Effect of gaps around a TDR probe on water content measurement: Experimental verification of analytical and numerical solutions

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Abstract: When installing TDR probes to rock, void spaces (gaps) between the probe rods and rock may be encountered. In this study, the dielectric constants of water and air were measured with various controlled gaps and effects of the gaps were experimentally investigated. We focused on a two-rod probe for which analytical and numerical solutions were available. Symmetric longitudinal gaps (identical uniform gaps along both rods), non-symmetric longitudinal gaps (uniform gaps along only one rod), and end gaps beyond the end of the rods were considered. For the symmetric cases, measured dielectric constant values of water and air were compared with analytical and/or numerically simulated values, and a close agreement was observed. For the non-symmetric cases, such agreement was seen only when the gap width was relatively small. As the gap widths increased, the dielectric constant of water was underestimated compared to the numerically estimated values. Such underestimation was more significant when the gaps were along the rod connected to the center conductor, suggesting that the sensitivities of the two rods were uneven. The effect of the end gaps was very limited whereas the longitudinal gaps, e.g., due to loose guide holes or soil shrinkage can lead to significant measurement errors.
Key Words : water content, dielectric constant, time domain reflectometry, gap effects, measurement errors

1. Introduction

After the work by Topp et al. (1980), time domain reflectometry (TDR) has been widely used since the early 1980's for soil water content measurement in various problems in soil science, agriculture, environmental and geotechnical applications. The standard device consists of a pulse generator, a probe and a data logger. The method requires the probe to be embedded into the material of interest. The probe is usually made of two or three metal rods connected to a coaxial cable. The transmission velocity of an electromagnetic step pulse along the probe is measured and converted into water content (e.g., Topp et al., 1980).

When applying TDR to rock, guide holes must be drilled prior to the probe installation. Hokett et al. (1992) reported that the probe must be in good contact with rock in order to obtain accurate measurements of moisture content. Even when slightly undersized guide holes are used, it is difficult to eliminate the longitudinal and end gaps around the probe completely, because the guide holes are not drilled with a perfectly-matching diameter, nor are they exactly as long as the probe rods. Sakaki et al. (1998) showed a couple of photographs in which these gaps are clearly visible.

Annan (1977) considered the case of non-concentric gaps, which coincided with a bipolar coordinate system (Morse and Feshbach, 1953) centered at the probe locations, and derived an analytical expression for the apparent dielectric constant (K_a). Knight (1992) analytically showed that the highest measurement sensitivity occurs in the vicinity of the probe rod surface. This implies that if slight void spaces or gaps exist between the rod and the material, the measurement accuracy may be affected. This is especially true if the gaps are filled with material that has a smaller dielectric constant than that of the surrounding medium. Ferré et al. (1996) and Knight et al. (1997) used numerical simulations of the Laplace equation to estimate the influence of gaps on apparent dielectric constant. They showed that for small gaps, the analytical results of Annan (1977) were valid even for concentric gaps. Sakaki et al. (1998) and Sakaki and Rajaram (2006) presented extensive data on the application of TDR to water content (θ) measurement on rocks. The data of Sakaki et al. (1998) were obtained using probes hammered into slightly undersized guide holes. The K_a-θ data could not be explained without invoking the potential role of air-filled gaps around the probe rods, which was eliminated later by filling the gaps with electrically conductive silicone (Sakaki and Rajaram, 2006). Despite the above mentioned works for identifying the effect of gaps, to our best knowledge, the gap effects have never been experimentally "measured" in a quantitative fashion under well-controlled conditions, and the analytical and numerical approaches for quantifying the gap effects have never been verified against experimental data.

The objectives of this study were; (1) to experimentally

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demonstrate the influence of gaps on errors in estimates of K_a under well-controlled conditions, (2) to verify the analytical and numerical solutions for the gap effects and (3) to quantitatively illustrate the magnitude of potential errors in moisture content estimates, resulting from gaps around TDR probe rods in soils/rocks based on analytical/numerical calculations for some practically relevant situations. We considered gaps along the rod surfaces (hereafter referred to as the "longitudinal gaps") and gaps beyond the end of the rods (hereafter referred to as the "end gaps"). Because the analytical and numerical solutions were available for the longitudinal gaps along a two-rod probe, we focused only on the two-rod probe. The experimental results were compared to theoretical estimates, where available, obtained using the analytical solution as well as numerical solution of the Laplace equation, with specified potential on the rod surfaces, and incorporating the influence of longitudinal gaps.

2. Material and methods

We considered uniform longitudinal gaps around the rods and end gaps beyond the end of the rods to mimic the gaps that are expected in the field applications as shown in Fig. 1(a). When fully saturated, the gaps are filled with water whereas the gaps are likely to be filled with air when unsaturated. The typical pore size in the rock matrix is usually smaller than the size of the gaps, causing a larger suction in the matrix. Therefore, water tends to be retained in the matrix due to its larger suction, which consequently makes the gaps fill with air.

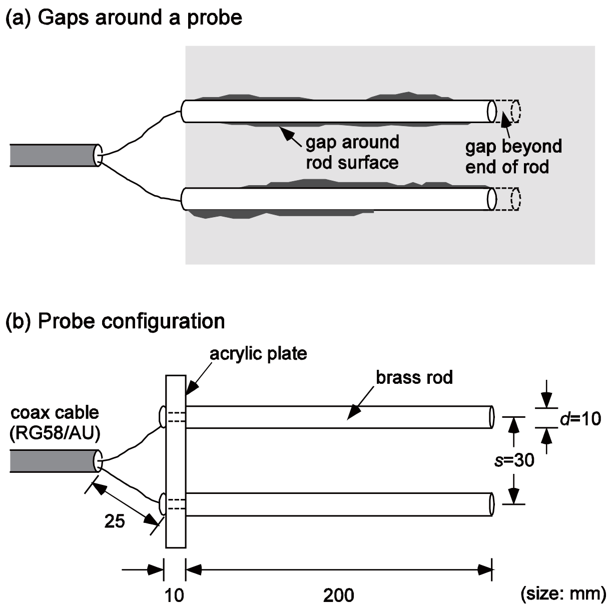

Fig. 1 Two-rod TDR probe; (a) Longitudinal and end gaps when installed into rocks, (b) Tested configuration in the experiments.

2.1 Probe configuration

The TDR probe used in this study was the two-rod type as shown in Fig. 1(b) and is a practical configuration for application to rocks. A couple of spade tongues were soldered to the split end of a 50 Ω coaxial cable (RG58/AU), which were screwed to an acrylic plate having dimensions of 60 × 100 × 10 mm. Brass rods with a diameter d = 10 mm, center-to-center spacing s = 30 mm, and length l = 200 mm, were attached to the screws above. The cable was, in turn, connected to a commercially available time domain reflectometer TDR100 (Campbell Scientific, Inc., Logan, Utah). The reflectometer emits an electromagnetic step-pulse with a voltage of 250 mV and a 10 ∼ 90 % rise time of 200 picoseconds (frequency spectrum roughly up to 1.75 GHz, Tektronix, Inc.,1987), which is transmitted along the coaxial cable and probe. The TDR traces were processed by software PCTDR (Campbell Scientific, Inc., Logan, Utah) and apparent dielectric constant K_a was calculated.

2.2 Longitudinal gaps

2.2.1 Experimental setup for longitudinal gaps

In reality, the longitudinal gaps may vary in space as in Fig. 1(a) but those cannot be quantified. Therefore, in the context of quantifying the effects of longitudinal gaps around a TDR probe, we considered *equivalent* uniform widths. In order to mimic air-filled gaps with thin but uniform thickness in water, polyvinyl chloride (PVC) tape with a uniform thickness was used. The dielectric constant of PVC is substantially smaller than that of water ($K_{PVC} = 2.9 \ll 81$) (e.g., Converting Technology Institute, 1997) thus, its effect is analogous to air-filled gaps in unsaturated rock, which is considered to be the most likely situation in the field. The PVC tape was carefully wound to the rod surface to create uniform-thickness gaps. The PVC gap thicknesses (δ) considered were; 0.0 (no gap), 0.107, 0.160, 0.317, 0.475, 0.636, 0.792 and 0.950 mm. The PVC tape was applied up to 6 layers so that the gap width (thickness of the entire PVC layer) was approximately 1 mm (10 % of the rod diameter), which seemed to be large enough for the investigation of gap effects in a practical sense. The values of gap width were obtained by measuring the diameter of the rod with and without the PVC tape using a digital caliper, taking the difference of the two, and were considered the "actual" thickness of the PVC tapes when the measurements were taken. For each gap width, uniform identical gaps along both rods (hereafter "symmetric cases") and uniform gaps only along one rod (hereafter "non-symmetric cases") were considered. The non-symmetric cases were further divided into two categories; uniform gap along the rod connected to the center conductor (hereafter "center rod" or CT), and uniform gap only along the rod connected to the shield (hereafter "shield rod" or SH).

2.2.2 Analytical solution for longitudinal gap effect

Using the bipolar coordinate system (Morse and Feshbach, 1953), Annan (1977) first derived the analytical solution for the longitudinal gap effect for a two-wire probe with non-concentric gaps around the rods. Based on his solution, the analytical solution for the apparent dielectric constant K_a of water measured by a two-rod probe with non-concentric circular gaps is;

$$K_a = \frac{K_{gap}\xi_0}{K_{material}(\xi_0 - \xi_1) + K_{gap}\xi_1} K_{material} \tag{1}$$

where, K_{gap} is the dielectric constant of the gap material, $K_{material}$ is the true dielectric constant of the material of interest, ξ_0 and ξ_1 are the radial bipolar coordinates that can be calculated from rod radius, gap width, and the half-distance between bipolar foci (see Annan, 1977 for details).

2.2.3 Numerical solution for longitudinal gap effect

Unfortunately, use of equation (1) is limited to symmetric cases where identical uniform gaps exist along both rods. If the gaps exist only partially, or more generally, if the medium surrounding the probe is heterogeneous, a numerical method must be employed.

Assuming that the TDR probe rods have an infinite length, the electrostatic potential field in the plane perpendicular to the rods is described by the Laplace equation. Knight et al. (1997) showed that the apparent relative dielectric constant K_a could be calculated by the following equation.

$$K_a = \frac{\int_{S_1} K_{gap}\left(\frac{\partial \phi}{\partial n}\right) ds}{\int_{S_1} \left(\frac{\partial \phi_0}{\partial n}\right) ds} \tag{2}$$

where, K_{gap} is the dielectric constant of gap material, ϕ is the electrostatic potential for non-homogeneous case (with gaps), ϕ_0 is the electrostatic potential for homogeneous case (without gaps), n is the outward pointing unit normal vector on the boundary, S_1 is the internal boundary for a rod.

Knight et al. (1997) showed that concentric gaps completely surrounding both rods could be modeled reasonably accurately using the analytical solution for non-concentric gaps. Thus, in this study, "concentric" gaps were defined in the finite element mesh around the rods of a two-rod probe. The dimensions of the domain were approximately 20 s in the x-direction and 12 s in the y-direction, where s was the center-to-center rod separation that was 30 mm in this case. The diameter of both rods was $d = 10$ mm. A no-flux boundary was imposed on the outer boundary (S_3) on the domain. The nodes on one rod (S_1) were set to a constant potential of -1, the potentials on the other rod (S_2) were set to 1 (see Knight et al., 1997 for details). PVC-filled gaps were incorporated by assigning $K_{PVC} = 2.9$ to appropriate elements whereas $K_{water} = 81$ was given to all the other elements. The finite element mesh was constructed so that the thickness of the gaps could be varied from 0.01 mm to 10 mm. To confirm the accuracy of the model, the symmetric cases were computed first and the results were compared to the analytical solution. Then, the non-symmetric cases were simulated. It should be noted that in the numerical simulation, both rods were identical and the possible uneven contribution between the center and shield conductors was not taken into account in the model.

2.3 Experimental setup for end gaps

For the investigation of the end gap effect, a solid PVC rod was used to establish gaps at the end of rods. A cylindrical piece of PVC rod with a diameter equal to the rod diameter of 10 mm sliced to have a pre-specified length was directly glued to the end face of each rod. The thickness of the glue was kept as thin as possible so that its effect was minimized. Since PVC has a dielectric constant of 2.9, it should act like air when measured in water. The end gap lengths considered were; 0, 1, 1.5, 2, 3, 4, 5, 7.5, 10, 15 and 20 mm.

3. Results and discussion

3.1 Effect of longitudinal gaps

Fig. 2 shows the experimental, analytical, and numerical results of the dielectric constant of water with the longitudinal PVC gaps. For each gap thickness, five measurements were taken and averaged. In the analytical and numerical calculations, $K_{water} = 81$ was used (von Hippel, 1995). For the symmetric cases, the experimental results (large solid circles) agreed closely with the analytical and numerical results. As can be intuitively inferred, the larger the gap widths δ, the larger their effects. In this case, since $K_{gap} < K_{water}$, the dielectric constant of water was more underestimated as δ increased. For comparison, the effects of "air"-filled gaps were also calculated using equation (1) and shown in Fig. 2 by a gray solid line. It caused more underestimation than PVC-filled gaps. This was expected because the dielectric constant of air was less than that of PVC. For the typical gap width range of 0.1 ~ 0.3 mm (Sakaki et al., 1998), PVC-filled and air-filled gaps caused up to 46 % and 71 % underestimation in the K_a values, respectively, when measured in water with the probe configuration tested. In this study, a relatively large rod diameter was used so that we were able to investigate gap effects for

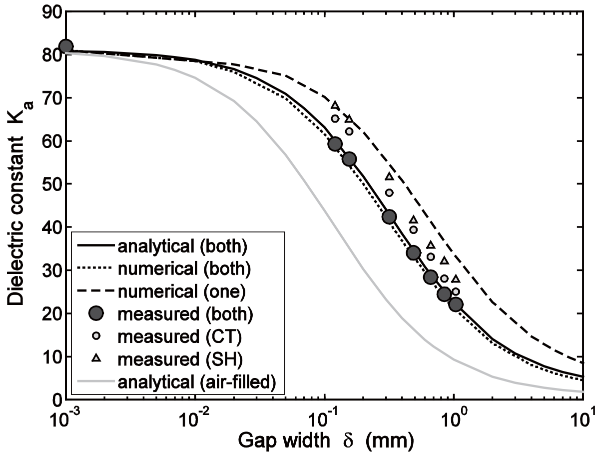

Fig. 2 Effect of PVC- filled gaps in water ($d = 10$ mm, $s = 30$ mm). The thick solid line denotes the analytical dielectric constant calculated using equation (1) when gaps are filled with PVC ($K_{PVC} = 2.9$). The dashed lines are the results from numerical simulation and equation (2) for the symmetric and non-symmetric cases. Data for the no gap are plotted at $\delta = 0.001$ mm. Note that the uneven contribution between the CT and SH rods was not taken into account in the numerical model.

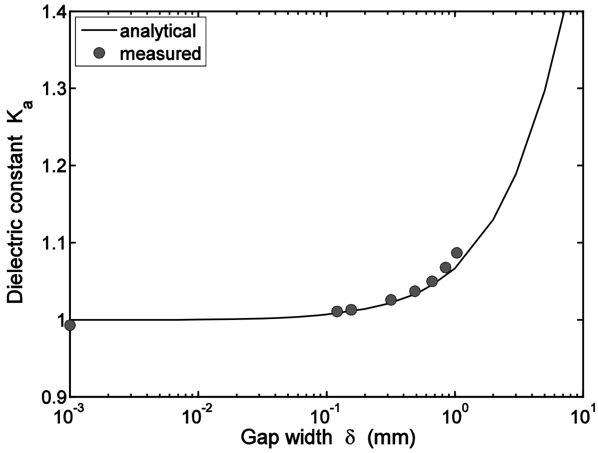

Fig. 3 Effect of PVC-filled gap in air ($d = 10$ mm, $s = 30$ mm). The solid line denotes the analytical dielectric constant calculated using equation (1) when gaps are filled with PVC ($K_{PVC} = 2.9$). The result for the no gap case is plotted at gap $= 0.001$ mm.

small δ/d ratios. However, it must be noted that equation (1) implies that for a probe with a smaller rod diameter, the underestimation will be even more significant.

For the non-symmetric cases, the K_a values were closer to 81 than those obtained for the symmetric cases. This observation was expected because only one rod had the gaps, thus, the effect was less. Two SH cases with $\delta = 0.107$ and 0.160 mm on the shield rod, where δ was small and within the typical range, agreed well with the numerical results. In other SH cases with $\delta = 0.317 \sim 0.950$ mm on the shield rod, the experimental results tend to show lower K_a values than numerical results. All CT cases with gaps on the center rod showed smaller K_a values than those in the SH cases.

Fig. 3 shows the results for PVC-filled gaps measured in air (gaps on both rods only). The analytical values calculated by equation (1) are denoted by a solid line. Although the measured dielectric constant values were slightly higher than the analytical values, their behavior was well explained by equation (1). For the typical gap width of $0.1 \sim 0.3$ mm as Sakaki et al. (1998) observed, the overestimation of the dielectric constant in air due to the PVC-filled gaps was up to 2 % and not as significant as the 46 % underestimation observed in water.

3.2 Effect of end gaps

The results for the end gap effects are plotted in Fig. 4. As there are no analytical and numerical solutions available for this case, only experimental results are presented. For each end gap length, ten measurements were taken. The effects were relatively small compared to those for the longitudinal gaps presented in the previous section. The obtained K_a values were normalized by 81 so that the end gap effects were seen in terms of relative errors. Baker and Lascano (1989) reported that sensitivity ends abruptly at the end of the probe, i.e., changes in water content just beyond the end of the rods have no effect on the signal. Our data showed that the presence of void space filled with air caused a slight underestimation of the apparent dielectric constant and that the effect was almost constant regardless the size of the void space. For an infinite transmission line, the electromagnetic pulse transmits in the simplest mode referred to as TEM (transverse electromagnetic wave), where the electric filed, magnetic field, and direction of propagation are perpendicular to each other (Kraus, 1991). Near the end of rods, the wave is transmitted in higher modes, which has possibly been affected by the presence of air and caused the slight underestimation of the dielectric constant. This is probably limited to a very small region at the end of the rods and thus the effect is as much as ~ 2 % regardless the size of the void space. Although the results are probably unique for the probe dimensions shown here, it is recommended that the void length be minimized as much as possible.

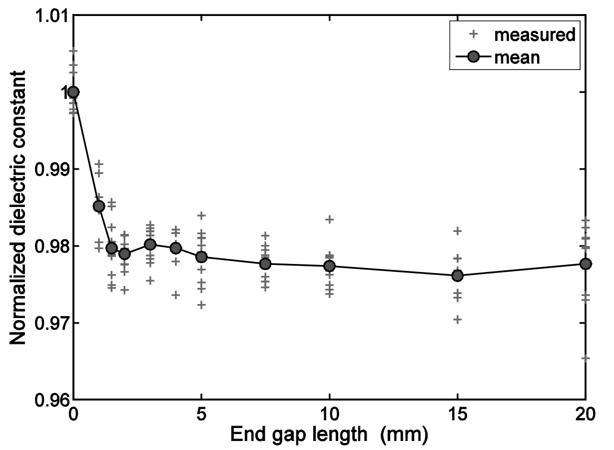

Fig. 4 Normalized dielectric constant of water measured with various end gap lengths.

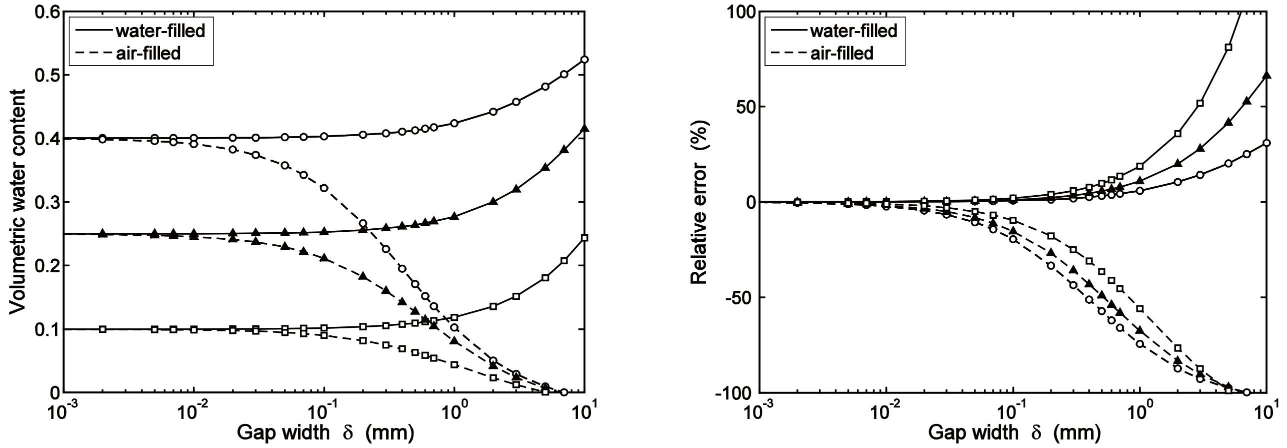

Fig. 5 Calculated water content and relative error with water- and air-filled gaps in a hypothetical rock with true water content of 0.1 (squares), 0.25 (triangles), and 0.4 (circles). Probe dimensions; $d = 10$ mm, $s = 30$ mm.

3.3 Gap effects on water content in soils and rocks

In the previous sections, the gap effects were investigated using limited materials such as water, air, and PVC. The combination of these materials resulted in somewhat different contrast of dielectric constants than that of our interest, i.e., rock and air-filled gaps, rock and water-filled gaps and so on. Similar relationships for apparent dielectric constant K_a vs. gap width δ were calculated using equation (1) for both air- and water-filled gaps in a hypothetical rock material. The dimensions of the two-wire TDR probe were assumed to be $d = 5$ mm, $s = 30$ mm which are typical for commercially available probes ($d = 2.4 \sim 4.8$ mm, $s = 14 \sim 40$ mm, TRIME system, IMKO, Inc., Ettlingen, Germany; $d = 3.2 \sim 4.8$ mm, $s = 30 \sim 45$ mm, Campbell scientific, Inc., Logan, Utah; $d = 3$ mm, $s = 12.5 \sim 37.5$ mm, TRASE system, Soilmoisture Equipment Co., Santa Barbara, California). For demonstration purposes, it was assumed that Topp's equation (Topp et al., 1980) to relate K_a and θ was valid for the hypothetical rock material.

The apparent dielectric constant K_a of the rock (including air and water phases) was assumed to be 5.9, 13.4, and 25 that correspond to water content of 0.1, 0.25 and 0.4 using Topp's equation. For the probe configuration mentioned above, the apparent dielectric constant was computed using equation (1), and converted into water content. The calculated water content as well as relative errors are plotted in Fig. 5.

4. Discussion and conclusions

The effects of longitudinal and end gaps were experimentally investigated and, where available, the results were compared to the analytical and numerical solutions. Although the end gaps showed very little effects, the longitudinal gaps lead to significant errors. For the symmetric longitudinal gaps, where uniform identical longitudinal gaps were on both rods, the experimentally measured data showed good agreement with the analytical and numerical solutions. For the non-symmetric cases, where the longitudinal gaps exist along one rod only, the results were not as straightforward. The cases with gaps on the center rod showed more effect than those with gaps on the shield rod. When an electromagnetic step pulse propagates along a coaxial transmission line, the center conductor carries the signal and the shield conductor is ground; i.e., "unbalanced" signal. In a transmission line consisting of two parallel conductors, both conductors carry a signal, equal in magnitude but opposite in sign with the ground potential in the center plane; this is referred to as "balanced" with respect to ground. For a two-rod TDR probe, the electrical field will gradually change from unbalanced to balanced (without using a balanced-unbalanced transformer, e.g., Spaans and Baker, 1993), which often leads to higher sensitivity on the rod connected to the center conductor. The uneven contribution of each rod leads to a difference in the trace data depending on whether the gaps are on the CT or the SH rod as shown in Fig. 6. If the balanced electrical field cannot be obtained within the length of the probe, the

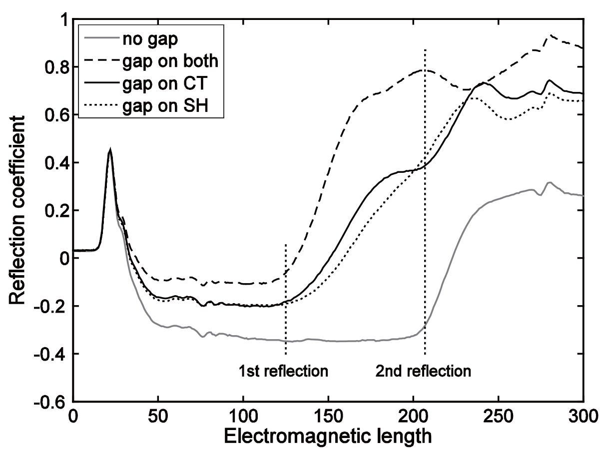

Fig. 6 Example traces with $\delta = 0.636$ mm obtained in water. Longitudinal gaps are on CT rod only, SH rod only, and both rods. Trace with no gap is also shown for comparison.

CT rod will carry more signal than the SH rod. Therefore, when measured in water, the gap effect is expected to be more distinct when PVC-filled gaps are present along the CT rod, which resulted in more underestimation in K_a in this case. The trace with gaps on the CT rod shows two reflections; one from the CT rod, and another from the SH rod without gaps that indeed corresponds to the reflection point of the no gap case. For the trace with gaps on the SH rod, the second reflection disappeared. Overall, the experimental data revealed that the analytical and numerical solutions were valid to quantify the effect of symmetric longitudinal gaps. Because of the uneven contribution of the rods, the numerical solution tends to somewhat underestimate the effects when the longitudinal gaps are not symmetric.

When applying TDR to unsaturated rocks, it is likely that the gaps are filled with air rather than with water due to larger suction in the surrounding matrix. Thus, the results imply that much attention should be paid to minimize gaps around the probe rods when applying TDR to rocks, as air-filled gaps are the potential cause for significant underestimation of K_a values of the rocks, thus, water content. An electrically conductive material may be used to fill such gaps to minimize their effects on the measurement accuracy (Sakaki and Rajaram, 2006). Moreover, gaps can arise not only for rocks but also for soils if sufficient care is not taken when packing soil around the probes (Decagon Devices, 2010), if the sensor is dislocated inside the soil, or when soil shrinkage occurs. Therefore, maximum attention has to be paid to ensure good contact between the probe and the material of interest when installing probes in soils or rocks.

We have experimentally shown that the center rod is more sensitive than the shield rod. Limsuwat et al. (2009) showed similar non-symmetric characteristics in the commercially available capacitance sensors. Even when there is no gap, the non-symmetric characteristics can lead to some implications. For example, if a probe is aligned such that the rods experience a large water content difference between the two, the measurement may be biased. When measuring a wetting front migration and one of the rods is in the wet region and the other is in the dry region, the resulting K_a is likely to be affected more when the center rod is in the dry region.

Acknowledgements

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要　　旨

TDR プローブを岩石に設置する際にはプローブと岩石試料との間に隙間が発生することがある．本研究では，既知の隙間を持つプローブを用いて水と空気の比誘電率を計測し隙間の影響を評価した．隙間の影響に関する理論解および数値解が存在する 2 ロッド型プローブについて，両ロッドに対称に隙間がある場合，片方のロッドのみに隙間がある場合，そしてロッド先端以深に隙間がある場合について検討した．対称な隙間のケースでは，水と空気の比誘電率の計測値は理論解および数値解とよく一致した．非対称のケースでは隙間幅が比較的小さい場合は数値解と一致したが，隙間幅が大きくなるとともに実験結果の方が数値解より大きな影響を示した．実験結果および数値解の差異は隙間が同軸ケーブルの芯線に接続したロッドにある場合により顕著に見られ，ロッド間で感度が異なることがわかった．ロッド先端部以深の隙間の影響は小さかったが，ガイド孔が緩い場合やプローブ周辺の土壌で乾燥収縮が発生するような場合には含水率が過小評価される可能性があることが示された．

キーワード：含水率, 比誘電率, 時間領域反射率法, 隙間の影響, 計測誤差