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A Comparison Experiment of Two Types of Printed Circuit Board TDR Probes

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An experiment designed to compare two types of printed circuit board TDR probes (PCBPs) was conducted using the Tottori-Dune sand. Although the material and design of the two types were almost the same, the results differed much between them. This suggests that the performance of PCBPs is highly sensitive to their probe material and/or layout of wave-guide. Furthermore, the sensitivity to soil wetness differed from each other and changed also with soil wetness itself. Therefore the probe that is suitable for the particular purpose should be selected in each application.

INTRODUCTION

Wang et al. (2000) made newly designed printed circuit board TDR probes (henceforth C-type PCBPs) and used them to measure the average water content over the top 5 cm of unvegetated soils in an arid area in the northwest of China. They compared the measurements taken with the C-type PCBP and those by the oven-dry method, and showed that this type of probe does a good job as the sensor to get the ground truth of surface wetness against remotely sensed data obtained with microwave techniques. Other kinds of PCBPs were produced and tested by Nissen et al. (1999) and concluded also that they were promising for obtaining small-scale TDR measurements of soil water.

One of the authors (H. Cho) got some pieces of another type of PCBP produced by Dr. Nissen (henceforth N-type PCBP). Hence we carried out an indoor experiment to compare the results obtained with the two types of PCBPs when they were used to measure the average water content over the top 5 cm of the soil. This paper describes the experimental results, and discusses some differences between the two types and their characteristics.

DESCRIPTIONS OF PCBPS

The C-type PCBP was made of 15×60 mm paper-phenol resin of 1.3 mm thickness

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with a copper cladding on one side. The two-wire serpentine wave-guide 158 mm long were produced by printing two parallel rods 0.7 mm wide at a 23-mm spacing onto the copper cladding and etching away the metal outside of them (Fig. 1). The effective length (the soil layer thickness over which this probe measure the average wetness) was 50 mm. On the other hand, the N-type PCB was made of 12×50 mm glass-epoxy resin of 1 mm thickness. The two-wire serpentine wave-guide 86 mm in length was produced with two parallel rods 0.5 mm in width at a 3.35 mm spacing in the copper cladding. Its effective length was 50 mm. Their probe designs are shown in Fig. 1 and important properties are given in Table 1.

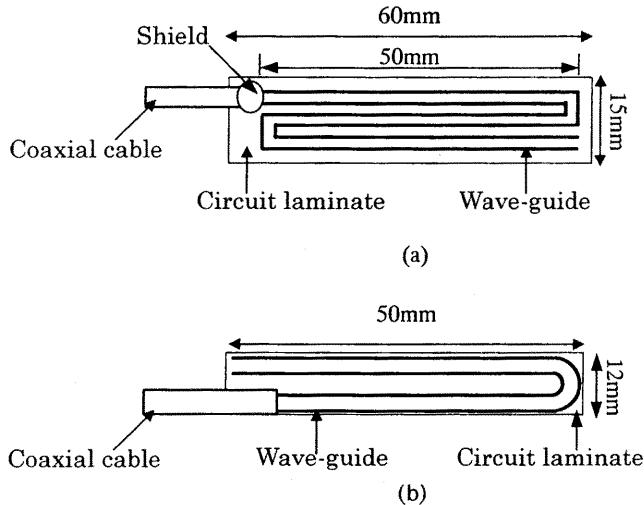


Fig. 1. Serpentine layouts of (a) C-type and (b) N-type probes.

Table 1. Properties of two types of PCBPs.

	C-type	N-type
Circuit board	paper-phenol	glass-epoxy
Dielectric thickness (mm)	1.3	1
Thickness of cladding (μm)	—	35
Wave-guide length (mm)	158	86
Width of rods (mm)	0.7	0.4
Spacing (mm)	2.3	3.35
Water absorption (%)	—	0.35
Dielectric constant	4.6–5.5	5.8

EXPERIMENT

An indoor experiment to compare the two kinds of PCBPs was conducted using the Tottori-Dune sand, the physical properties of which are shown in Table 2. The sand was packed into containers, which were made of two 5-cm-long acrylic resin tubes of 10 cm inside diameter. The two tubes were joined end to end with adhesive, waterproof tape to be a cylinder 10 cm long. The bottom of the cylinder was made of wire netting, which was covered with a filter paper of 10 cm diameter before the air-dried sand was packed into it.

Table 2. Physical properties of the Tottori-Dune sand.

Particle size	by weight
>2 mm	0%
2.0~0.42 mm	14.9%
0.42~0.075 mm	80.9%
0.075~0.005 mm	1.3%
0.005>	2.9%
Bulk density	1.50 gcm ⁻³
Porosity	0.434

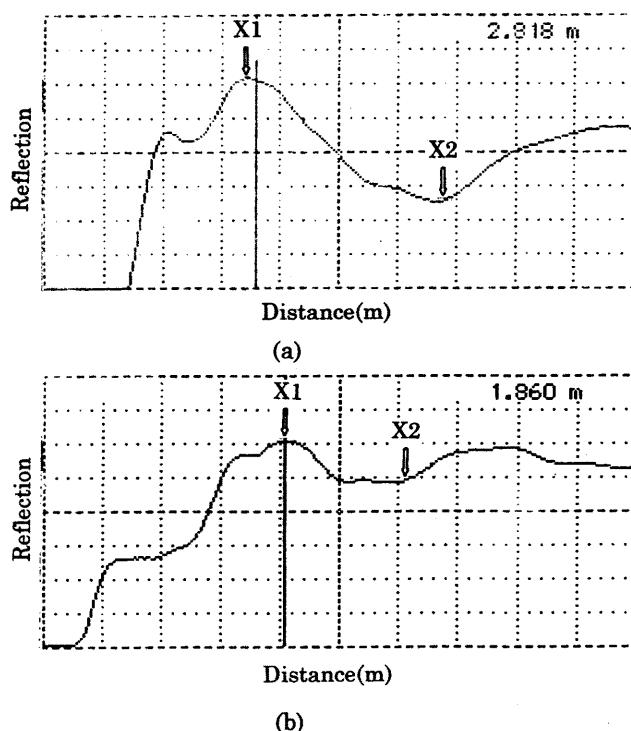


Fig. 2. Comparison of TDR oscilloscope traces of (a) C-type and (b) N-type probes.

Four containers were constructed and one set of C-type and N-type probes was embedded vertically in each container to measure the average water content for the uppermost 5 cm of the sand, and water was poured on the surface until drainage from the bottom occurred. Once in several days measurements of the dielectric constant were made with Tektronix cable tester 1502C for one of the containers. After the measurement, a soil-sampling pipe 5 cm in length and 100 cm³ in volume was inserted from the surface into the container and a soil specimen was sampled from the top 5 cm of the profile and its water content was gravimetrically measured. These runs were made several times.

Figure 2 shows a comparison of TDR output traces measured using Tektronix 1502C, showing reflection as a function of equivalent cable distance, of the two types of PCBPs. These oscilloscope traces show similar waveforms for the two types, but the equivalent cable distance (m) between the points X_1 and X_2 in Fig. 2 for the C-type probe is much longer than for the N-type probe. The reason for this is that the length of wave-guide of C-type probe is longer than of N-type probe (Table 1). The apparent relative dielectric permittivity, or the dielectric constant (K_a) of the medium of interest is calculated by

$$K_a = [(X_2 - X_1)/LV_p]^2 \quad (1)$$

where L is the length of wave guide (m) and V_p is the relative velocity of propagation (as usual set as $V_p=0.99$).

RESULTS AND DISCUSSION

Figure 3 shows the relationship between the dielectric constant measured with C-type PCBPs ($K_{a,PCBP-C}$) and volumetric water content θ_v . For the sake of brevity, hereafter, we shall use K_a instead of $K_{a,PCBP-C}$ unless otherwise mentioned. The solid line shows the regression curve obtained by Wang *et al.* (2000). Our measurements made in this experiment were put together with those by Wang *et al.* (2000) because their material and method were the same as ours, which are denoted by open circle in Fig.3. The dotted line describes the third-order polynomial regression equation that is fit to the whole data.

$$K_{a,PCBP-C} = 3.58 + 15.6\theta_v + 37.7\theta_v^2 + 167.4\theta_v^3 \quad (2)$$

The two regression curves are close together, which means that the experimental results are reliable. Figure 4 shows the relationship between the dielectric constant measured with N-type PCBPs ($K_{a,PCBP-N}$) and θ_v . We shall use also K_a instead of $K_{a,PCBP-N}$ unless otherwise mentioned. The regression equation is written

$$K_{a,PCBP-N} = 2.78 + 40.8\theta_v - 219.0\theta_v^2 + 553.7\theta_v^3 \quad (3)$$

The value of $K_{a,PCBP-C}$ at any given value of θ_v is larger than that of $K_{a,PCBP-N}$. The dielectric constant measured with PCBPs ($K_{a,PCBP}$) is regarded as the weighted mean of the laminate's value ($K_{a,L}$) and the surrounding medium's value ($K_{a,m}$) (Nissen *et al.*, 1999).

$$K_{a,PCBP}^n = w_L(K_{a,L})^n + (1-w_L)(K_{a,m})^n \quad (4)$$

Since the value of $K_{a,L}$ of the N-type probe is larger than of the C-type probe (Table 1),

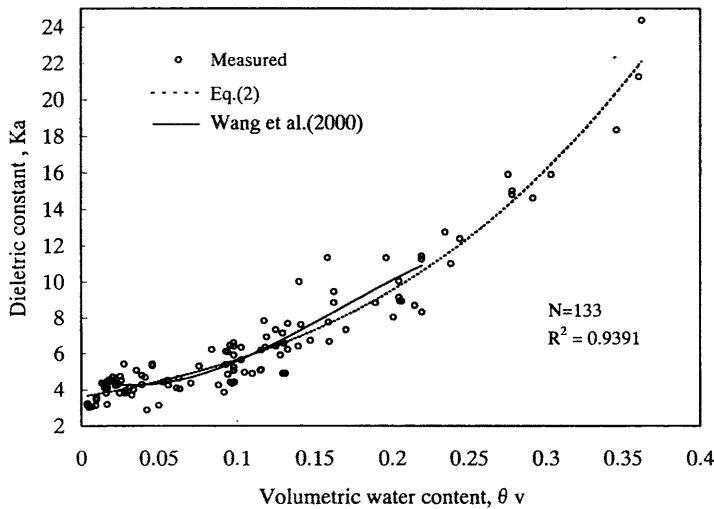


Fig. 3. Relationship between K_a measured with C-type PCBPs and θ_v for the Tottori-Dune sand. The relationship obtained by Wang et al. (2000) is also shown for reference.

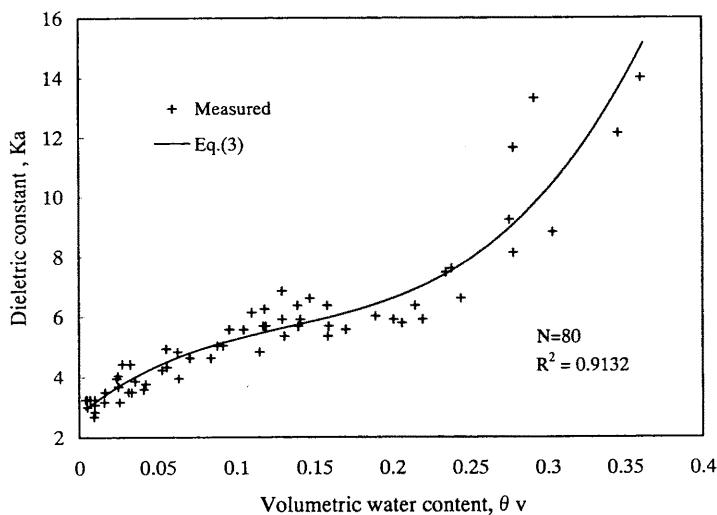


Fig. 4. Same as Fig. 3, but for K_a measured with N-type PCBPs.

the value of weighting factor w_L for the N-type probe must be smaller than for the C-type probe, especially when θ_v is nearly equal to zero. The value of w_L depends on the degree of contact between the probe and the soil, and hence it seems reasonable to conclude that the contact of the N-type probe with the soil is not so good as the C-type probe.

One of the reasons for this seems to be a delicate difference in structure between them; that is, the N-type probe has the wave-guide with a short length (86 mm) and its ratio between rod width and rod spacing is small (0.12) compared to those of the C-type probe (158 mm and 0.3, respectively). In this experiment, these probes were embedded vertically in the top 5 cm of the soil, and soil wetness changed with depth in the upper layers. Therefore, there was also a difference in experimental conditions between them; that is, the end of wave-guide of the N-type probe was near the soil surface where the soil was drier than below, while the end of wave-guide of the C-type probe was located at the lowest point where the soil was wetter than above. However, we are not sure whether or not this difference can be another reason for the result above.

In reality, we estimate θ_v from the measurement of K_a using the regression equation of θ_v on K_a . The regression equations for the two probes are as follows.

$$\theta_v = -0.09 + 3.54 \times 10^{-2} K_a - 0.69 \times 10^{-3} K_a^2 - 0.18 \times 10^{-6} K_a^3 \quad : \text{C-type} \quad (5)$$

$$\theta_v = -0.19 + 6.47 \times 10^{-2} K_a - 1.25 \times 10^{-3} K_a^2 - 0.44 \times 10^{-4} K_a^3 \quad : \text{N-type} \quad (6)$$

These lines are shown in Fig. 5 together with the line given by Topp *et al.* (1980):

$$\theta_v = -0.05 + 2.92 \times 10^{-2} K_a - 0.55 \times 10^{-3} K_a^2 + 0.43 \times 10^{-5} K_a^3 \quad (7)$$

As can be seen, the line for the N-type probe differs from the other two lines.

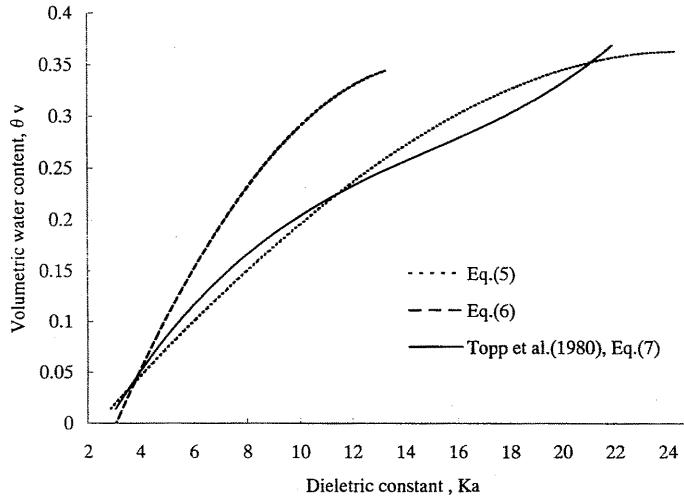


Fig. 5. Regression lines of θ_v on K_a for the Tottori-Dune sands.

CONCLUDING REMARKS

The performance of two types of printed circuit board TDR probes (PCBPs) was tested using the Tottori-Desert sand. Although their material and design are almost the same, the results of one type differed considerably from the other. This suggests that the performance is highly sensitive to probe material and/or layout of wave-guide.

The sensitivity of the PCBP changes with soil wetness. For example, the sensitivity of the N-type probe is rather good at volumetric water contents smaller than 0.1, however it becomes rather bad in the range of 0.1 to 0.25 (Fig. 4). Therefore, the PCBP that is suitable for the particular purpose should be selected in each application.

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