Multi-TDR probe designed for measuring soil moisture distribution near the soil surface

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Abstract
To establish a method for monitoring the vertical profile of volumetric water content (θ) near a soil surface, a multi-TDR (time domain reflectometry) probe was designed and applied to θ-profile observations during the evaporation processes for sand soil and decomposed granite soil (DG soil). The multi-TDR probe consists of 8 sets of 3-line TDR probes, being on a print-circuit board with a low dielectric constant and able to measure dielectric constant ($\varepsilon_{\text{Multi-TDR}}$) at intervals of 3 mm. We individually calibrated the probes for sand with different moisture conditions and found that the probes can determine θ within acceptable accuracy. The effectiveness of the multi-TDR probe was examined in the evaporation processes for sand and DG soils. The observed θ-profiles showed that the moisture contents for sand at 3 and 6 mm depths decreased locally in the initial stage of the process, while the moisture contents for DG soil decreased uniformly at all depths. These results demonstrated the features of moisture content variation experienced in the evaporation process in these soils. We concluded that the newly designed multi-TDR probe would be useful for millimeter-interval measurements of vertical θ-profiles near a soil surface.

Key Words
Time domain reflectometry (TDR), Multi-TDR probe, Dielectric constant, Topp equation, Soil surface evaporation

Introduction
It is important to evaluate quantitatively the water content profile within 2 cm depth from the surface for understanding the hydrological processes of evaporation, runoff, and water infiltration near the soil surface. Two or three parallel metal rods are often used as a conventional time domain reflectometry (TDR) probe for measuring dielectric constant, while a variety of customized probes have been developed for different purposes (Selker *et al*., 1993; Inoue *et al*., 2001; Miyamoto and Chikushi, 2006). Although a vertical water content profile can be measured by setting several probes with different depths horizontally, the space between the probes should be at least a few centimeters to avoid interference between them (Inoue *et al*., 2001; Suleiman and Ritchie, 2003). However, for the evaporation process from soil composed of only coarse particles such as sand with no silt and clay, a dried thin layer with a steep gradient of water content profile can develop. Such a layer may affect the macroscopic water movement including the surface runoff and water infiltration. To understand temporal and spatial change in local water content in the layer, a down-sized probe has been required for measuring a water content profile with a limited space of only several millimetres. For the present paper, we developed a multi-TDR probe being able to measure water contents of small volumes and applied it to evaporation experiments for a sand soil and decomposed granite soil (DG soil). In the experiments we monitored the variation of water content profiles with time and examined the effectiveness of the probe based on the profiles obtained.

Materials and Methods
Figure 1 shows the schematic diagram of the multi-TDR probe we developed. The multi-TDR probe used in this study was made of a piled electrical board of a mixture of glass and epoxy resin, in which 17 copper lines (electrodes) 100 mm long, 0.2 mm wide, and 0.01 mm thick were aligned parallel at 1.6 mm intervals. These lines were used for constructing 8 sets of TDR probes by taking 3-lines from one end and shifting by the two lines to the other end. Thus, soil moisture measurements at 8 different points with 3.2 mm intervals can be conducted by setting the multi-TDR probe horizontally on its side. A cable tester (Textronix, 1502C) connected with a multiplexer (Campbell Scientific, SDMX50) was used to emit the step pulse and to receive its reflectance, from which the dielectric constants at the points can be estimated by using the software Win TDR (Or *et al*., 2004).

To clarify the dielectric characteristics of the multi-TDR probe, we measured the dielectric constants for 9 different types of materials. As the materials we used distilled water at 24°C, ethanol-water mixtures with different ethanol concentrations (20, 40, 60, 80, and 100% in volume), a mixture of ethanol and vegetable oil with the ratio of 1 to 1, vegetable oil, and air. For each material, the multi-TDR probe was set up in the centre of a cylindrical container (7.5 cm in diameter and 15 cm in height) filled with the material. The dielectric constant was measured three times and they were averaged for every TDR probe in the multi-TDR probe (P1 to P8). For a comparison, a conventional three-wire probe (C3 probe) made of stainless steel rods 100 mm long and 1.2 mm in diameter was also used for the measurement.
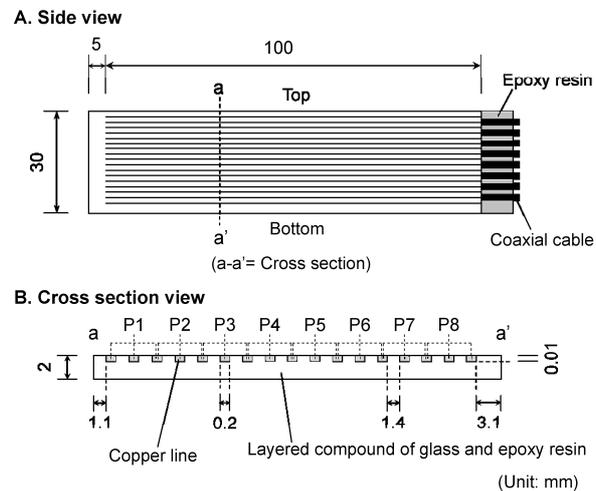
Figure 1. Schematic diagram of the multi-TDR probe (Diagram B shows the cross section view at the a-a' line in diagram A).

To calibrate the multi-TDR probe for the sand soil, we vertically fixed the probe in the centre of the plexiglass column (5 cm in diameter and 13 cm in height) and filled the column uniformly with the air-dried sand soil (No.6, grain size of 0.15-0.6 mm, Saitozaki Kousan Co., Ltd., Japan). Dielectric constants were measured after water sprayed on the soil surface had diffused uniformly. Simultaneously, soil water content of the sand was also measured gravimetrically by weighing the total weight of the column. By repeating the measurements at different moisture conditions, we investigated the relationship between the dielectric constant and water content for the probes.

To investigate the temporal variations of the water content profile in the evaporation processes of sand and DG soils, we fixed the multi-TDR probe (placing P1 at the top and P8 at the bottom) in a perpendicular container of poly-vinyl chloride sized 10 cm long, 20 cm wide, and 4 cm high. The container was filled with soil along with water, resulting in a water saturated medium. During the evaporation process under the condition of open soil surface, the dielectric constant profile was measured at 5 min intervals. The relationship between dielectric constant and volumetric water content was assumed to be the same for both sand and DG soils as suggested by Lin *et al*. (2001).

Results and discussion
Table 1 shows the dielectric constants measured by the C3 probe and the multi-TDR probe for the materials used. Thus, the measured values by the C3 probe effectively indicate the unique values for different solutions. On the other hand, the dielectric constants of different materials measured by the multi-TDR probe were about half of those done by the C3 probe. Since the calibration for each probe was conducted individually, there was little difference between the probes on the measurements of dielectric constant.

Figure 2 shows the relationship between the dielectric constant and the volumetric water content of sand measured by the multi-TDR probe and the thin line calculated by the Topp equation (Topp *et al*. 1980). The measurements disagreed generally with the estimation by the Topp equation. Thus, we need an alternative calibration equation instead of the Topp equation and proposed as,

$$\theta_{\text{Multi-TDR}} = a(\log \varepsilon_{\text{Multi-TDR}})^2 + b \log \varepsilon_{\text{Multi-TDR}} + c \qquad (1)$$

where $\varepsilon_{\text{Multi-TDR}}$ is dielectric constant measured by the multi-TDR probe, a, b, and c are fitting parameters, and $\theta_{\text{Multi-TDR}}$ is volumetric water content estimated by Eq. (1). The parameters were determined by the nonlinear least square method. The resulting calibration equations fitted well (solid and dashed lines in Figure 2) with

the observed data.

Table 1. Dielectric constants of distilled water, ethanol-water mixtures with different concentrations, ethanol-oil mixture, vegetable oil, and air measured by the 3-wire and the multi-TDR probe.

Material	Dielectric constant									
	Measured with 3-wire probe	Measured with multi-TDR probe								
		Average *	Differences from average							
			P1	P2	P3	P4	P5	P6	P7	P8
Distilled water	80.1	43.7	-1.0	-0.6	-0.3	0.0	0.5	-1.1	2.0	0.4
20%-ethanol solution	68.1	37.1	-0.7	-0.7	-0.4	0.0	0.6	-0.9	1.8	0.3
40%-ethanol solution	54.3	30.3	-0.7	-0.5	-0.2	0.1	0.5	-0.9	1.4	0.3
60%-ethanol solution	41.3	23.4	-0.5	-0.4	-0.2	0.0	0.3	-0.8	1.3	0.2
80%-ethanol solution	30.3	17.7	-0.5	-0.4	-0.1	0.1	0.4	-0.7	1.1	0.1
Ethanol	20.8	12.1	-0.4	-0.2	-0.1	0.1	0.3	-0.6	0.8	0.0
Ethanol-oil mixture	9.2	8.2	-0.2	-0.3	-0.2	-0.1	0.4	-0.4	0.8	-0.1
Vegetable oil	3.5	4.8	-0.2	-0.1	0.0	0.1	0.2	-0.3	0.5	0.0
Air	1.5	3.6	-0.1	-0.1	0.0	0.1	0.1	-0.3	0.3	0.0

* Average is a mean value of the dielectric constans measured by P1 to P8. Ethanol solutions were made by mixing different mass of ethanol in distilled water. Ethanol and vegetable oil were mixed in same mass when the mixture was made.
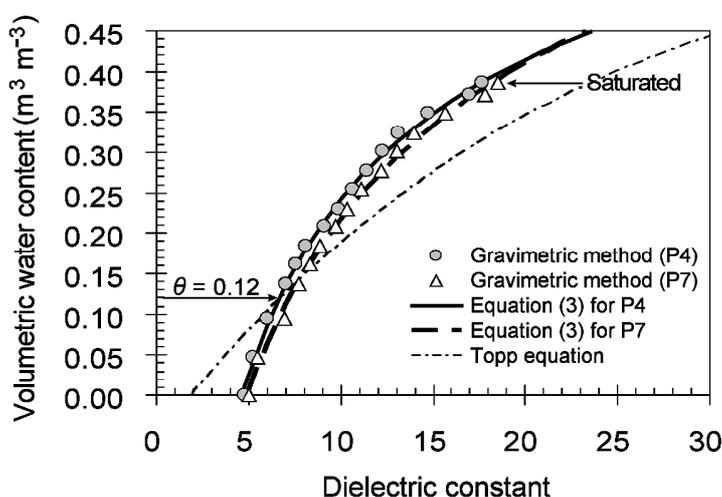
Figure 2. Relationships between dielectric constant and volumetric water content for sand.

Figure 3a shows the temporal variation of the water content profile in the evaporation process for sand. At the depths of 0.28 and 0.6 cm, volumetric water content abruptly decreased to about half during 2 hours following the start of the experiment. On the other hand, in the range of the depths 1.56 to 2.52 cm, the change in water content was little and thus did not depend on the evaporation. In the water content profile, it was confirmed that the content decreases from the top soil as evaporation proceeds and the drying front also goes down. After 12 hours from the initiation, the dry process proceeded in the whole profile. Finally after 168 hours (about 1 week) water contents at all the depths became constant to about 0 m^3/m^3.

Figure 3b shows the experiment results for DG soil. Volumetric water content for DG soil uniformly decreased with time in every depth. Thus, unlike with sand, the progression of the drying front with time was not observed. The comparison of water content between sand and DG soils after 12 hours from the start of the experiment shows that water was lost for sand faster than for DG soil in the region of 0.28-1.24 cm depth, while the difference between them was not so large in the region more than 1.56 cm in depth. During 12 to 24 hours from the initiation, the amount of water lost was higher for DG soil than for sand.

There are few reports on evaporation processes for different soils, especially on the water content close to the soil surface. However, Hillel (1977) showed that water content near the surface abruptly decreases for sand, while the decrease in the deeper zone is larger for loam than for sand. After soil water near the surface decreased, corresponding to at about 5-12 hours from the start of the experiment, water in the lower region tends to decrease for loam faster than for sand (Suleiman and Ritchie, 2003). Soil surface boundary conditions due to the difference in air temperature and humidity during the experiment may change the evaporation processes. The measured temporal changes in soil water profile revealed the difference of water

content variation during evaporation between sand and DG soils. Most of the studies on the measurement of soil water profile have been concerned with the surface zone of a few to several 10 cm (Richards *et al.*, 1956; Bruckler *et al.*, 1988; Inoue *et al.*, 2001; Suleiman and Ritchie, 2003). Our study concentrates on the region of 0.28-2.52 cm in depth, which is closer to the surface than in the other studies. From the measured results, we can conclude that the multi-TDR probe is useful for investigating the water profile near the soil surface.
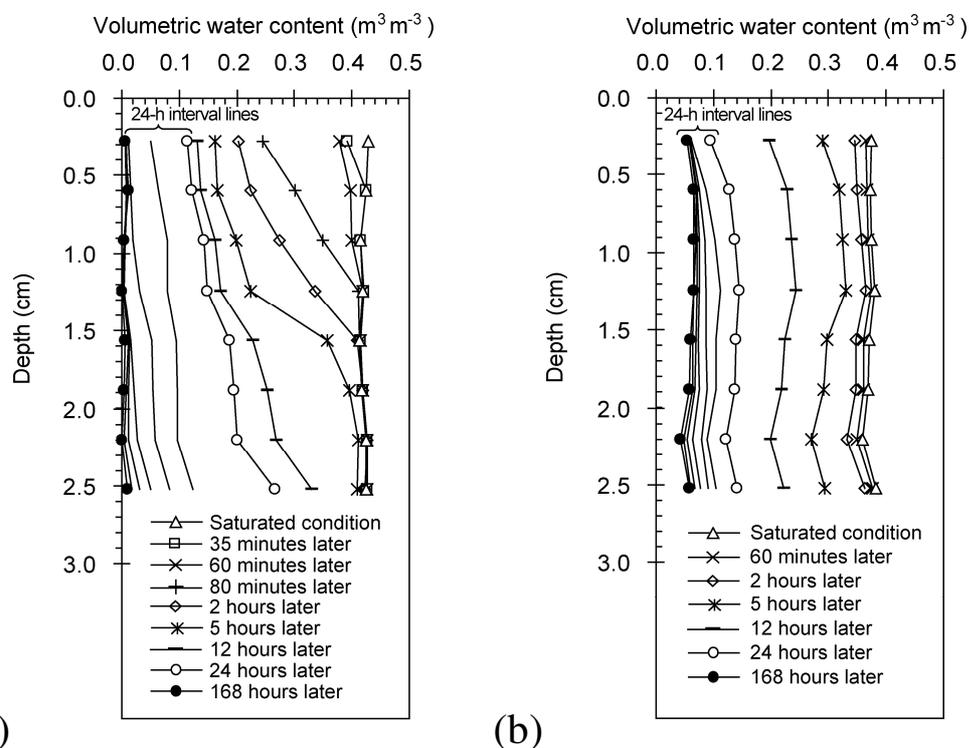
Figure 3. **Temporal changes in vertical volumetric water content profiles.** **(a) Sand soil. (b) Decomposed granite soil (DG soil).**

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