

THE TIME-DOMAIN REFLECTOMETRY METHOD FOR MEASURING SOIL WATER CONTENT AND SALINITY

F.N. DALTON and M. Th. VAN GENUCHTEN

U.S. Salinity Laboratory, 4500 Glenwood Drive, Riverside, Calif. (U.S.A.)

(Accepted for publication February 28, 1986)

ABSTRACT

Dalton, F.N. and van Genuchten, M.Th., 1986. The time-domain reflectometry method for measuring soil water content and salinity. *Geoderma*, 38: 237–250.

This paper discusses the physical principles and use of time-domain reflectometry as a new tool for studying water and solute transport in unsaturated soils. In-situ measurements of water content and bulk soil electrical conductivity are shown to give results that are comparable with those obtained by conventional non-destructive techniques. An equation is presented that relates the bulk soil electrical conductivity to the soil solution electrical conductivity. Also derived are constraints that water content and electrical conductivity place on the use of time domain reflectometry sensors.

INTRODUCTION

The spatial and temporal variability of water and solute fluxes in the field makes it difficult to obtain a quantitative understanding of the dynamics of the water and salt regimes needed for the solution of any practical field water and/or salinity problem. For example, proper management of the soil root zone of actively transpiring plants is only possible when accurate estimates of the spatial and temporal distributions of the soil water pressure and osmotic potentials are available. It is apparent that efficient and non-destructive methods for measuring water content and ionic concentration are crucial for any experimental ion transport study in the field.

Presently, few methods exist for measuring water content and salinity simultaneously and in a non-destructive fashion. Field soil water content can be measured non-destructively (non-gravimetrically) by the in-situ neutron scattering method. Limitations of this method are its relatively large sampling volume, the inability to measure close to the soil surface, the need for individual soil calibration, and the radiation hazard. A few more methods exist for non-destructively measuring soil salinity. The four-probe (Rhoades and van Schilfgaarde, 1976) measures an in-situ electrical conductivity which can be related to the soil solution concentration if the water content is

known. Another measuring device is the "porous ceramic" salinity sensor (Richards, 1966; Oster and Ingvalson, 1967). This method uses platinum electrodes that are embedded in a porous ceramic whose water content changes very little over a wide range of soil water potentials. When the soil and ceramic ion concentrations are in equilibrium, a direct measurement of soil water electrical conductivity is then possible. The only other direct and non-destructive method for obtaining soil water ionic concentrations is with a porous ceramic extraction cup. Unfortunately, this method is limited to a relatively narrow range of soil water pressure heads. Also, small volumes of contacted soil can contribute to large measurement variations when suction cups are used, especially in aggregated soils. A related problem is that water content and soil salinity measurements usually are obtained from separate samples at separate locations in the field, thus contributing to additional sampling errors.

Recent studies have shown that time-domain reflectometry (TDR) is a much easier and perhaps more reliable technique for simultaneously measuring water content and soil salinity. Fellner-Feldegg (1969) showed how TDR could be used to measure the dielectric constant of liquids in a coaxial wave guide. Topp et al. (1980, 1985) showed the applicability of the method for measuring the volumetric water content of unsaturated soils. Dalton et al. (1984) subsequently demonstrated how the TDR method can be used to simultaneously measure water content and electrical conductivity on the same undisturbed soil volume.

This paper gives a comprehensive analysis of the physical principles that form the basis of the time domain reflectometry method. After showing how TDR can be used to evaluate the dielectric constant, the method is applied to the measurement of the soil electrical conductivity. Accuracy of the procedure is verified with recent soil salinity measurements. Also presented in this paper are constraints that water content and soil salinity place on the TDR probe lengths.

PHYSICAL PRINCIPLES

This section gives a brief summary of the physical principles that relate to the dielectric constant. Additional details can be found in standard reference books (e.g., see von Hippel, 1953, and Kittel, 1960). First, consider the situation where an instantaneous voltage V is applied across an ideal, air-filled parallel plate capacitor with capacitance C_0 . The electric charge Q stored on the capacitor is then given by:

$$Q = C_0 V \quad (1)$$

Next, if an insulating material is placed between the parallel plates, the electric charge will increase, and hence also the capacitance C . One can give

an operational definition of the dielectric constant of the material in terms of the capacitance of the air-filled and material-filled capacitors:

$$C = C_0 \frac{\epsilon'}{\epsilon_0} = C_0 \epsilon \quad (2)$$

where ϵ' and ϵ_0 are the dielectric constant of the material and the air, respectively, and ϵ is the relative dielectric constant, or alternatively termed the relative permittivity. The latter term has been the more popular one in the literature. When the applied voltage is sinusoidal in time, i.e., of the form:

$$V = V_0 e^{i\omega t} \quad (3)$$

where complex notation is used ($i^2 = -1$) and ω is the angular frequency, then the charging current I_c represents the time rate of change of the stored charge:

$$I_c = \frac{dQ}{dt} = C_0 \frac{dV}{dt} = i\omega C_0 V \quad (4)$$

which will be 90 degrees out of phase with the applied voltage.

If the material between the capacitor plates is not a perfect insulator, as would be the case for a saline soil, then there will be a conduction or loss current I_1 proportional to the material conductance G and applied voltage V such that $I_1 = GV$. The conduction current I_c is said to be in phase with the applied voltage. Both the loss current and the charge current are key properties that ultimately allow one to measure the electrical conductivity and dielectric constant simultaneously. The ratio of the loss current to the conduction current is called the dissipation factor D or loss tangent, $\tan \delta$:

$$D = \tan \delta = \frac{I_1}{I_c} \quad (5)$$

The total current I_t (charging current + loss current) becomes:

$$I_t = I_1 + I_c = (G + i\omega C)V \quad (6)$$

which shows that the total current can be viewed as a complex variable consisting of real and imaginary components. Since the loss current may be due to any energy consuming process and not just to conduction losses, it is convenient to introduce in analogy to eq. 6 a complex dielectric constant (von Hippel, 1953):

$$\epsilon^* = \epsilon' - i\epsilon'' \quad (7)$$

Using eqs. 2 and 7, the total current (eq. 6) can now be expanded into a form that does not specifically include the loss current:

$$I_t = i\omega CV = i\omega \epsilon^* \frac{C_0 V}{\epsilon_0} = (i\omega \epsilon' + \omega \epsilon'') \frac{C_0 V}{\epsilon_0} \quad (8)$$

The parameter ϵ'' is called the loss factor, whereas $\omega\epsilon''$ is equivalent to the dielectric conductivity (von Hippel, 1953). In materials research one is usually interested in both the real and imaginary components of the dielectric constant. As was shown by Fellner-Feldegg (1969), it is possible to obtain in one measurement the frequency-dependent dielectric properties of a medium. Topp et al. (1980) further demonstrated that the low-frequency or static component of the dielectric constant can be used to correlate with the soil water content. The relative dielectric constant of distilled water is about 81; ϵ for a dry soil is approximately 3, while ϵ for a saturated soil is about 25.

TDR MEASUREMENTS OF THE DIELECTRIC CONSTANT

The first measurements of the dielectric constant of organic solutions using time-domain reflectometry were made by Fellner-Feldegg (1969). He calculated ϵ using a model describing the propagation of an electromagnetic wave in a cylindrical wave guide filled with a homogeneous and isotropic liquid. Topp et al. (1980) extended this technique to porous media and showed that for a large range of soils and soil-like materials a unique relationship exists between an apparent relative dielectric constant ϵ and the volumetric water content θ . Parallel rod electrodes were subsequently used as wave guides by Topp and Davis (1985) to measure field soil water contents and by Dasberg and Dalton (1985) to measure soil water content and electrical conductivities.

Measurements at the U.S. Salinity Laboratory (Dasberg and Dalton, 1985) were made with a Tektronic S-52 pulse generator, 7S12 sampling unit, S-6 sampling head and a 7603 oscilloscope (names of products are included for benefit of the reader and do not imply endorsement or preferential treatment by USDA). This system obtains the soil dielectric constant by measuring the transit time of an electromagnetic pulse launched along a pair of metallic parallel rods of known length embedded in the soils (Fig. 1). At the end of the wave guide, the launched electromagnetic pulse is reflected back to its source. Thus, the path length of the voltage pulse is twice the length of the parallel rods. If we measure the transit time t , then the propagation velocity of the pulse is given by:

$$V = 2L/t \quad (9)$$

Electromagnetic theory (e.g., see Ramo and Whinnery, 1959) shows that the velocity can be expressed in terms of the dielectric constant of the medium and the velocity of light in free space, c ($3 \cdot 10^8$ m/s):

$$v = \frac{c}{\sqrt{\epsilon}} \quad (10)$$

Combining eqs. 9 and 10 gives the dielectric constant in terms of transit

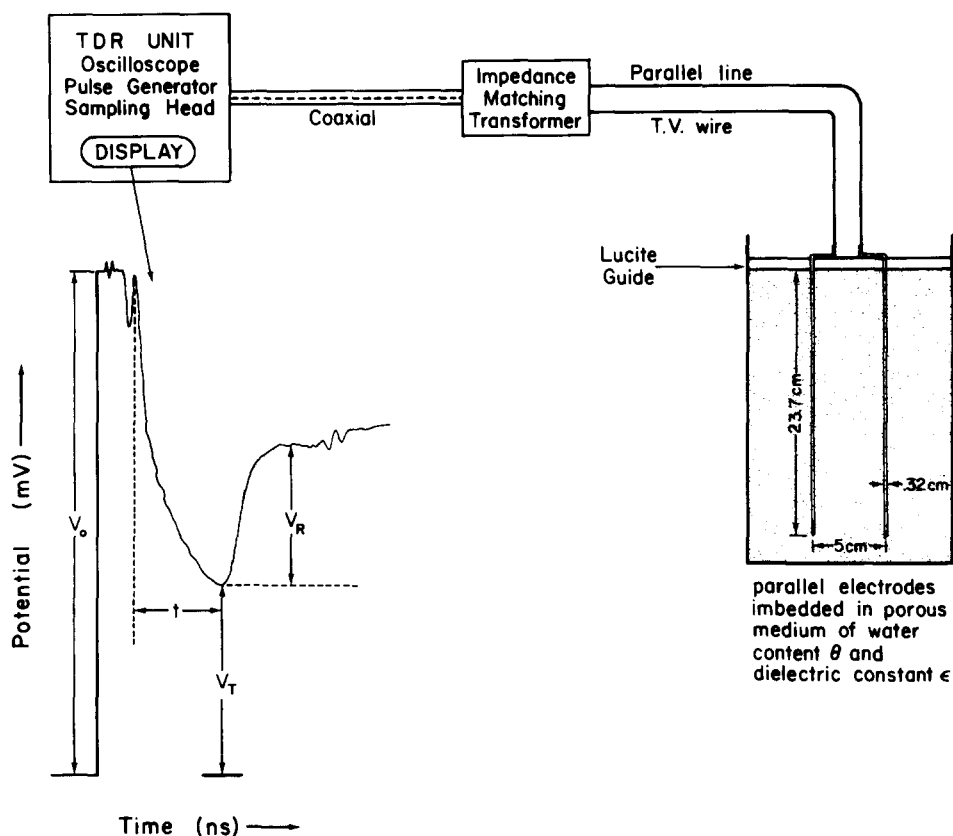


Fig. 1. Schematic diagram of time-domain reflectometry system for measuring soil water content and electrical conductivity (after Dalton et al., 1984).

time, path length and velocity of light in free space:

$$\epsilon = \left(\frac{ct}{2L} \right)^2 \quad (11)$$

Fig. 1 shows schematically a time domain reflectometry system with a typical TDR output signal. The signal is analysed to obtain the transit time of the launched voltage pulse. Other aspects of the signal will be discussed later. For a typical electrode length of 30 cm, the transit time varies from about 4 ns for dry soils to about 10 ns for saturated soils.

Once an estimate for ϵ is obtained with eq. 11, the dielectric constant must still be correlated with the volumetric soil water content θ . An empirical relationship between ϵ and θ was obtained by Topp et al. (1980). Ansoult et al. (1985) recently developed a statistical model that also relates an apparent dielectric constant with the soil water content. The equation given by Topp et al. (1980) is:

$$\theta = (-530 + 292 \epsilon - 5.5 \epsilon^2 + 0.043 \epsilon^3) / 10000 \quad (12)$$

which was found to be nearly independent of soil texture, soil bulk density, temperature and soil salinity. The standard error of estimate was reported to be 1.3% for all soils considered in the study, and could be decreased to about 1% by calibrating for a specific soil. The TDR method thus obtained for measuring water contents compares favorably with conventional methods (Topp and Davis, 1985; Dasberg and Dalton, 1985) and does not involve the radiation hazard associated with the neutron probe. The method is also more adaptable to special applications, such as those involving undisturbed laboratory soil columns. Equally as important, the use of eq. 12 obviates the need for special calibrations.

TDR MEASUREMENTS OF SOIL ELECTRICAL CONDUCTIVITY

Fig. 2 shows schematically how a voltage pulse propagates along a parallel rod wave guide in both a conducting and a non-conducting medium. For an ideal non-conducting medium, the amplitude of the launched voltage pulse is

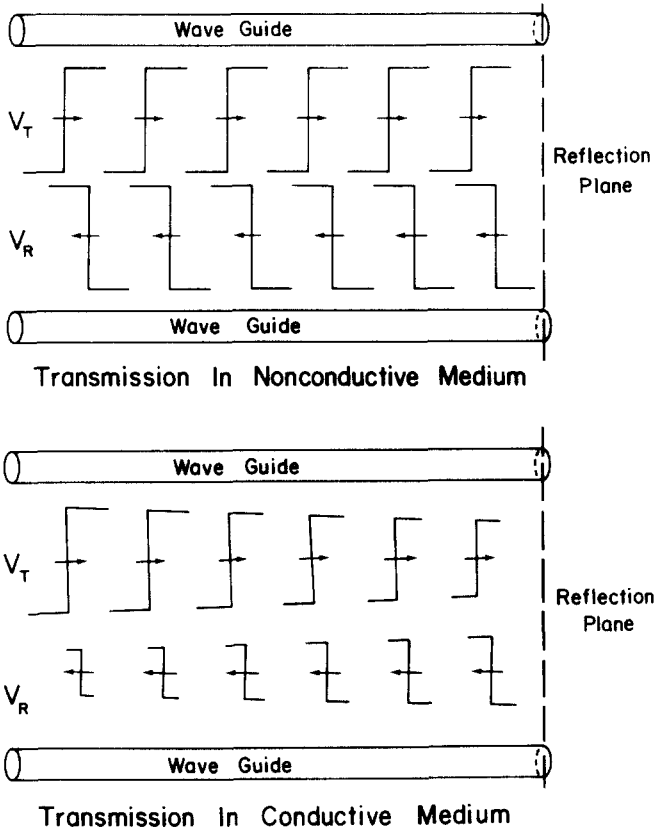


Fig. 2. Schematic representation of transmitted and reflected voltage pulses in non-conducting and conducting media.

equal to the reflected voltage pulse. For a conducting medium such as a saline soil, the launched voltage pulse is attenuated due to conduction losses into the medium. The amplitude of the reflected voltage pulse is thus diminished in proportion to the electrical conductivity. As is shown in Fig. 1, V_T will be used to designate the magnitude of the voltage pulse that enters the parallel-rod wave guide, while V_R designates the magnitude of the reflected pulse when it has returned to its source (Fellner-Feldegg, 1969). Fig. 1 also shows schematically the output voltage V_0 of the pulse generator.

Fig. 3 shows in a schematic fashion how the TDR signal output trace changes as the electrical conductivity σ of the medium increases. This dependency of the reflected signal amplitude on σ constitutes the key of the TDR method for measuring the soil electrical conductivity. Still needed is a method to relate the amplitude attenuation process to the electrical conductivity. This can be done in an approximate fashion by considering a lossy parallel transmission line as a distributed system of inductance L , capacitance C , resistance R and conductance G (Fig. 4). While details of the analysis are beyond the scope of this paper (for more information, see Ramo and Whinnery, 1959), two important results are obtained. Assuming perfect reflection at the end of the parallel rod transmission line, the reflected voltage returning to the source is given by:

$$V_R = V_T \exp(-2\alpha L) \quad (13)$$

where α is an attenuation coefficient. An approximate relation for α ap-

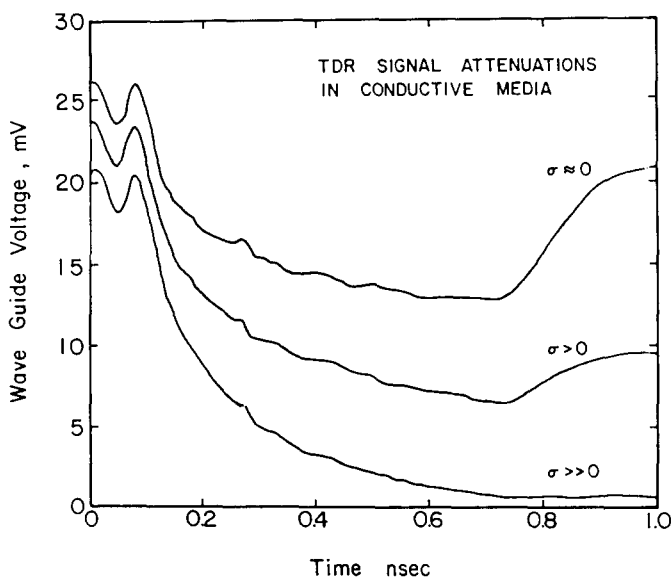


Fig. 3. TDR signal output from parallel rod electrodes in media of low, moderate and extreme electrical conductivities.

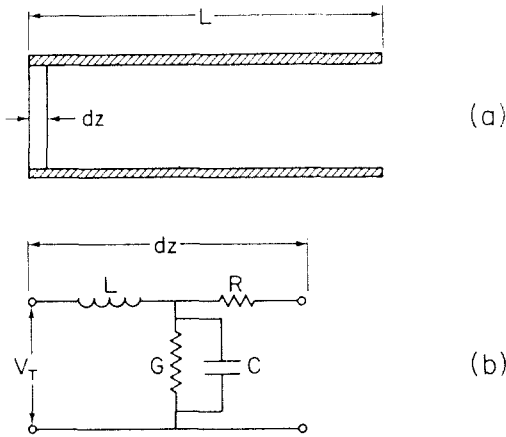


Fig. 4. (a) Parallel transmission line (PTL) of length L and (b) distributed inductance L , resistance R , shunting conductance G and capacitance C along a differential element of the PTL (from Dasberg and Dalton, 1985)

plicable to steady-state, sinusoidal input conditions and low loss lines is given by (Ramo and Whinnery, 1959):

$$\alpha = \frac{R \sqrt{C}}{2 \sqrt{L}} + \frac{G \sqrt{L}}{2 \sqrt{C}} \quad (14)$$

Expressions of L , C and G for parallel rod transmission lines are (Am. Inst. of Phys. Handbook, 1957):

$$L = \frac{\mu'}{\pi} \cosh^{-1}(s/d) \quad (15)$$

$$C = \frac{\pi \epsilon'}{\cosh^{-1}(s/d)} \quad (16)$$

and

$$G = \frac{\pi \sigma}{\cosh^{-1}(s/d)} \quad (17)$$

in which σ is the electrical conductivity of the medium (siemens/meter); μ' is the magnetic permeability of the medium, $\mu_0 \mu$, where μ_0 is the magnetic permeability of free space ($\mu_0 = 4\pi \times 10^{-7}$ henrys/meter) and μ is the relative magnetic permeability of the medium; ϵ' is the dielectric constant of the medium, $\epsilon_0 \epsilon$, where ϵ_0 is the dielectric constant of free space ($\epsilon_0 = 10^9/36\pi$ farads/meter) and ϵ the relative dielectric constant of the medium; s and d are the electrode separation and diameter, respectively (meter).

For soils low in magnetic materials, μ' equals 1. Substituting eqs. 15, 16

and 17 into 14 and assuming negligible skin resistance leads to:

$$\alpha = \frac{60\pi\sigma}{\sqrt{\epsilon}} \quad (18)$$

Finally, using eq. 13 in 18 gives the following equation for the electrical conductivity:

$$\sigma = \frac{\sqrt{\epsilon}}{120\pi} \ln(V_T/V_R) \quad (19)$$

Eq. 19 in conjunction with eqs. 9 and 10 forms the basis for simultaneously determining θ and σ from measured parameters t , V_T and V_R .

To study the effect of pore water electrical conductivity on the dielectric constant of a wet soil, Dalton et al. (1984) equilibrated ten columns to equal water contents using waters of different but known soil water electrical conductivities, σ_w . TDR measurements of t , V_T and V_R were made after equilibrating for 20 days. The average water content of each column was also measured gravimetrically. To obtain the average soil solution conductivity, solution extracts of subsamples were obtained by centrifuging. Values of σ_w were measured with a standard conductivity bridge.

Table I shows composite results of this experiment. During the equilibration period, some dissolution of residual salt occurred, which is reflected by an increase in measured σ_w at the end of the experiment. Values of σ_w ranged from 0.8 to 11.1 dS/m, whereas θ for the ten experiments was fairly constant at 0.34 ± 0.01 . The average value of ϵ was 19.48 ± 0.53 , which is in good agreement with the value 19.57 determined by Topp et al. (1980) on a number of soils, all at $\theta = 0.34$. Large variations in σ_w of the medium thus had little effect on θ . The data also showed a good linear relationship be-

TABLE 1

TDR measurements V_R/V_T , ϵ and σ in columns with known θ and σ_w

Exp. No.	Liquid phase conductivity (dS/m)		Reflected Transmitted V_R/V_T	Water content θ_v	Dielectric Bulk conductivity constant (dS/m)	
	initial σ_w	final σ_w			ϵ	σ
2	.19	.8	.54	.35	20.27	.30
4	1.32	1.7	.43	.33	18.72	.42
6	3.4	3.83	.26	.33	19.96	.66
8	5.2	5.6	.18	.35	19.15	.84
10	10.25	11.1	.06	.33	19.89	1.37
Mean	—	—	—	.34	19.48	—
St. dev.	—	—	—	.01	.53	—

tween the bulk soil electrical conductivity σ and the pore water electrical conductivity σ_w . This relationship is discussed next.

SALINITY MEASUREMENTS

The relationship between σ , σ_w and θ was investigated by Rhoades et al. (1976) in their development of the four-electrode probe measurement of σ . Their study led to the expression:

$$\sigma = \sigma_w \theta T(\theta) + \sigma_s \tag{20}$$

where σ_s is the solid phase electrical conductivity and T is a transmission coefficient that depends linearly on the water content:

$$T(\theta) = a\theta + b \tag{21}$$

where a and b are empirical constants. Eq. 20 views the equivalent circuit for the bulk soil electrical conductivity as two parallel conductors consisting of a liquid phase component σ_w and solid phase component σ_s . The transmission coefficient accounts for the tortuous current paths in the soil.

Values for the coefficients a and b in eq. 21 were available for a fine sandy loam similar to the soil used in the experiments described above. The following relation resulted:

$$T = 1.29 \theta - 0.116 \tag{23}$$

The value of the solid phase electrical conductivity σ_s was similarly measured to be 0.25 dS/m. Fig. 5 shows the relationship between bulk soil elec-

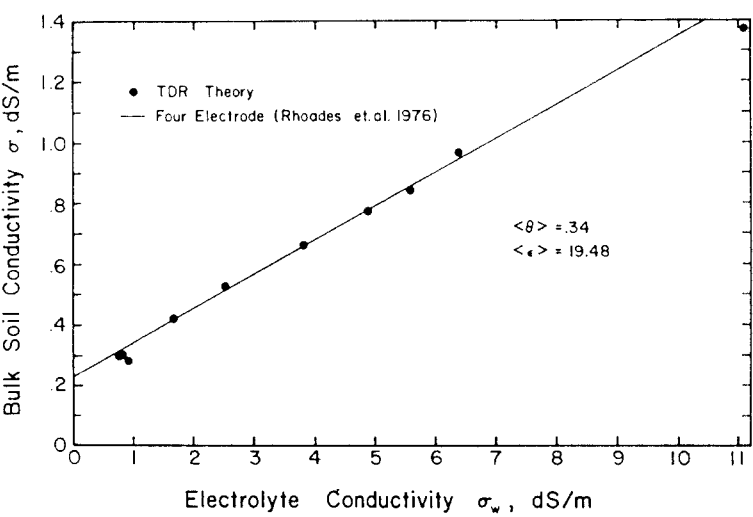


Fig. 5. The relation between bulk soil electrical conductivity and soil water electrical conductivity as determined by four-electrode measurements (eq. 10) and TDR measurements (data points).

trical conductivity and soil water electrical conductivity as determined by TDR on the ten columns (data points as in Table I). The solid line is given by eq. 18 and is based on independent four-probe measurements. The close agreement between the two measurement techniques demonstrates that TDR indeed can be used to obtain bulk medium electrical conductivities and volumetric water contents with a single probe. Moreover, the measurements are obtained on the same volume of soil. This is an important consideration, especially for aggregated and layered soils where large variations in θ and σ can occur over relatively small distances. Because the TDR probe measures spatially averaged values between the rods, vertical water and solute distributions can be monitored if the probes are placed horizontally at specified locations along the vertical. Alternatively, vertical installations with probes of various lengths can yield depth-averaged values. This ability to monitor simultaneously and in a near-continuous fashion water content and electrical conductivity distributions should make the TDR method an attractive tool for studies on ion transport in unsaturated soils.

FIELD MEASUREMENTS

Simultaneous measurements of volumetric water content and bulk soil electrical conductivity were made with time domain reflectometry using parallel rod electrodes embedded in the soil. A total of 60 units were installed at 5 depths in 12 existing lysimeter plots, irrigated with different amounts of water at two salt concentrations: 1.3 and 3.1 dS/m (Dasberg and Dalton, 1985). TDR water content measurements compared well with neutron measurements, and also showed a good correlation with gravimetric determinations ($r^2=0.84$). TDR measurements of σ were found to be in somewhat lesser agreement with measurements obtained with the four-probe technique. Results are shown in Fig. 6. The solid line represents the one-to-one relation that is expected when the two measurements are identical. We emphasize that Fig. 6 compares independent estimates of the same physical property based on completely different measurement principles. It is evident from the figure that further research is needed to determine which of the two techniques provides a better estimate of the bulk soil electrical conductivity. Carefully controlled laboratory measurements are currently being carried out to verify the accuracy of the simultaneous θ and σ measurements over a wide range of parameter values.

WATER CONTENT AND SALINITY CONSTRAINTS

As exemplified by one of the curves in Fig. 3 ($\sigma \gg 0$), the electrical conductivity of the medium can be so large that the launched voltage pulse becomes completely dissipated by conduction losses before it has returned to the source. No water content or electrical conductivity measurements are possible for such media. Because the power output of the pulse generator is

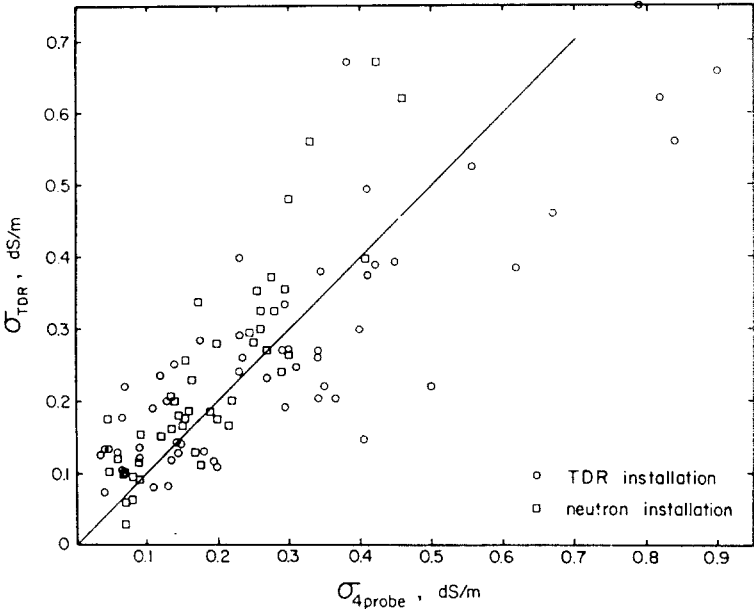


Fig. 6. Bulk soil electrical conductivity measured by TDR versus measurement with four-electrode probe and 1:1 line (from Dasberg and Dalton, 1985).

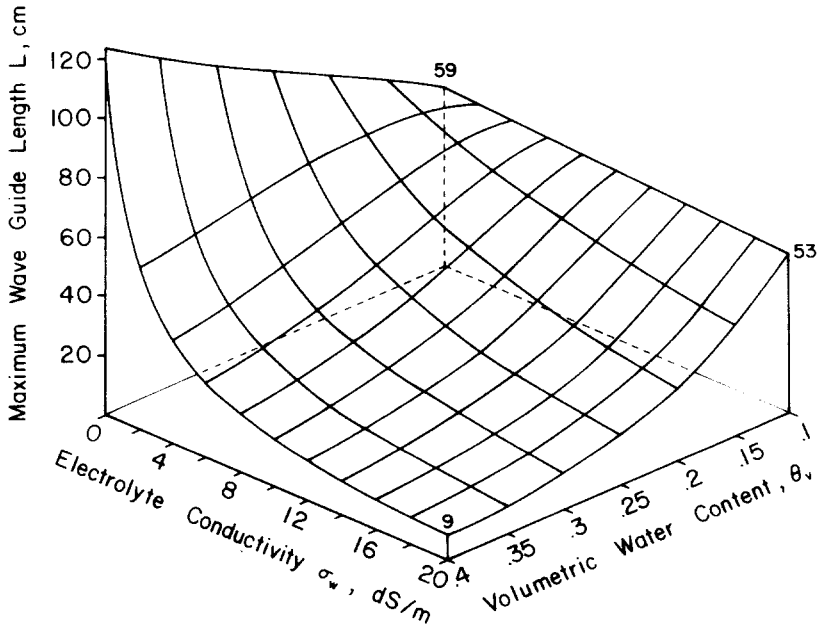


Fig. 7. Maximum parallel rod length as a function of soil water content and soil water electrical conductivity.

fixed, the only remedy for this condition is a reduction of the path length for the launched voltage pulse. This can be accomplished by changing the length of the parallel rod TDR probe. A useful estimate of the maximum electrode length for a soil with given water content and electrical conductivity can be deduced from eq. 19. Solving that equation for the maximum electrode length $L=L_{\max}$ yields:

$$L_{\max} = \frac{\ln(V_T/V_R)\sqrt{\epsilon(\theta)}}{120\pi\sigma(\theta, \sigma_w)} \quad (24)$$

where the relation $\epsilon=\epsilon(\theta)$ follows from eq. 12, while $\sigma=\sigma(\theta, \sigma_w)$ follows from eq. 20. Fig. 7 shows a plot of $L_{\max}$ as a function of θ and σ_w , using as a criterion that the reflected voltage be at least 10% of the transmitted voltage ($V_R/V_T=0.1$). It is evident that the maximum length of the parallel rod electrodes depends significantly on the water content and electrical conductivity. The practical lower limit for water measurements is about 10 cm. Hence, TDR measurements of θ and/or σ are possible in all but the most saline, saturated soils.

SUMMARY AND CONCLUSIONS

This paper gives a comprehensive discussion of the physical principles that form the basis of the time-domain reflectometry method for simultaneously measuring water content and bulk soil electrical conductivity. The description of ion transport in unsaturated soils often requires numerous in-situ measurements of both water content and ionic concentrations. TDR methods are well suited for such situations; they allow measurements to be made quickly and simultaneously using a single and relatively inexpensive sensing probe. Because sampling volumes for the two measurements are identical, the simultaneous measurement seems especially attractive for spatial variability studies involving heterogeneous soils. TDR techniques also have great potential for obtaining non-destructive, in-situ measurements of the soil solution concentration during variably unsaturated flow. This ability may prove to be very useful for purposes of calibration and verification of theoretical flow and transport models.

REFERENCES

- American Institute of Physics Handbook, 2nd ed., 1957. D. Gray (Editor), McGraw-Hill Book Co., New York, NY, pp. 48—49.
- Ansault, M., De Backer, L.W. and Declercq, M., 1985. Statistical relationship between apparent dielectric constant and water content in porous media. *Soil Sci. Soc. Am. J.*, 49: 47—50.
- Dalton, F.N., Herkelrath, W.N., Rawlins, D.S. and Rhoades, J.D., 1984. Time-domain reflectometry: Simultaneous measurement of soil water content and electrical conductivity with a single probe. *Science*, 224: 989—990.

- Dasberg, S. and Dalton, F.N., 1985. Field measurement of soil water content and bulk electrical conductivity with time-domain reflectometry. *Soil Sci. Soc. Am. J.*, 49: 293–297.
- Fellner-Feldegg, H., 1969. The measurement of dielectrics in the time domain. *J. Phys. Chem.*, 73: 616–623.
- Kittel, C., 1960. *Introduction to Solid State Physics*, 3rd ed. Wiley, New York, N.Y.
- Oster, J.D. and Ingvalson, R.D., 1967. In situ measurement of soil salinity with a sensor. *Soil Sci. Soc. Am. Proc.*, 31: 572–574.
- Ramo, S. and Whinnery, J.R., 1959. *Fields and Waves in Modern Radio*. Wiley, New York, N.Y.
- Rhoades, J.D. and van Schilfgaarde, J., 1976. An electrical conductivity probe for determining soil salinity. *Soil Sci. Soc. Am. J.*, 40: 647–651.
- Rhoades, J.D., Raats, P.A.C. and Prather, R.J., 1976. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. *Soil Sci. Soc. Am. J.*, 40: 651–655.
- Richards, L.A., 1966. A soil salinity sensor of improved design. *Soil Sci. Soc. Am. Proc.*, 30: 333–337.
- Topp, G.C. and Davis, J.L., 1985. Measurement of soil water content using time-domain reflectometry. *Soil Sci. Soc. Am. J.*, 49: 19–24.
- Topp, G.C., Davis, J.L. and Annan, A.P., 1980. Electromagnetic determination of soil water content: Measurement in coaxial transmission lines. *Water Resour. Res.*, 16: 579–582.
- von Hippel, A., 1953. Dielectrics. In: Candon and Odishaw (Editors), *Handbook of Physics*. McGraw-Hill, New York, N.Y.