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Practical Aspects of TDR for Simultaneous Measurements of Water and Solute in a Dune Sand Field

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Abstract

Simultaneous measurement of volumetric soil water content (θw) and soil solution electrical conductivity (ECw) was made for dune sand soil using Time Domain Reflectometry (TDR). The best relationship between TDR dielectric constant (Ka) and θw, and that for bulk soil electrical conductivity (ECb) and ECw were defined for dune sand soil and assessed in a dune sand field. The salinity of soil solution showed no effect on Ka and consequent θw. The commonly used linear relation between TDR transmission coefficient (T) and θw was inaccurate for dune sand soil when θw was in the range of soil water holding capacity. A polynomial equation was suggested for expressing the relation between T and θw, with less variation than a power relation. Based on field assessment, there was a better agreement between θw recorded by TDR and that from soil sampling than a similar relation for ECw. The relative error (RE) between TDR measured and soil sampling was 4.97% and 10.67% for θw and ECw, respectively.

Key words : TDR, Dune sand soil, Soil water content, Soil solution electrical conductivity

1. Introduction

Simultaneously and non-destructively measuring soil water content (θw) and soil solution electrical conductivity (ECw) can be a useful approach at critical stages of crop growth in fields under irrigation with saline water. The conventional method for measuring soil salinity is by taking soil samples and determining the electrical conductivity of the extract of a saturated soil paste (Rhoades, 1982). These measurements can be converted into the soil solution salt concentration by correcting for the soil water content at the time of sampling. The soil solution can be sampled directly by porous suction cups. This method, however, is limited to a narrow range of soil moisture between (approximately) field capacity and saturation and the small sample volume tends to make the measurement variable (Broadbent, 1981). Soil water content can be measured by destructive sampling and gravimetric determination or by the in situ neutron scattering method (Graecen, 1981). The two main limitations of the neutron method are its relatively large sampling and the radiation hazard involved. The fact that θw and ECw are usually obtained from separate samples with different geometry would introduce an additional error in soil salinity assessment due to changes associated with spatial and temporal variations in θw and ECw of soil samples (Dasberg and Dalton, 1985) ; besides continues measurement is not possible.

The development of Time Domain Reflectometry (TDR) as a method for automated in-situ measurement of bulk soil electrical conductivity (ECb) offers the promise of improved temporal resolution in tackling solute movement. During the last two decades, TDR method has become an established method to measure both θw (Topp *et al.* 1982) and ECb as a nondestructive technique (Dalton *et al.*, 1984 ; Nadler *et al.*, 1991 ; Dalton, 1992). The TDR principle is based on launching a spectrum of electromagnetic waves into a waveguide (TDR probe) embedded in the soil under investigation and measuring the reflected signal as a function of time.

The travel time of the waves in the waveguide is proportional to the θw and the attenuation can be related to *ECb*. Topp *et al.* (1980) showed a unique equation between the apparent dielectric constant (*Ka*) and θw of measured soil for a large range of soil structures from clay to sandy loam, which is applied globally to calculate θw from *Ka* (Drungil *et al.*, 1989 ; Grantz *et al.,* 1990 ; Pepin *et al.*, 1992). However, there are some potential sources of error that have received attention : (i) low density soil (Dirksen and Dasberg, 1993 ; Weitz *et al.*, 1997), (ii) clay and organic soils which caused a sharper-than-average curvature of *Ka*-θw rela tions (Brisco *et al.*, 1992 ; Dasberg and Hopmans, 1992 ; Roth *et al.*, 1992 ; Weitz *et al.*, 1997 ; Nadler *et al.*, 1999), and (iii) temperature whose effect on TDR-measured *Ka* is related to the soil texture and water content. According to Pepin *et al.* (1995), the temperature effect on TDR-measured *Ka* is large in a wetter and finer textural soil. They speculated that a larger temperature effect on wetter and finer-textured soils dominated by free water might be attributed to bound water, which had a smaller temperature dependency for *Ka* than free water. The temperature effect on TDR-measured *Ka* for different textural soils was investigated experimentally and theoretically by Or and Wraith (1999). They concluded that the amount of bound water restricted, depending on clay minerals, on soil particles was attributed to the temperature effect.

On the basis of TDR measurement in soils wetted with solutions of a given salt concentration there are conflicting reports on the effect of salinity on the *Ka* and on θw. Some studies suggest that elevated salinity of the soil solution can cause over-estimation of *Ka*, resulting in an over-estimation of θw (Dalton, 1992 ; Noborio *et al.*, 1994 ; Wyseure *et al.*, 1997), while others show no effect (Mallants *et al.*, 1996 ; Dalton and van Genuchten, 1986 ; Timlin and Pachesky, 1996) and some show both under- and over-estimation (Borner *et al.*, 1996 ; Bridge *et al.*, 1996 ; Gregory *et al.*, 1995). Salinity affects TDR functionality in measuring θw by increasing the attenuation of the TDR signal, reducing its accuracy and eventually leading to its disappearance (Nadler *et al.*, 1999). From these results, there is need to explore how to measure θw and *ECw* simultaneously. Moreover, in some exceptional conditions TDR method is constrained by uncertainty about its accuracy and their applicability (Kachanoski *et al.*, 1992). Dune sand soil, where the soil water-holding capacity is 0.03–0.08 $cm^3\ cm^{-3}$ and even a small error (0.01 $cm^3\ cm^{-3}$ error≅20% of soil water holding capacity) is very critical for crops life could be such exception.

Some probes can measure θw and *ECw* from soil samples with different geometry. Inoue and Shiozawa (1994) calibrated a four-electrode probe and tensiometer in dune sand soil for measuring θw and *ECw* simultaneously. They found a relative error (RE) of 2.4% and 5.6% for θw and *ECw* respectively. However, they used two different probes for measuring θw and *ECw* simultaneously, which were not set up in the same sampling area. As a result, hand made TDR probes were developed to measure θw, *ECb* and temperature simultaneously from a soil sample for a given interval of time.

The objectives of this study were (i) to determine *Ka*-θw relationships and the best model for the estimation of *ECw* from *ECb* in dune sand soil and (ii) to assess some aspects of TDR method for the estimation *ECw* and θw in a dune sand field.

2. Theory

2.1 Relation between *Ka* and θw

The travel time for a pulsed electromagnetic signal along a TDR probe is dependent on the velocity of the signal and the length of the wave-guide. The velocity is dependent on *Ka* of the material surrounding the wave-guide. This relation can be expressed by the following equation (Topp *et al.,* 1980) :

$$\sqrt{Ka} = \frac{La}{L} = \frac{c\,\Delta t}{2L} \tag{1}$$

where *La* (m) is apparent probe length, *L* (m) is the wave-guide length, and *c* (m s^{-1}) is the velocity of the electromagnetic signals in free space. The dielectric constant of water relative to other soil constituents is high. Consequently, changes in soil water content (θw) are directly related to the change in the *Ka* of bulk soil material, $\theta w = f\,(Ka)$ (Topp *et al.,* 1980).

2.2 Relation between *ECw* and *ECb*

While the velocity of the applied pulse along a waveguide is dependent on the dielectric constant of the material surrounding the waveguide, the amplitude of the reflected voltage is dependent on electrical conduction of the applied signal between probe rods. The presence of free ions in the soil solution will result in attenuation of the applied signal. The TDR100 (Campbell Scientific) was used in this study for measuring both *Ka* and *ECb*. The theory of Giese and Tiemann (1975) has been applied to the measurement of soil bulk electrical conductivity in TDR100. A commonly used expression is :

$$ECb = \frac{Kp}{Zc}\frac{1-\rho}{1+\rho} \tag{2}$$

where *Kp* is a probe constant, *Zc* is the cable impedance, and ρ is the reflection coefficient. The reflection coefficient is the ratio of the reflected voltage to the applied voltage and ranges between plus and minus one.

A two-pathway model (Rhoades *et al.,* 1976) was used in this study to find the relation between *ECw* and *ECb*. In a two-pathway model, electrical conduction is assumed to take place along two parallel conducting paths. The predominant path is through the soil solution, *ECw,* also known as pore water electrical conductivity. The contribution of the solid fraction, *ECs*, takes place along the continuous films of exchangeable cations residing on the surface of the solid particles. According to this model, *ECb* at constant θw is linearly related to *ECw* :

$$ECb = ECs + T\theta wECw \tag{3}$$

where *T* is a transmission coefficient. The *T* can be expressed as a function of θw by a linear (Rhoades *et al.*, 1976) or power (Amente *et al.*, 2000) curve and the empirical constant of linear ($a\ \theta w + b$) or power ($a\theta w^b$) can be estimated by fitting *ECb* against θw measured under constant *ECw*. This technique of keeping *ECw* constant is used in the determination of the two constants, *a* and *b*. Under field conditions, however, *ECw* is rarely constant because of changes in θw due to evaporation, drainage or infiltration. Although originally Rhoades *et al.* (1976) reported that *ECs* was essentially independent of water content, their later model showed a dependency of the *ECs* on the θw (Rhoades *et al.*, 1989). As a result, the relation between *ECb* and *ECw* is function of θw, for a defined *T* and *ECs* as a function of θw.

3. Materials and Methods

The experiments were conducted at the Arid Land Research Center (ALRC), Tottori University, Japan (35°32′N, 134°13′E). The relations between θw and *Ka*, and between *ECw* and *ECb* in dune sand soil collected from ALRC field was evaluated and quantified in a controlled temperature environment (25℃) using TDR probes. Soil water characteristics curve for the dune sand soil is shown in Fig. 1 and the physical properties are given in Table 1.

The 36 TDR probes (Fig. 2) used as a waveguide, were each connected to the Campbell Co. TDR100 and SDMX50 multiplexers by 11-meter Fujikura RG-58A cable. The handmade TDR probes used in this study were designed with similar structure as the ThetaProbe (Gaskin and Miller, 1996). It included 4 rods, 3 of which performed as shield rods and one (central rode) as signal rod (Fig. 2). The calibration processes were examined on dune sand soil columns, with 8 levels of θw (0.031, 0.063, 0.094, 0.123, 0.149, 0.232, 0.291, and 0.363 $cm^3\ cm^{-3}$) and 8 levels of

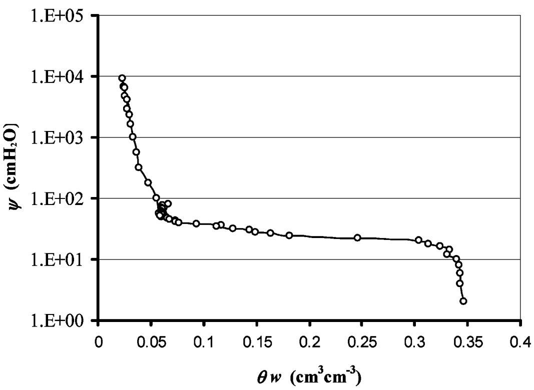

Fig. 1 Relationship between matric-potential (Ψ) and soil water content (θ_w) in dune soil.

Table 1 The physical properties of dune sand soil

Factors	Values
Sand (%)	96.1
Silt (%)	0.4
Clay (%)	3.5
Specific gravity (%)	2.66
Apparent specific gravity (%)	1.56
Field capacity, FC ($cm^3\ cm^{-3}$)	0.074
Initial wilting point, IWP ($cm^3\ cm^{-3}$)	0.025
Permanent wilting point, PWP ($cm^3\ cm^{-3}$)	0.022
Saturated soil moisture content ($cm^3\ cm^{-3}$)	0.413

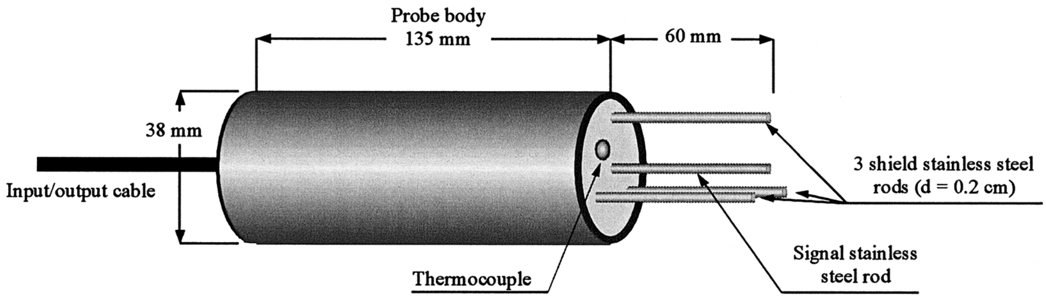

Fig. 2 Structure diagram of handmade soil-TDR probe.

NaCL (*ECw*) concentration (0.0, 0.62, 1.22, 1.99, 2.56, 3.10, 3.83 and 5.64 dS m^{-1}), in a total of 64 soil column samples. Each column with 20 cm ×25 cm (diameter×height) dimension was packed with oven-dried soil mixed with the above NaCl solutions.

The TDR probes were installed in vertical direction, individually, in each soil column (64 soil column samples. The gravimetric water content was determined by oven drying 3 soil samples taken from each column and θw was calculated using the known bulk density of the soil (1.56 Mg m^{-3}). The *ECw* of the soil samples was determined based on the conductivity of 1 : 5 extracts (Richards, 1954) of oven-dried soil : distilled water. Each soil column sample was shaken and repacked with known bulk density after measuring θw and *ECw* by 6 of TDR probes to minimize the error due to movement of solution during the measurement. The soil column sample was always covered and only opened shortly during the measurement to prevent evaporation.

The relation between θw and *Ka* was defined and statistically compared with Topp *et al.* model (1980) using the root mean square error (RMSE) and regression analyses. The following equation was used for the computation of the RMSE :

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}} \tag{6}$$

where ; d_i is the difference between ith predicted by model and ith measured values and n is number of the data pairs.

The models defined for the relationship between *ECw* and *ECb* were compared using the relative errors of measuring soil solution electrical conductivity (*ECw*/ECw*). Where *ECw** is soil solution electrical conductivity with a measurement error of $\delta = \pm 0.01\,cm^3\ cm^{-3}$ ($\theta w^* = \theta w \pm \delta$) and *ECw* is the actual soil solution electrical conductivity.

Finally, the relationship between θw and *Ka*, and between *ECw* and *ECb* in dune sand soil was assessed using field data. The soil samples for the field data were collected at the end of a field study on water and solute movement under drip irrigation system using TDR, where all the 36 TDR probes were buried in the field of ALRC for 3 months (DehghaniSanij *et al.*, 2003). The *Ka* and *ECb* were recorded for each TDR probe (θ_{TDR} and EC_{TDR}). At about the same time soil samples were collected from the each TDR probe geometry to determine θw and *ECw* in the laboratory (θ_{ref} and EC_{ref}).

Relative error statistical analyses were used to compare θw and *ECw* measured by TDR method (θ_{TDR} and EC_{TDR}) with the results of soil sampling θ_{ref} and EC_{ref} determined by conventional methods as follows :

$$RE = \frac{\sum_{i=1}^{n} |X_i - Y_i|/n}{\overline{X}} \times 100 \qquad (7)$$

where ; *RE* is relative error (%), *i* is number of samples ($i = 1, \cdots, n$), *n* is total number of samples, *X* is θ_{ref} or EC_{ref}, *Y* is θ_{TDR} or EC_{TDR} and $\overline{X}$ is average of θ_{ref} or EC_{ref}.

4. Results and Discussion

4.1 Water content measurement

The relationship between *Ka* measured with TDR and the θw obtained by gravimetric method for all soil column samples was found by making a polynomial plot between *Ka* and θw (Fig. 3). The relationship as given by Topp *et al.* (1980) for different soil materials is also shown. The regression equation for the relationship between *Ka* and θw obtained from our data (Fig. 3) showed less *RMSE* than that reported by Topp *et al.* (1980) (Table 2). Obviously, Topp's model predicted soil water content $\cong 0.02\,cm^3\ cm^{-3}$ less for dune sand soil in the area between field capacity (FC) and near saturation condition (Fig. 3). However, between field capacity (FC) and initial wilting point (IWP) when $\theta w = 0.03$–$0.08\,cm^3\ cm^{-3}$, the results of Topp *et al.* (1980) model are very similar to that from gravimetric determination (Fig. 3). Fig. 3 shows the scattering of data when $\theta w \geq 0.10\,cm^3\ cm^{-3}$, which can be attributed to solution movement in the soil column samples during the experiments. Statistically the difference between results of calibration equation and Topp model was not significant ($P < 0.05$). This result is in agreement with the results of Dalton and van Genuchten (1986) and Mallants *et al.* (1996) for a sandy loam soil with θw in the range of 0.12–$0.40\,cm^3\ cm^{-3}$, and

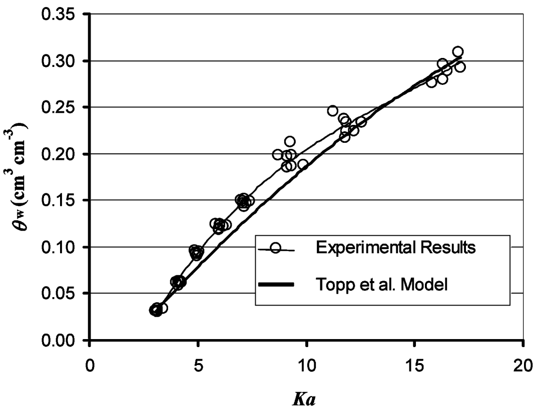

Fig. 3 Relation between dielectric constant (*Ka*) and soil water content (θ_w) in dune soil.

Table 2 Regression coefficients (R^2) and root mean square error (RMSE) for the relationship between dielectric constant (*Ka*) and soil water content (θw) using equation $\theta w = a\,Ka^3 + b\,Ka^2 + c\,Ka + d$ and Topp model

Experiment	*n*	*a*	*b*	*c*	*d*	R^2	RMSE
Topp *et al.* (1980)		0.43×10^{-5}	−0.00055	0.0292	−0.0530		0.016
Experimental data	56	7×10^{-5}	−0.0031	0.0558	−0.1168	0.992	0.009

Timlin and Pachesky (1996) for loamy sand and silty clay soils with θw in the range of 0.08–0.43 $cm^3\ cm^{-3}$. From the soil texture and range of θw in our study (Fig. 3) and the results of other researchers, salinity of soil solution showed no effect on Ka and consequent θw in a wide range of soil water content (0.03–0.43 $cm^3\ cm^{-3}$) and soil texture (sand to silty clay).

4.2 Soil solution electrical conductivity measurements

To use the TDR method (Eq. 5), the T and ECs must be defined for any individual soil. Theoretically, the interception of curves of ECb and θw give ECs (Eq. 5). However, arbitrarily selecting water content values and evaluating ECb corresponding with different ECw at the same θw can make better estimation of both T and ECs (Mallants *et al.*, 1996).

According to Eq. (5), the ratio of $(ECb-ECs)/ECw$ is equal to $T\theta w$ which is plotted vs. θw in

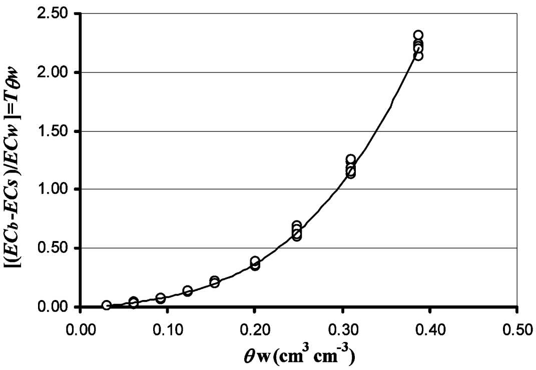

Fig. 4 Relation between (bulk soil electrical conductivity (EC_b)– apparent electrical conductivity (ECs)/soil solution electrical conductivity (ECw)) vs. soil water content (θ_w), in dune soil.

Table 3 Transmission coefficient (T) of dune soil expressed as linear, polynomial and power function of soil water content, θw ($cm^3\ cm^{-3}$)

Expression	a	b	c	R^2
$T=a\ \theta w+b$	18.242	−1.5647		0.991
$T=a\ \theta w^2+b\ \theta w+c$	37.15	−1.3116	0.6099	0.999
$T=a\ \theta w^b$	11.591	2.0709		0.986

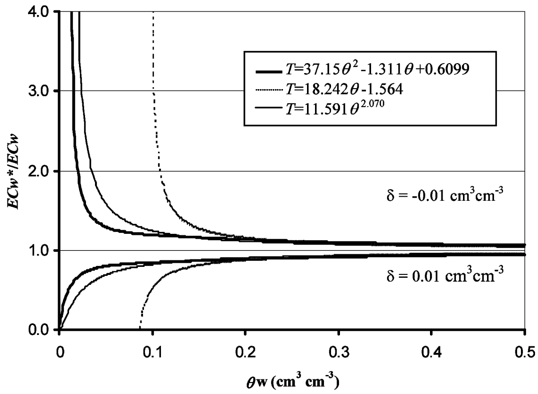

Fig. 5 Variation in ratio of soil electrical conductivity with measurement error of $\delta=\pm 0.01\ cm^3\ cm^{-3}$ (ECw^*) and actual soil electrical conductivity (ECw) with soil volumetric water content (θ_w).

Fig. 4. T can be related to θw using a linear (Rhoades *et al.*, 1976), polynomial and power relation with relatively high correlation (Table 3). The polynomial relation showed higher correlation ($R^2=0.999$). The relative errors of measuring soil solution electrical conductivity (ECw^*/ECw) were determined for each correlation equation in Table 3 to reduce the variation in measuring ECw. The variation in ECw^*/ECw with θw for a $\delta=\pm 0.01\ cm^3\ cm^{-3}$ are illustrated in Fig. 5. The ratio of ECw^*/ECw is >1.0 when $\delta=-0.01$ and vise versa. The commonly used linear relation between T and θw, suggested by Rhoades *et al.* (1976), is inaccurate for dune sand soil when θw is in dune sand soil water holding capacity and the polynomial relation showed less variation than the power relationship (Fig. 5). Consequently, we suggest a polynomial relation between T and θw for dune sand soil as used in this study.

4.3 Soil water content and soil salinity measurements

The relationship between gravimetric determinations of soil water content from the experimental field (θ_{ref}) compared to values measured by TDR (θ_{TDR}) and those calculated with Topp *et al.* (1980) model (θ_{Topp}) is presented in Fig. 6. The correlation between $\theta_{ref}-\theta_{TDR}$ and $\theta_{ref}-\theta_{Topp}$ was almost same (0.950 and 0.945 respec-

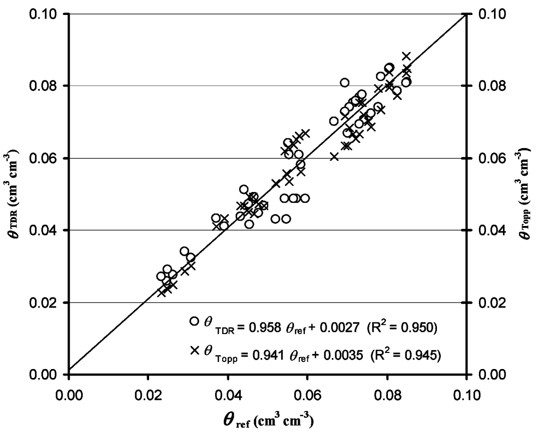

Fig. 6 Relation between volumetric soil water content measured by TDR (θ_{TDR}) and that calculated by Topp *et al.* (1980) model (θ_{Topp}) vs. gravimetric determination (θ_{ref}).

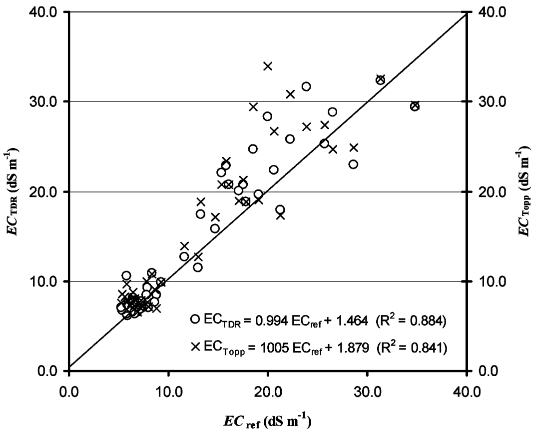

Fig. 7 Relation between soil solution electrical conductivity measured by TDR (EC_{TDR}) and that calculated by Topp *et al.* model (EC_{Topp}) vs. soil sampling determination (EC_{ref}).

tively). The good agreement between $\theta_{ref}-\theta_{TDR}$ and $\theta_{ref}-\theta_{Topp}$ where θ_{TDR} and θ_{Topp} was calculated using different calibration equation can be contributed to applicability of Topp model for measuring θw in dune sand soil when $0.02<\theta w<0.01$ cm^3 cm^{-3}, same results was concluded earlier. The result of relative error (*RE*) statistical analysis was 4.97% between θ_{ref} and θ_{TDR}. These results show that the TDR method is reliable and can be used for measuring θw in dune sand field. Dasberg and Dalton (1985), and Nadler *et al.* (1991) presented a relatively high correlation between TDR and gravimetric determination in sandy loam soil ($R^2=0.842$) and silty loam soil ($R^2=0.982$) respectively.

The data for soil solution electrical conductivity measured by soil sampling from the experimental field (EC_{ref}) and that measured by TDR (EC_{TDR}), and calculated with substitution of Topp *et al.* (1980) model in Eq. 5 (EC_{Topp}) are presented in Fig. 7. The percentage of *RE* for EC_{TDR} was about 10.67%, which was higher than that for θ_{TDR}. The percentage of *RE* was higher than that reported by Inoue and Shiozawa (1994), possibly due to (i) the soil used in their study was washed dune sand soil, where the percentage of clay was almost zero, (ii) they used different type of probes for measuring θw and ECw in soil samples with different geometry.

The correlation between $EC_{ref}-EC_{TDR}$ was higher than between $EC_{ref}-EC_{Topp}$ (Fig. 7). This can be ascribed to less estimation of θw by Topp et al (1980) model when $\theta_{ref}\geq 0.08$ cm^3 cm^{-3}. Regardless of the high correlation between the EC_{TDR} and EC_{ref} (Fig. 7), many points are not close to the 1 : 1 line. There was a low scattering for both TDR data and data estimated from Topp *et al.* (1980) model when EC_{ref} was low and vice versa, which can lead to less accuracy of TDR method under high salinity. Similar results were reported by Dasberg and Dalton (1985) for a sandy loam soil with less scattering of the data, and for a silty loam soil (Nadler *et al.*, 1991) with much less scattering.

Since the main effective factor on soil electrical conductivity is soil water content values, variation of EC_{TDR} and θ_{TDR} simultaneously plotted in Fig. 8. There was a relatively high negative agreement between changes in θ_{TDR} and EC_{TDR} (Fig. 8). However, the scattering of the data was high when θ_{TDR} was low. From these results we conclude that the accuracy of

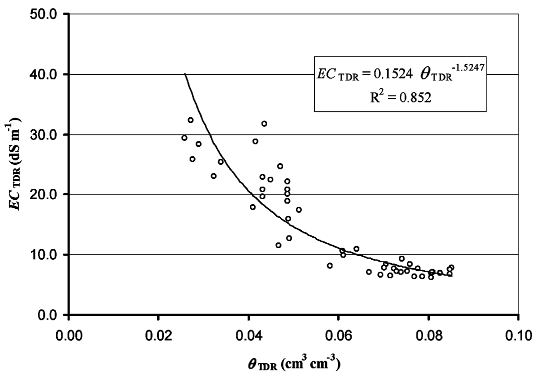

Fig. 8 Simultaneous variation in soil solution electrical conductivity (EC_{TDR}) and volumetric soil water content (θ_{TDR}) for dune sand field.

EC_{TDR} values is low when $\theta w \leq 0.03$ cm^3 cm^{-3} and high when $0.05 \leq \theta w \leq 0.08$ cm^3 cm^{-3}. We confirm the reliability and accuracy of TDR in a dune sand field when the irrigation intensity is high or soil water content is near field capacity.

5. Conclusion

The TDR method was tested for measuring θw and ECw simultaneously in a dune sand soil. The preliminary conclusion reached by Dalton *et al.* (1984) that "TDR, in conjunction with known relations between relative electrical conductivity and soil water conductivity, provides a new and powerful tool in soil water research in that a measurement can yield both θw and ECw" has been confirmed by the data presented in this paper for dune sand soil. The volumetric soil water contents were found to be accurately determined by the TDR method for dune sand soil, except in the case of very dry ($\theta w < 0.03$ cm^3 cm^{-3}) or very wet ($\theta w \geq 0.10$ cm^3 cm^{-3}) dune sand soil. This may be attributed to (i) the difficulty in interpreting the TDR in dune sand soil where the water holding capacity is low and not related to the basic principles of TDR technique and (ii) high spatial variability of θw in dune sand soil under very wet condition. The commonly used linear relation between T and θw was inaccurate for dune sand soil when θw was in water holding capacity range. From our field assessment, the *RE* for measuring ECw using TDR was relatively higher than that for θw. The accuracy of TDR was less when ECw was high or θw was low (<0.03 cm^3 cm^{-3}). Practically, the TDR can be used in a dune sand field for recording ECw and θw, when θw ranges between FC and IWP.

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水分塩分同時測定に関する砂丘畑への TDR の実用評価

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要　　旨

砂丘砂に対して，TDR センサーを用いて体積含水率（θw）と土壌溶液の電気伝導度（ECw）との同時測定を行い，TDR の誘電率（Ka）と θw の関係，ならびに土壌の電気伝導度（ECb）と ECw の関係を決定し，それらの関係を砂丘畑で評価した。土壌溶液の塩類濃度は Ka に影響を与えなかった。結果として，θw にも影響を与えなかった。θw が有効水分の範囲では，よく採用される TDR の伝達係数（T）と θw との直線関係では精度が低く，多項式が指数関数よりも適合度が高かった。圃場における採土データで測定精度を評価した結果，TDR センサーで測定した ECw と土壌サンプリングによる ECw との関係よりも，TDR センサーで測定した θw と土壌サンプリングによる θw との関係がよく一致した。TDR センサーによる推定値と採土データとの相対誤差（RE）は，θw と ECw に関して，それぞれ，4.97%，10.67% であった。

キーワード : TDR，砂丘砂，体積含水率，土壌溶液の電気伝導度

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