theta = 3 \times 10^{-5} * \varepsilon_b^3 - 0.0017 * \varepsilon_b^2 + 0.0412 * \varepsilon_b - 0.0603.
\]

**Figure 2. Symmetrical disposition of the TDR probes and soil water content**

**RESULTS AND DISCUSSION**

**Part 1**

**Performance of the Multi-wire probes with electrical impedance discontinuities**

The estimated characteristic impedances are showed in Table 1. Analyzing the results obtained by the equation (1), it is observed that the values calculated for the Multi-wire probes are close to the values of the common probes (3-wire). According to Zegelin et al. (1989), the Multi-wire probes present lower values of measured impedance, but did not exceed 173 \( \Omega \). The probe impedance values showed that the designed dimensions were appropriate to be used in soil water monitoring.
Table 1. Characteristic impedance

<table>
<thead>
<tr>
<th>Probes</th>
<th>Dimension (2*s)/d, mm/mm</th>
<th>Geometric (1)</th>
<th>Measured (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe 1 (segment number)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>58/6</td>
<td>136</td>
<td>171</td>
</tr>
<tr>
<td>2</td>
<td>58/6</td>
<td>136</td>
<td>170</td>
</tr>
<tr>
<td>3</td>
<td>58/6</td>
<td>136</td>
<td>169</td>
</tr>
<tr>
<td>4</td>
<td>58/6</td>
<td>136</td>
<td>168</td>
</tr>
<tr>
<td>5</td>
<td>58/6</td>
<td>136</td>
<td>167</td>
</tr>
<tr>
<td>6</td>
<td>58/6</td>
<td>136</td>
<td>166</td>
</tr>
<tr>
<td>Probe 2 (segment number)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>58/6</td>
<td>136</td>
<td>168</td>
</tr>
<tr>
<td>2</td>
<td>58/6</td>
<td>136</td>
<td>167</td>
</tr>
<tr>
<td>3</td>
<td>58/6</td>
<td>136</td>
<td>166</td>
</tr>
<tr>
<td>Probe 3-wire – 0.10 m</td>
<td>20/2.1</td>
<td>135</td>
<td>198</td>
</tr>
<tr>
<td>Probe 3-wire – 0.20 m</td>
<td>28/3.1</td>
<td>132</td>
<td>196</td>
</tr>
</tbody>
</table>

The length for each segment of the Probe 1 and 2 is, respectively, 0.10 and 0.20 m.

Figure 3 shows the difference between the readings graphs obtained for the two probes, and how difficulty is to interpret peaks impedance for the Probe 1 due to the reflection phenomenon. This phenomenon was caused by the interface between different electric property materials. Using (1), it were found impedance of 136 and 177 Ω for the brass segments and stainless steel, respectively. Summarizing, the signal loss was caused by the rod design that has different material and geometry along its length.

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**Figure 3. Comparison of travel time signal readings**

**Evaluation of the Multi-wire probe in monitoring the water content variation in a porous media profile**

Table 2 shows the results of the water dynamics process in tested porous media. To obtain values of water content in same depths for Probes 1 and 2, the average of each depth were estimated taking the average of the measured water content of the segments 1 and 2, 3 and 4, and 5 and 6 for Probe 1. It was verified that there are no differences of water content readings between the different probes, showing that both have similar characteristics in the electromagnetic waves propagation along of the guide. However, Probe 1 showed more difficulties to interpret the impedance peaks in its extremities (Table 2 and Figure 4) than Probe 2. This behavior confirmed the previous observations, showing that the high number of segmentations increased considerably the reflections of the pulse. In agreement with these observations, Topp & Davis (1985) presented results showing the difficulty of waveforms interpretation in probes with more than five segments.
Table 2. Comparison among volumetric water content results in function of the time for probe 1 and 2

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>Depth (0 - 0.20 m)</th>
<th>Volumetric water content, m³/m³</th>
<th>Depth (0.20 - 0.40 m)</th>
<th>Volumetric water content, m³/m³</th>
<th>Depth (0.40 - 0.60 m)</th>
<th>Volumetric water content, m³/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Probe 1</td>
<td>Probe 2</td>
<td>Probe 1</td>
<td>Probe 2</td>
<td>Probe 1</td>
<td>Probe 2</td>
</tr>
<tr>
<td>0:00</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>NE</td>
<td>0.04</td>
</tr>
<tr>
<td>0:10</td>
<td>0.14</td>
<td>0.13</td>
<td>0.04</td>
<td>0.04</td>
<td>NE</td>
<td>0.04</td>
</tr>
<tr>
<td>0:20</td>
<td>0.26</td>
<td>0.26</td>
<td>0.09</td>
<td>0.08</td>
<td>NE</td>
<td>0.04</td>
</tr>
<tr>
<td>0:30</td>
<td>0.21</td>
<td>0.21</td>
<td>0.17</td>
<td>0.17</td>
<td>NE</td>
<td>0.04</td>
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<tr>
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<td>0.17</td>
<td>0.17</td>
<td>0.23</td>
<td>0.23</td>
<td>NE</td>
<td>0.04</td>
</tr>
<tr>
<td>3:10</td>
<td>0.14</td>
<td>0.14</td>
<td>0.20</td>
<td>0.20</td>
<td>NE</td>
<td>0.08</td>
</tr>
<tr>
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<td>0.12</td>
<td>0.20</td>
<td>0.20</td>
<td>NE</td>
<td>0.10</td>
</tr>
<tr>
<td>5:00</td>
<td>0.13</td>
<td>0.12</td>
<td>0.18</td>
<td>0.18</td>
<td>NE</td>
<td>0.11</td>
</tr>
<tr>
<td>6:10</td>
<td>0.11</td>
<td>0.11</td>
<td>0.18</td>
<td>0.18</td>
<td>NE</td>
<td>0.12</td>
</tr>
<tr>
<td>8:00</td>
<td>0.11</td>
<td>0.11</td>
<td>0.18</td>
<td>0.18</td>
<td>NE</td>
<td>0.12</td>
</tr>
</tbody>
</table>

NE = Not estimated due to difficulty to interpret of the impedance peaks.

In Figure 4 it was possible to identify water content variations of the porous media water dynamics. Although Probe 1 showed limitations it offers a better detail of the water content of the porous media profile, showing the variation in each 0.10 m.

Figure 4. Comparison between the probes 1 and 2 in the estimate of the porous media profile water content

Part 2

Evaluation of the Multi-wire probe in the determination of the wetting front in drip irrigation

The use of Multi-wire probes in the TDR equipment showed a readily determination of the soil water content in dynamic processes. This evaluation is based in acquisitions of the water content variations in the wetting front, which it was below a 2 minutes of intervals. This characteristic was possible due the use of a multiplexer, which make automated the acquisition of the water content readings.

For experimental conditions was found symmetry in the water movement between the different axes (x,y) in all the treatments. This observation facilitated to use just 2 probes in the last observation circle. The wetting front did not reach the probes disposed 0.24 m of the emitter, turning fastest readings and producing a smaller amount of graphs for the interpretation. The advantage of producing small amount of graphs became interesting due to equipment memory limitation, which is approximately 180 graphs. It was also observed that it is possible to use one quadrant to monitor the wetting front in laboratory conditions, due to the soil homogeneity.

The wetted front evolution was monitored with 2 h of intervals, but on Figure 5 is presented the soil water content profiles 48 h after each irrigation (Figure 5). It was possible to verify that doubling the rate (2 for 4 L/h) happen a larger
water horizontal movement evolution in the soil and, consequently, decrease of the vertical movement. These results agree with the observations done by Bresler et al. (1971) and Keller & Bliesner (1990).

It is observed that the higher values of the water content concentrated in the central area of wetted front, confirming the results obtained by Botrel (1988) and Zanini (1991).

It was also verified an expansion of the different axes (x,y) for successive irrigations. These results coincide with the tendency observed by Nogueira et al. (1999). The authors found an expansion of the wetted volume due to second and third irrigation in field conditions. The requirement to accomplish 2 or more successive irrigations to estimate the wetted front was confirmed, evidencing that initial conditions of the water content is essential for wetted front determination. The knowledge of these initial soil conditions is also important when mathematical model is used to simulated water movement in the soil profile. Bad simulations can promote crop stress risks, salinity problems and bad distribution of the root system.

CONCLUSION

Using different Multi-wire probe configurations it was possible to obtain the water content measurements in water dynamic processes in laboratory, what is very desirable in studies to optimize the irrigation management. However, the configuration of the Probe 1 showed limitations for interpreting the impedance peaks in its extremities.
The results demonstrated the viability to use the Multi-wire probes with electrical impedance discontinuities to determine of the wetting front in drip irrigation. It is suggested to future researches the evaluations of others probe configurations with smaller segment, which will help to detail the water content in the profile to decrease the soil space variability.

REFERENCES


