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# Parallel Plates Compared with Conventional Rods as TDR Waveguides for Sensing Soil Moisture

**D. A. Robinson and S. P. Friedman**

Institute of Soil, Water and Environmental Sciences, (ARO),
Volcani Center, Bet Dagan 50250, Israel

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Dielectric methods of estimating the water content of soils, especially TDR, have become accepted as routine measurement techniques. Basic to the TDR technique is the waveguide, which is inserted into the soil for obtaining measurements of the effective soil permittivity, from which water content is estimated. In this study we compare the use of flat stainless steel plates with cylindrical stainless steel rods. We suggest that the use of plates gives a more even distribution of electromagnetic energy within the soil volume sampled and reduces the so called "skin effect" where the electromagnetic energy is concentrated close to the surface of the electrodes. Plates will not be suitable for all measurement purposes but wherever they can be applied they should result in more representative measurements from the medium under investigation. Calculations of electrical field intensity are presented to compare the relative energy density between the electrodes. Field and laboratory studies were also conducted considering some of the practicalities of using the alternative waveguides.

**Key Words.** relative permittivity, dielectric constant, waveguide, lateral sensitivity, TDR.

## 1. Introduction

The aim of any sensor is to obtain a representative measurement from the material being measured. Time domain reflectometry (TDR) has been demonstrated to be a method of obtaining a reliable estimate of the soil water content ($\theta$) from a measurement of the real part ($\varepsilon'$) of the relative permittivity ($\varepsilon_r$) in soils [1–4], where $\varepsilon_r$ is defined as:

$$\varepsilon_r = \varepsilon' + j\varepsilon''$$

where, $j$ is $\sqrt{-1}$ and $\varepsilon''$ is relaxation losses plus $\sigma/\omega\varepsilon_0$, ($\sigma$) is the dc conductivity, ($\varepsilon_0$) is the permittivity of vacuum (8.854 pF m$^{-1}$) and ($\omega$) is the angular frequency. The use of the term relative permittivity ($\varepsilon_r$) is maintained for measured permittivity values, whilst the term effective permittivity ($\varepsilon_{\text{eff}}$)

describes the permittivity of a dielectric mixture without effects arising from the measurement method. The volume of soil, for which the estimate is valid, depends primarily upon the design of the waveguide. As such, much discussion has focused on the design and construction of different waveguides for differing applications [5–13]. In early work, Annan [14] derived an analytical solution for the apparent permittivity of a two-rod waveguide with circular air gaps around the rods. As a practical guideline Topp and Davies [15] suggested that the soil sampled was essentially contained within a cylinder centered between two parallel rods with a diameter of 1.4 times the rod spacing. Zegelin *et al.* [6] presented an approximate analytical expression for the relative voltage distribution around two wire and multi-wire waveguides in the transverse plane. Knight [16] suggested using the energy storage/dissipation $(\nabla\phi)^2$ as a spatial weighting function, which is a satisfactory first order approximation for small perturbations from a homogeneous medium. Knight [17] then analyzed the waveguide configurations presented by Zegelin *et al.* [6] characterizing their sensitivity to lateral heterogeneities. Solving the Laplace equation for the energy dissipation is analogous to solving steady state groundwater flow problems as argued by Knight *et al.* [18], when studying the effect of coatings and gaps on TDR electrodes. The present study examines the use of plates as waveguides and is concerned with the lateral sensitivity to heterogeneities in a plane perpendicular to the waveguide. The averaging along the waveguide is very close to arithmetic because of the electromagnetic wave propagation velocity being proportional to $\varepsilon_r^{-0.5}$ and the approximate $\varepsilon_r \propto \theta^2$ [4] relationship.

## 2. Materials and Methods

### 2.1. Waveguide Design

All the waveguides were constructed from stainless steel, which was cut to lengths of 0.16 m. Both the rods and plates were silver soldered to 2.5 m of 50 Ω, (RG-58) coaxial cable. The inner core was soldered to one electrode and the outer sheath was soldered to the other. These were then set in Epoxy with 10 mm of steel embedded in the epoxy giving a sensing electrode length of 150 mm (Fig. 1). The dimensions of the plates used were 20 mm high and 2 mm thick, the rods were 4 mm in diameter. The spacing between the electrodes was 20 mm between surfaces for both waveguides. Knight [16] suggested that waveguides constructed using rods should have a ratio of diameter to spacing in excess of 0.1, this is the case for the waveguide presented here which has a value of 0.17 (4/24).

Similar waveguides were also constructed in the same manner for use in the field study, where the layout is shown in Figure 2. Four types of

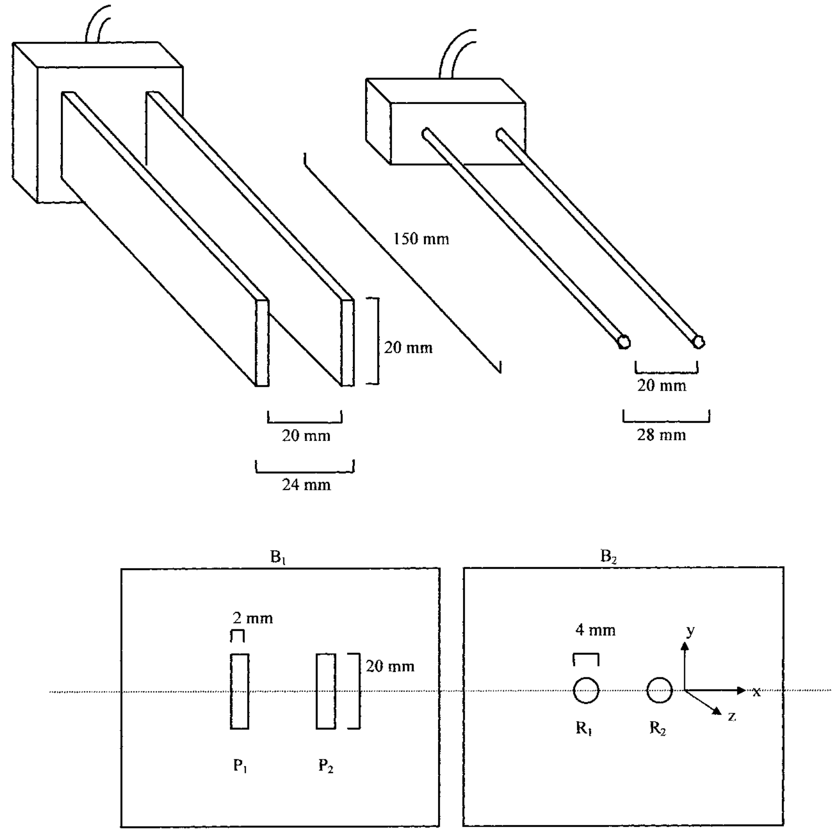


**Figure 1.** A 3-dimensional diagram illustrating the waveguide designs, left, the plates and right the rods. Below are the 2-dimensional cross sections where $P_1$ and $P_2$ are the stainless steel plates and $R_1$ and $R_2$ are the stainless steel rods. $B_1$ and $B_2$ represent the distant boundaries where the electric field intensity was set to zero, ($E = 0$) for the plates and rods respectively. The dashed line represents the transection taken through the electrodes to obtain the electrical potential, field intensity and energy storage density (Fig. 3a, b, and c).

waveguide were compared, each with two replicates. Parallel, two rod and parallel three rod waveguides were constructed, all were 150 mm in length and made with 4 mm diameter stainless steel. The two wire electrodes (1,2R and 2,2R) had a center spacing of 24 mm and the three wire probes (1,3R and 2,3R) had a 24 mm center spacing between inner and each of the outer wires. The two plates (1,2P and 2,2P) had a center spacing of 22 mm and the three plates (1,3P and 2,3P) had a center spacing of 22 mm between the inner and each of the outer plates.

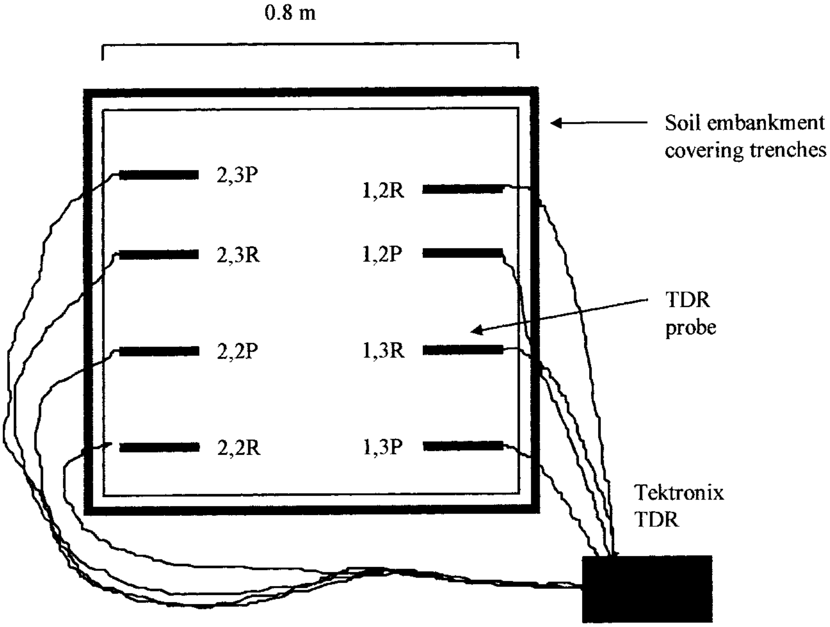


Figure 2. The experimental layout for the comparison of the waveguides in natural soil conditions.

The permittivity measurements were with the waveguides attached to a Tektronix 1502C cable tester and the waveforms were collected and analyzed using software developed by Heimovaara and de Water [19].

## 2.2. Theory and Computations

The electrostatic potential ($\phi$) surrounding TDR electrodes in the general case, where the effective permittivity ($\varepsilon_{\mathrm{eff}}$) varies with position, satisfies:

$$\nabla(\varepsilon_{\mathrm{eff}}\nabla\phi) = 0 \tag{1}$$

In the special case of a homogeneous medium the potential ($\phi$) satisfies the Laplace equation:

$$\nabla^2\phi = 0 \tag{2}$$

The electric field intensity is defined as:

$$E = -\nabla\phi \tag{3}$$

Once the electric field intensity (E) has been determined the density of stored electrical energy at a point is given by:

$$w = \varepsilon_{\text{eff}}(\nabla\phi)^2 \tag{4}$$

To demonstrate this, the 2-dimensional electrical fields surrounding the electrodes presented in Figure 1 were analyzed; the potential ($\phi_1$) on surface $P_1$ was set to 1 and the potential ($\phi_2$) on surface $P_2$ to 0. $B_1$ represents the distant boundary, where the boundary condition was set to zero flux ($\nabla\phi = 0$); the same procedure was used for the rod surfaces $R_1$ and $R_2$. The Laplace equation was solved numerically using the finite element numerical code, "SWMS-2D for simulating water flow and solute transport in two dimensional variably saturated media" [20]. The advantage of a software package that provides numerical solutions is that all manners of probe configurations can be tested for which analytical solutions may well be unavailable.

## 3. Results and Discussion

### 3.1 Modeling

Figures 3a, b, and c present the numerical results for the normalized electrical potential, electrical field intensity and energy storage density obtained with SWMS-2D. The graphs represent a line connecting the centers of the electrodes in the x–y plane (Fig. 1). All values given were normalized by the highest value obtained for each respective configuration. Figure 3a, presents the normalized electrical potential ($\phi$), 3b, the normalized electrical field intensity ($\Delta\phi$) and 3c, the normalized electrical energy storage $(\nabla\phi)^2$.

Figure 3b clearly demonstrates that the electric field intensity surrounding the rods is most intense, close to the surface of the cylindrical electrodes and results in distinct spikes. The electric field intensity between the plates is much more even. It is the electric field intensity, which is squared to give the normalized energy storage and results in much of the energy storage around the rods being close to the electrode surface (Fig. 3c). The percentage decrease in the normalized energy storage density in the center of the electrodes was 87.2% for the rods and 9.5% for the plates (Fig. 3c).

### 3.2. Laboratory Experiments

Three laboratory experiments were conducted to demonstrate that the energy storage distribution between the plates was more even than with

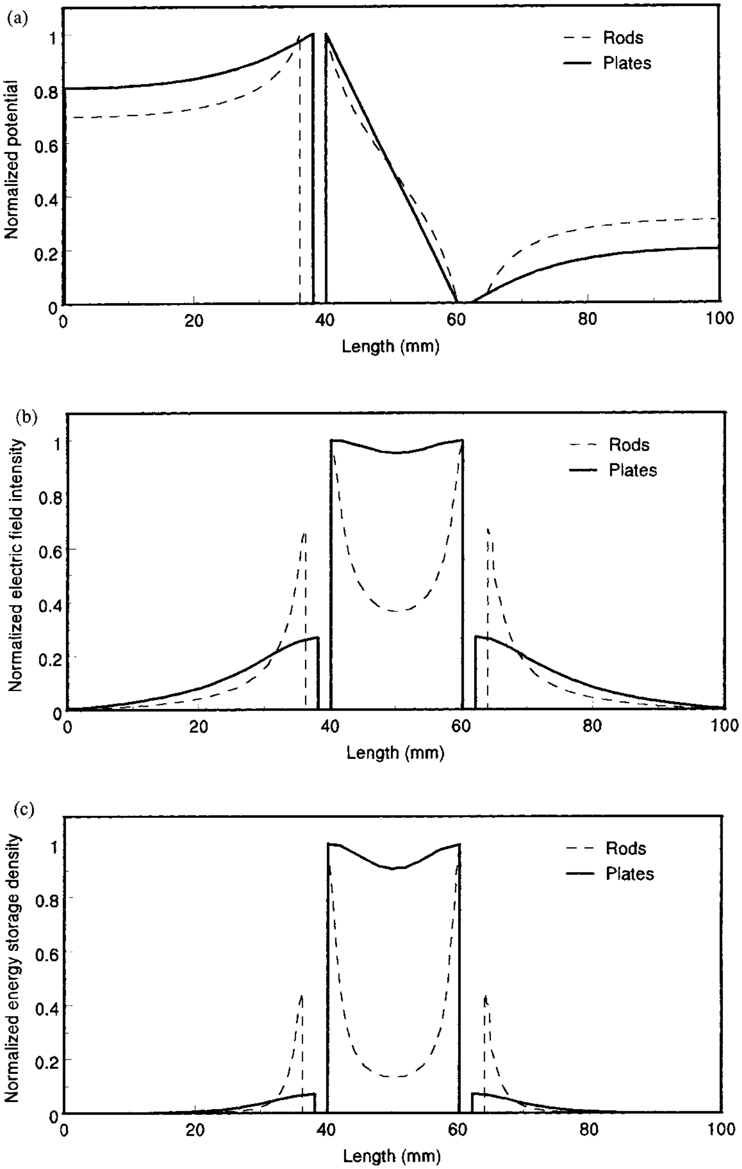


**Figure 3.** (a) The normalized electrical potential for the plates and rods, the transection is along the x axis through the center of the electrodes. (b) The normalized electric field intensity for the plates and rods, the transection is along the x axis through the center of the electrodes. (c) The normalized electric energy storage density for the plates and rods, the transection is along the x axis through the center of the electrodes.

the rods. We first used porous polyethylene sheets with a porosity of about 0.38, 16.5 cm long, 9 cm high and 0.16 cm thick placed between the electrodes. Initially, two plates were placed between the electrodes immersed in water and the permittivity measured, the number of plates in the water was increased sequentially in twos, to a total of 12. The hydrophobic nature of the polyethylene allowed two sets of measurements to be taken in water, one with the sheets containing air (Fig. 4, Expt. A), the other with the sheet pores saturated with water (Fig. 4, Expt. B). The figures clearly demonstrate that the permittivity measured with the plates is lower than with the rods, indicating greater penetration of the field into the porous media using the plates. The presence of the first two plastic sheets reduced the permittivity by 47% and 38% for the plates and rods respectively in Expt. A (air filled), and by 18% and 9% for the plates and rods respectively in Expt. B (water filled). Clearly the plates "see" much more of the porous plastic than the rods.

A second experiment coated both waveguides with successively thicker layers of an insulating tape as in Whalley [21] and measured the apparent permittivity with the waveguides immersed in water. Initial measurements were made in a 10 l bucket of de-ionized water at 25°C. A single layer of a 0.1 mm thick sticky electrical insulating tape was applied completely covering the metal electrodes. The waveguides were again immersed in the water and the permittivity measured. This procedure was repeated for a total of 5 layers of insulation, equivalent to a thickness of 0.5 mm.

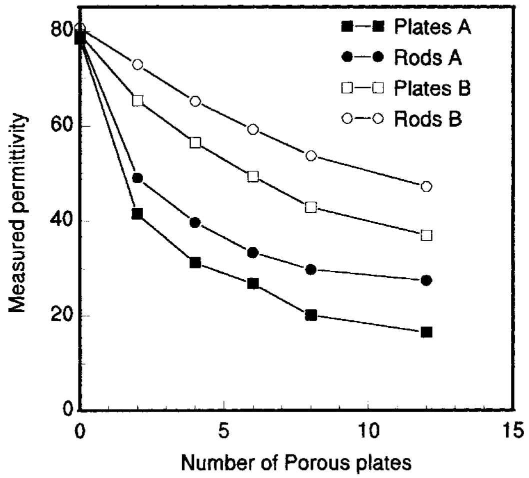


**Figure 4.** The measured permittivity as a function of the number of porous sheets placed between the electrodes. A, refers to the porous plates being filled with air (closed symbols) and B, refers to the porous plates being filled with water (open symbols).

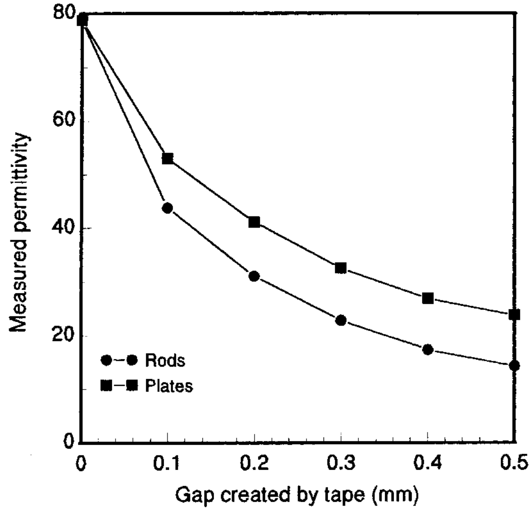


**Figure 5.** The lowered, measured permittivity, as a function of the increasing number of layers of 0.1 mm thick electrical insulating tape.

The results in terms of the relative permittivity measured after isolating the electrodes with successive layers of insulating electrical tape are presented in Figure 5. This time the permittivity measured by the plates was higher than with the rods as expected if more of the energy storage is further from the electrode surface. The measured permittivity values initially diverge as the insulating tape more significantly influences the measurements with the rods. After 5 layers of insulation, the recorded permittivity using the rods was 18% of the permittivity of the bulk water, where as, the permittivity measured using the plates was 30% that of bulk water. The divergence between the permittivity values measured appears to reduce as the number of tape layers increases, this was expected as a large number of layers results in the permittivity of the tape.

The last laboratory experiment utilized a compartmentalized box placed between the electrodes to examine the effect of water distribution on the measured permittivity, similar to the experiment of Baker and Lascano [22]. The box was constructed from reinforced plastic sheets with rectangular tubes, which were approximately 2 mm by 3mm in dimension. Eight sheets, 0.25 cm thick, 17 cm long and 10 cm high were stuck together and sealed at the base. The box with 392 individual cells was placed between the electrodes as in the plan view in Figure 6. Each of the square tubes was individually filled with water and the permittivity measured. The presence of the non-conducting plastic, in much the same way as an air gap, severally

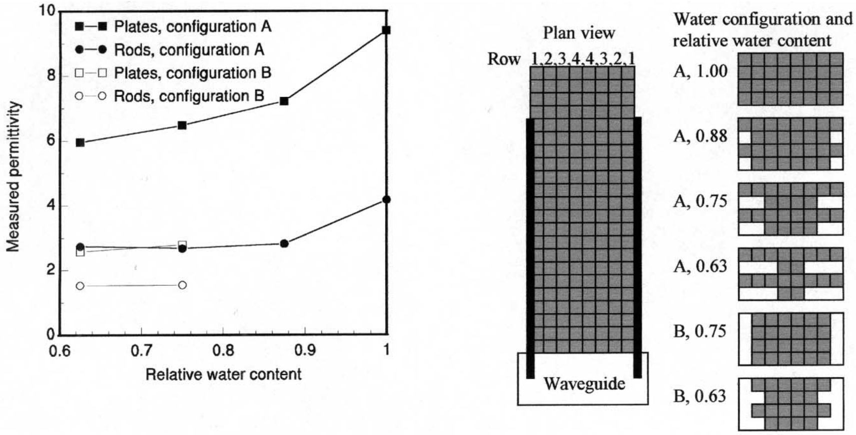


**Figure 6.** The graph on the left side gives the measured permittivity as a function of the repeating water body configurations pictured on the far right. The relative water content is the water content of the box for a given configuration relative to the box full of water. The plan view shows the configuration of the experiment with the box placed between the electrodes of the waveguide.

reduces the measured permittivity, for the plates by 88% and for the rods by 95% when all the cells were filled with water.

Different configurations of water removal were now considered. The first configuration (A, Fig. 6) removed water from every other cell in rows 1, then 2, then 3. This allowed parallel connection of water filled cells in every other column between the electrodes. The measured permittivity dropped according to Figure 6. This can now be compared with removing all the water from the cells in rows 1 (configuration B, Fig. 6), which is like having water filled cells and dry cells connected in series between the electrodes. For the same given water content as cells connected in parallel the permittivity is much lower, demonstrating the importance of a connecting pathway between the electrodes.

The results of the three sets of experiments clearly demonstrate that the plate electrodes are less sensitive to the "skin effect" than the rods and are more sensitive to the variations in permittivity in the main sampling volume. The energy storage distribution is more even between the plates and we believe, will result in improved measurements of permittivity.

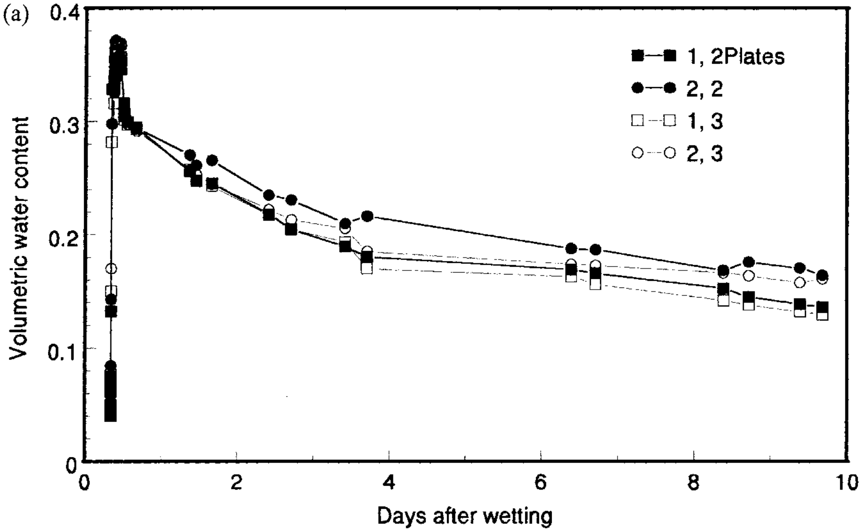
## 3.3. Field Experiment

Eight waveguides described in the materials and methods were installed in loamy sand in an experimental plot as shown in Figure 2. Two trenches were dug on either side of the experimental plot, the soil was saturated with water to reduce its resistance to inserting the TDR waveguides, which were installed horizontally via the trenches at a depth of 0.1 m and separated by a distance of approximately 0.2 m. After installation the trenches were backfilled and an embankment of soil was placed over the top so that it could be saturated by ponding water on the surface. This method of installation maintained an undisturbed soil layer around the sensors.

Once constructed in June and wetted, it was left to settle for 3 months before measurements commenced. Two periods of saturating and drying were monitored, the first in September and the second in October. Initial measurements were made in the dry soil and then water was ponded on the surface until the water content did not change for half an hour or more. The surface of the soil was then covered with a plastic sheet so that redistribution could take place without evaporation. The water content was then monitored over the following ten days with redistribution and drainage. After the first experiment the plastic cover was removed to hasten the drying for the next experiment. There was no rain during either of the drying periods or in-between them. The soil temperature was monitored over the period of measurements and found to be 30°C ± 2°C. The permittivity measurements were converted to water content using the empirical function of Topp *et al.* [2] as it had been found to be suitable for the Bet Dagan loamy sand [23].

The field experiment was designed to test the applicability of parallel plates to routine field measurements. The results from the two wetting and drying experiments are presented in Figures 7 and 8. The first wetting and drying appeared to produce little difference between the results obtained using the plates and those using rods (Fig. 7a and b). The second wetting and drying produced results, which provided more information for the comparison (Fig. 8a and b). By the second experimental run the water content values obtained with the plates (Fig. 8a) were far more consistent than with the rods (Fig. 8). The reason for the seemingly low water contents obtained using rod sensor 2,2R was probably due to the presence of an air gap close to the base of the waveguide, which occurred even though great care was taken installing the waveguides. The reduced spread of the data in the second experiment with the plates was considered to be due to a period of settling. Although the waveguides had been installed into wet soil, a further wetting (Fig. 7a) appears to have been required to allow the waveguides to bed properly into the soil (Fig. 8a).

An observed difference between the results was that the maximum water content attained using plates was slightly but consistently higher than with the rods by about 2%. This was considered to reflect the rods greater



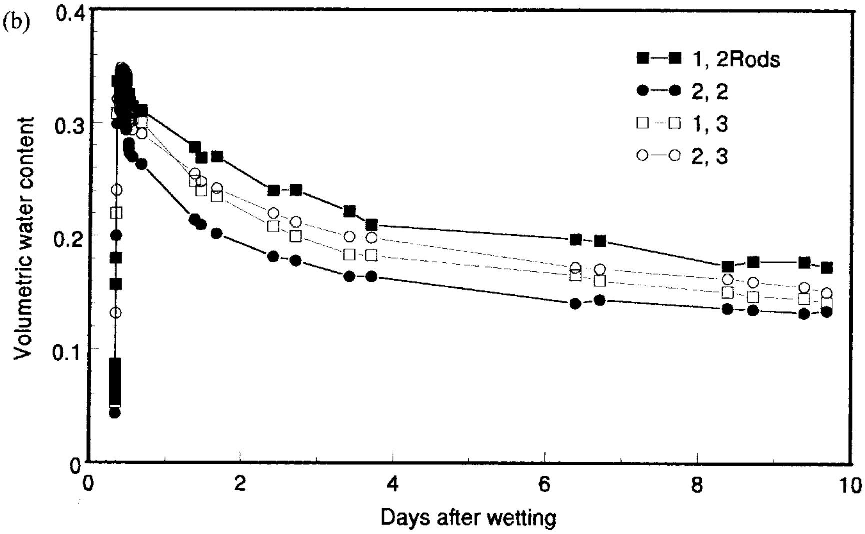


**Figure 7.** (a) Volumetric water content, estimated from the effective permittivity measured using plates. The solid symbols represent two plates and the open symbols represent three plates. The first experimental run, September 1999. (b) Volumetric water content, estimated from the effective permittivity measured using rods, symbols as before.

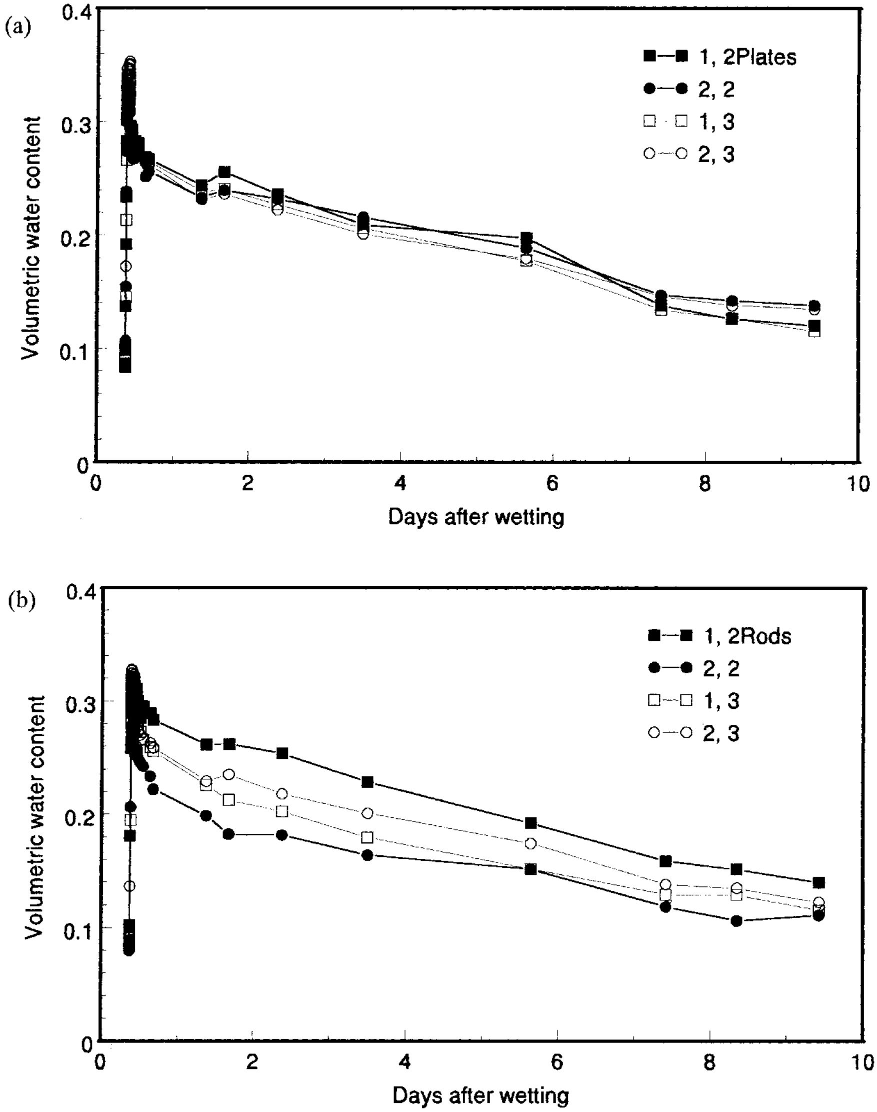


**Figure 8.** (a) Volumetric water content, estimated from the effective permittivity measured using plates. The solid symbols represent two plates and the open symbols represent three plates. The second experimental run, October 1999. (b) Volumetric water content, estimated from the effective permittivity measured using rods, symbols as before.

sensitivity to the first millimeter of soil surrounding the electrodes. As the waveguides are installed some compaction occurs which reduces the porosity of the soil immediately around the electrodes. Our interpretation of the data is that the reduced water content readings obtained using rods are a reflection of the compaction phenomena described.

The performance of the plates appears marginally better than that of the rods at first sight. However, there are other factors to consider; one of which is installation. The plates must be oriented vertically for satisfactory settling of the soil at the plate surface, when placing the probes horizontally in the soil. In the sandy soil used for these experiments installing the plates was not difficult once the soil had been wetted. However, we believe that, installing plates into stonier or harder, more compacted soil would become increasingly more difficult than with rods. Endeavoring to keep an accurate spacing between plates in practice is more difficult than with rods as the plates tend to diverge easily upon resistance.

A further consideration is the electrode cell constant, which is smaller for the plates due to the greater surface area than for rods with a similar spacing. This means that signal attenuation is higher and so the reflection for measuring permittivity is lost sooner; plates therefore, are not practical for use in saline soils. The greatest advantage of using plates can be achieved when they are used in controlled laboratory experiments, where a representative measurement of a materials permittivity is of greatest interest. In other experiments conducted by Robinson and Friedman [24] plates were used to measure small differences in effective permittivity due to differing particle size distributions. Preliminary experiments were conducted with rods with poor success, the use of plates greatly improved the measurement accuracy.

## 4. Conclusions

The comparison of a parallel plate TDR waveguide design with that of circular rods is presented. Computations of the electrical energy density surrounding the different waveguides suggest that the energy distribution between plates is more even than with rods. In the central position between the electrodes the modeling showed that the energy storage density dropped by 87.2% for the rods and 9.5% for the plates relative to the value at the surface of the electrodes. More of the field evenly penetrates the sample using plates overcoming the so-called "skin effect", often experienced with rods. Plates are most suitable for laboratory experiments but as this study demonstrates they can be successfully applied to field measurements as well. This is however, likely to be limited to lighter textured, stone free soils where insertion into the soil is easier and nonsaline soils where signal attenuation is not a problem.

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