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Evaluation of the WET sensor compared to time domain reflectometry

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Abstract This paper concentrates on the experimental calibration of a rapid, non-destructive sensor to investigate the salinization process by measuring the dielectric properties of the soil to estimate both the soil water content (θ) and pore water electrical conductivity (σ_p) for different soil types. The proposed sensor depends on the frequency domain reflectometry (FDR) technique and is called the WET sensor. It estimates the dielectric permittivity (K_a) and bulk electrical conductivity (σ_a) of soil. Then, it utilizes both of them to estimate θ and σ_p. The new sensor is compared to time domain reflectometry (TDR) measurements. Time domain reflectometry is a well established technique for K_a and σ_a measurements in soils. The study involves experimental measurements in the laboratory using five different soil types and a range of θ values. In each soil type, three different electrical conductivity solutions (σ_w) were used. The results revealed that the calibration coefficients of water content and the soil parameter are significantly dependent on the soil type and slightly affected by electrical conductivity of the moistening solution.

Key words calibration; frequency domain reflectometry (FDR); soil salinity; time domain reflectometry (TDR); WET sensor

Evaluation de la sonde WET par comparaison avec la réflectométrie en domaine temporel

Résume Cet article s'intéresse au calage expérimental d'un capteur rapide et non-destructif, dans le cadre de l'étude du processus de salinisation, qui s'appuie sur la mesure des propriétés diélectriques du sol pour estimer la teneur en eau volumique (θ) et la conductivité électrique de la solution du sol (σ_p) de différents types de sol. Le capteur proposé relève de la technique de la réflectométrie en domaine fréquentiel (FDR) et est appelé sonde WET. Il estime la constante diélectrique (K_a) et la conductivité électrique apparente (σ_a) du sol et en déduit l'estimation de θ et de σ_p. Les mesures du nouveau capteur sont comparées à des mesures par réflectométrie en domaine temporel (TDR). La TDR est une technique bien établie pour la mesure de K_a et de σ_a dans les sols. Cette étude a nécessité des mesures expérimentales au laboratoire avec cinq types de sol et une gamme de valeurs de θ. Pour chaque type de sol, trois valeurs différentes de la conductivité électrique de la solution du sol (σ_w) ont été utilisées. Les résultats obtenus révèlent que les coefficients de calage de la teneur en eau et le paramètre du sol sont significativement dépendants du type de sol et peu sensibles a la conductivité électrique de la solution du sol.

Mots clefs calage; réflectométrie dans le domaine fréquentiel (FDR); salinité du sol; réflectométrie en domaine temporel (TDR); sonde WET

INTRODUCTION

Soil water is essential for plant growth and is a vehicle for solute transport, including nutrients and soil contaminants. Accurate measurement of water content and solute concentrations are crucial for the better management of irrigation water. The technique of measurement should be accurate, rapid, reliable, simple and non-destructive.

The common direct method for water content (θ) and salinity measurement is soil sampling. The water content can be determined by oven drying, while the soil extract method is used for salinity measurements. This method is not practical when many samples are needed. Furthermore, it is destructive, as only a single measurement can be made for a sample soil volume.

Great effort has been devoted in the last decades to the development of new and more accurate methods of measuring water content (θ) and salinity. Time domain reflectometry (TDR) is an indirect method for determining θ. The method involves measuring the propagation velocity of an electromagnetic pulse travelling along a parallel metallic probe embedded in the soil. The propagation velocity is expressed as the dielectric constant (K_a). This measurement is converted to θ values by various calibration equations (Topp *et al*., 1980; Dalton *et al*., 1984). There are several advantages associated with the TDR technique: it is an accurate instrument and it can easily be automated to take scheduled readings. Some important disadvantages are: water content measurements cannot be made in highly saline soils and the initial costs are relatively high compared with other methods.

Frequency domain reflectometry (FDR) sensors have also been developed for continuous measurement of θ. This system uses the dielectric properties of water in a different approach from that of TDR. The FDR sensor sends an electromagnetic wave along its probes and measures the frequency of the reflected wave, which varies with θ. The FDR technique has a lower initial cost compared to TDR, but, for multiple site measurements, TDR might be more economical. Field studies have shown that the FDR technique can successfully be applied to irrigation scheduling (Laboski *et al*., 2001; Kukangu *et al*., 1999).

Both TDR and FDR are indirect techniques in measuring the pore water electrical conductivity (σ_p). Each of them measures the bulk soil electrical conductivity (σ_a) which depends on both σ_p and θ. Thus, the σ_p can only be predicted if θ is constant, or if the relationship between σ_p, σ_a and θ is known. Several different models of the σ_p–σ_a–θ relationship have been developed (e.g. Rhoades *et al*., 1976; Mualem & Friedman, 1991; Persson, 1997). However, these models have several drawbacks, such as the high dependency on soil type and the requirement for detailed soil-specific calibration. Recently, Hilhorst (2000) presented a theoretical model describing a linear relationship between bulk electrical conductivity, σ_a, and K_a in moist soil. Hilhorst found that, using this linear relationship, measurements of σ_p could be made in a wide range of soil types without soil-specific calibration. Persson (2002) presented an evaluation of the linear model using detailed TDR measurements in three sandy soils. He showed that the linear model was as good as other commonly used models for σ_p predictions with significant dependency of the linear model on soil type. Hamed *et al.* (2003) presented a further evaluation of the linear model in several different soil types using TDR measurements. They showed that the linear K_a–σ_a relationship was reasonably well predicted by Hilhorst's model and that the results could be improved using a soil-specific calibration.

This paper concentrates specifically on the calibration of a sensor that responds to the dielectric properties of the soil to estimate θ and σ_p. The WET sensor readings are compared to those made with TDR, which is a widely accepted technique for dielectric measurements in wet soil. This paper also investigates the effect of the electrical conductivity of the moistening solution on the calibration parameters. For this purpose, a series of laboratory experiments was conducted in five different soil types using three different soil solution electrical conductivity (σ_w) levels over a wide range of θ.

THEORY

Soil dielectric properties

When an electrical field passes through a material (such as soil) some of the energy in the field is transmitted, some is reflected, some is stored and, finally, some is absorbed and converted into heat. The extent to which each of these occurs within the soil is determined by its dielectric properties. These are quantified by a parameter called the relative electric permittivity of a material, which characterizes its response to the polarizing effect of an applied electric field. It is usually represented as a complex number. The real part of the permittivity represents the energy stored, and the imaginary component represents the total energy absorption or loss. For a static field, the real part of the permittivity is often referred to as the dielectric constant, K_a.

Ledieu *et al*. (1986), Whalley (1993) and White *et al*. (1994) have shown that there is a simple relationship between the measured permittivity of the soil, K_a, and θ of the form:

$$\sqrt{K_a} = b_0 + b_1\theta \tag{1}$$

where b_0 and b_1 are empirical parameters depending on soil type. This model appears to work very well for most non-magnetic soils over a range of frequencies between 1 MHz and 10 GHz. As the sensor estimates K_a, an experimental calibration is employed to determine b_0 and b_1. No sensor measures permittivity directly. The electromagnetic sensors measure either travel time or frequency directly, and then infer K_a.

The electrical conductivity of the bulk soil, σ_a, is a function of both θ and σ_p. Several different models have been developed for the σ_a–σ_p–θ relationship. Malicki *et al*. (1994) found a high degree of linear correlation between values of σ_a and K_a for a broad range of soil types. Inspired by this work, Hilhorst (2000) recently presented a theoretically-based linear σ_p–σ_a–K_a relationship:

$$\sigma_p = K_p\,\sigma_a/(K_a - K_0) \tag{2}$$

By rearranging equation (2), one obtains:

$$K_a = (K_p/\sigma_p)\,\sigma_a + K_0 \tag{3}$$

where K_p is the dielectric constant of the pore water and K_0 is the K_a value when $\sigma_a = 0$. However, the parameter K_0 is not the K_a value of dry soil, but appears as an offset of the linear relationship between K_a and σ_a. The equation only contains one fitting parameter K_0 which depends on the soil type and is called the soil parameter.

An experimental calibration of the WET sensor was conducted to determine the coefficients of water content and the soil parameter of the soil under investigation.

The WET sensor

The WET sensor is a relatively new dielectric sensor. The probe is built around an application specific integrated circuit (ASIC) that estimates the real and imaginary parts of the complex dielectric permittivity simultaneously at the single frequency of

20 MHz. The ASIC operates as a vector voltmeter to make precision measurements related to σ_a and K_a. The probe consists of thee metal rods 0.068 m long, 0.003 m in diameter and spaced 0.015 m apart. The central rod is covered by a coating material except at the tip.

The sensor is connected to an HH2 Moisture Meter (Delta-T Devices Ltd, Cambridge, UK), which applies power to the sensor and measures the output signal voltage returned. The measuring frequency is 20 MHz. The sensor probe detects the changes to the 20 MHz signal and sends this information to the HH2, which measures the capacitance (*C*) and conductance (*G*) of the material between the rods (soil). Then, it infers the dielectric properties using the sensor calibration file, which contains sets of capacitance and conductance readings obtained when the sensor was calibrated in various reference fluids with known electric properties. Finally, it calculates θ and σ_p using equations (1) and (2).

Water content and bulk electrical conductivity measurements with TDR

The TDR instrument sends a broad band frequency (20 kHz to 1.5 GHz) electromagnetic signal through a probe buried in the soil. The signal is reflected at the end of the probe and the travelling time of the signal can be measured. From the travelling time, the apparent permittivity can be calculated. It has also been shown that the bulk electrical conductivity can be calculated from the attenuation of the TDR trace (Dalton *et al*., 1984).

MATERIALS AND METHODS

TDR equipment

All TDR measurements were taken using a 1502C cable tester (Tektronix, Beaverton, Oregon, USA) with RS232 interface connected to a laptop computer. Estimates of K_a and σ_a were calculated from the TDR trace using WinTDR software (Soil Physics Group, Utah State University, Logan, Utah, USA). A three-rod probe, 0.10 m in length with a wire diameter of 0.003 m and an outer wire spacing of 0.05 m, was used for TDR measurements.

Measurements in different fluids

A series of experiments was conducted. First, two calibration experiments were conducted to test the performance and accuracy of the WET sensor compared to TDR measurements. The first experiment was carried out in order to investigate the response of the WET sensor measurements to salinity. In this experiment the WET sensor was immersed in distilled water. Potassium bromide salt was then added to increase the electrical conductivity of the solution. In total, 25 different electrical conductivity levels in the range of 0.003–13 dS m^{-1} were used. In addition to the WET probe, a digital conductivity meter (WTW, Weilheim, Germany) and a 0.1-m long TDR probe were immersed in the solution. For each conductivity level, three measurements of K_a and σ_a were taken and averaged for both TDR and the WET probe.

In the second calibration experiment, the accuracy of the K_a measurement of the WET probe was tested. In this experiment, both the TDR and the WET probes were immersed in seven different liquids with different K_a (air, rapeseed oil, syrup, ethanol, and water).

Measurements in soils

In order to examine the effect of soil type on the measurements, soil samples from four different locations in western north Sinai and one south of Port Said city, Egypt, were used. The four soils from Sinai all had rather similar soil texture. A summary of some selected soil properties is presented in Table 1. The first four soil samples were air-dried and passed through a 2-mm sieve. Then the samples were leached with distilled water and the excessive water was drained. This was done to remove any salt present in the soils. The soil was oven-dried after leaching. The soil sample was then moistened with a salt solution in seven increments to cover the range of θ from 0.1 $m^3 m^{-3}$ to saturation. First, the soil was physically mixed with a small amount of solution to bring it to the target water content. Then, the sample was packed in small layers into a cylinder (0.075 m diameter, 0.103 m height). Each layer was compacted as uniformly as possible using a rubber cork. The cylinder was filled and packed to reach the natural bulk density of the soil. Then, the WET probe was inserted vertically into the soil. Three WET sensor readings of K_a and σ_a were taken and averaged. This procedure was repeated seven times until saturation was reached. Three solutions with different salt concentrations were prepared, their respective σ_w were 0.70, 1.46 and 1.88 dS m^{-1}. All three solutions were used in all tested soil types. All experiments were carried out at constant temperature to eliminate the temperature effect. In field experiments, the temperature dependency is likely to be important and should be taken into consideration.

From the above-described experiment the parameters in equations (1) and (3) can be estimated. However, in the WET sensor manual, another method is described to determine the soil parameter K_0: mix a volume of soil with twice its volume of water; after settling for at least an hour readings of σ_a and K_a are taken in both the water and soil phase. The soil parameter can then be calculated using equation (2). This method was also used for all four soil types.

Finally an experiment was conducted to study the dependency of σ_a on the K_a measurement in a saline soil. For this an undisturbed soil sample was used, collected from the western part of the Suez Canal, 18 km south of Port Said city (Soil 5). The soil consists of heavy clay that exhibits very high salinity levels. The clay mineralogy of all the soil samples is smectitic clay. A column (0.1 m long, 0.09 m in diameter)

Table 1 Some selected soil properties.

Soil sample	Sand%	Silt%	Clay%	Soil type	Bulk density (g cm^{-3})
Soil 1	53.39	35.81	9.39	Sandy loam	1.42
Soil 2	62.15	27.44	7.47	Sandy loam	1.38
Soil 3	99.74	-	-	Medium sand	1.41
Soil 4	83.48	11.55	4.97	Loamy sand	1.54
Soil 5	4.00	30.8	65.2	Heavy clay	1.78

was leached from below using a peristaltic pump. Tap water (σ_w = 0.2 dS m^{-1}) was used to leach the soil. One 0.1-m long TDR probe and a WET sensor were inserted into the soil sample. Measurements of σ_a and K_a were taken several times a day using both sensors. The experiment was run until the measurements reached a constant level.

RESULTS AND DISCUSSION

Measurements in fluids

The WET probe slightly underestimated the salinity in the salt solutions. A linear relationship was used to calculate the real σ_a ($\sigma_a = 1.186\sigma_{wet} - 0.0293$, in dS m^{-1}) where σ_{wet} is the conductivity reading of the WET sensor. All WET sensor σ_a measurements will hereafter be corrected by this equation. Both the TDR and WET probe ε_a measurements are independent of σ_w until about 8 dS m^{-1} (Fig. 1). At larger σ_w, the K_a measurements increase. At approximately 10 dS m^{-1}, the TDR readings were unrealistically large; however, the WET sensor gave reasonable K_a measurements over the entire range of σ_w examined. Overestimation of θ due to high σ_a has previously also been shown, for example by Persson *et al*. (2004) and Hook *et al*. (2004). The K_a measurements in different solutions showed that both the TDR and the WET probe gave K_a values close to literature values (Weast, 1986, data not shown).

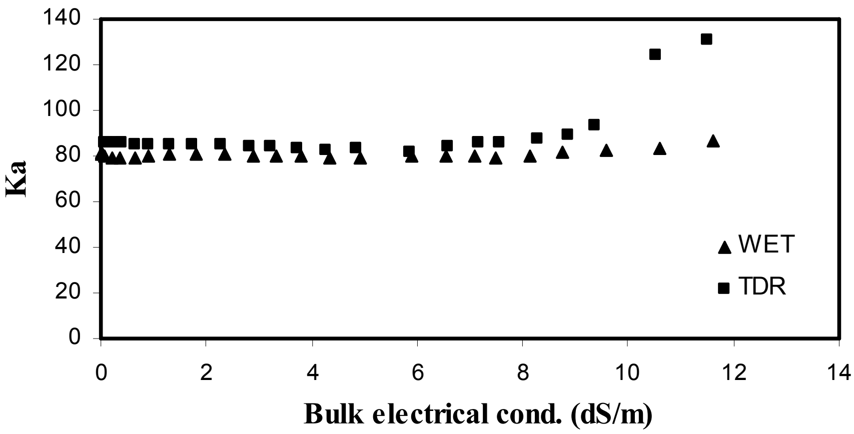

Fig. 1 The dielectric constant (K_a) measured using TDR and WET sensor in salt solutions plotted *vs* electrical conductivity.

Water content measurements in soil using the WET sensor

For each soil type, the relationship between K_a and θ was plotted. The offset, b_0, and the slope, b_1, of the K_a–θ relationship were determined by linear regression.

Figure 2 presents an example of the θ calibration results, which shows a linear relationship between $\sqrt{K_a}$ and θ. It is noticed that the conductivity of the salt solution does not affect the relationship. Therefore, the data of each soil type, regardless of σ_w, were used for fitting global values of b_0 and b_1 (Table 2). The values of these parameters agree well with those given in the WET sensor manual, with the exception

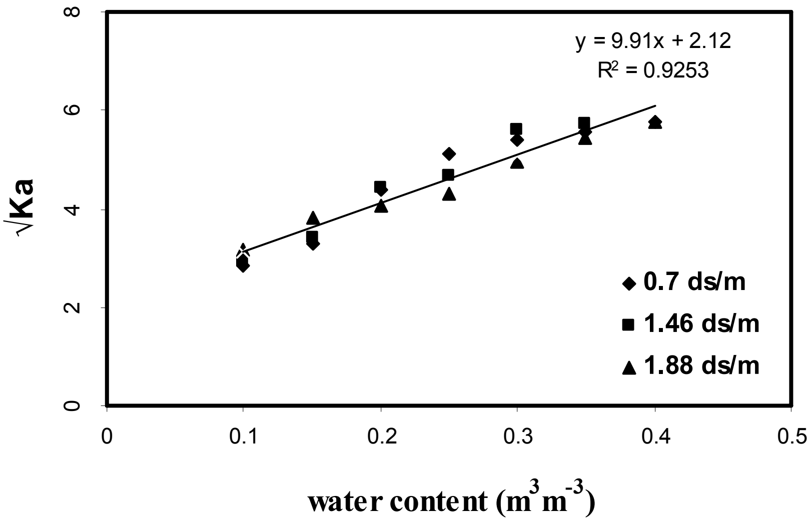

Fig. 2 The $\sqrt{K_a}$ from the WET sensor plotted against water content (θ) during the calibration experiments in Soil 1. The solid line is the linear regression of K_a–θ data.

Table 2 Results of the linear regression of K_a–θ data obtained in calibration experiment.

Soil type	Range of θ ($m^3\ m^{-3}$)	b_0	b_1	r^2
Soil 1	0.10–0.40	2.12	9.91	0.925
Soil 2	0.10–0.35	2.10	10.23	0.929
Soil 3	0.10–0.30	1.92	8.63	0.976
Soil 4	0.10–0.35	2.29	9.56	0.950
Soil 5	0.10–0.50	6.26	9.90	0.960

of Soil 5. In this soil, the K_a was much higher at any given θ compared to the other soils, with K_a values of over 100 at saturation. This effect can also be seen to some extent in the WET sensor manual for a clay soil. The reason that Soil 5 displayed such high K_a values can probably be explained by the smectite clay mineralogy. Kelleners *et al.* (2005) studied the dielectric properties of bentonite at several different frequencies. The result reported here is very similar to that which Kelleners *et al.* (2005) found for the bentonite clay at a frequency of 22.8 MHz. The reason for these high K_a values is the complex clay surface-water–ion interactions (Hasted, 1973; Sihvola, 1999; Kelleners *et al.*, 2005).

Pore water conductivity measurements in soil using the WET sensor

For each value of σ_w, the relationship between K_a and σ_a was plotted (e.g. Fig. 3). The K_a–σ_a relationship is linear for all levels of σ_w. The slope is affected by σ_w, decreasing with increasing σ_w. Furthermore, the offset (K_0) is almost the same for all σ_w values. The results agree with data from Hilhorst (2000), though he only presented one value of K_0 for each soil type. The offset K_0 was determined and averaged for each soil type and presented in Table 3. In Soil 5, no clear K_a–σ_a relationship could be found. This is likely due to the smectite clay mineralogy and the fact that is was not possible to

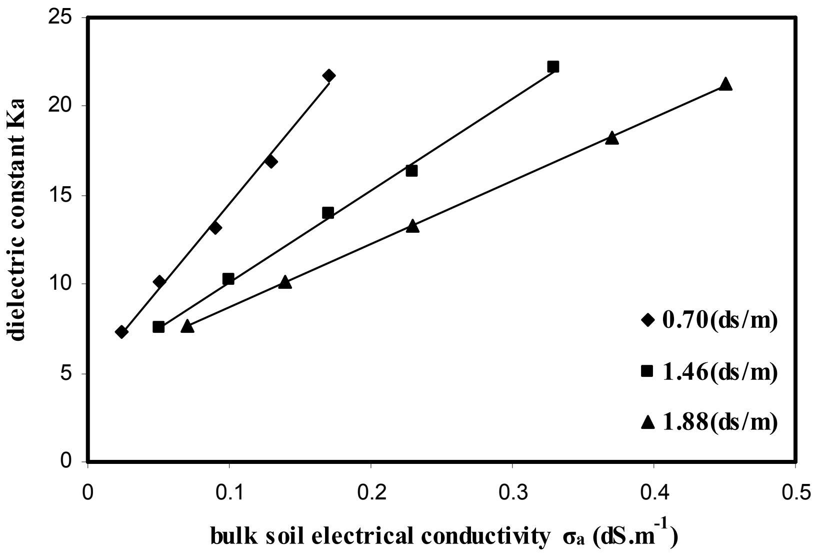

Fig. 3 Measured values of dielectric constant (K_a) and bulk electric conductivity (σ_a) in the Soil 1 The solid lines are the trend lines to the data points.

Table 3 Values of the offsets (K_0).

Soil type	Range of θ (m^3 m^{-3})	Offset K_0 *	Measured K_0 **
Soil 1	0.10–0.40	7.84	21.5
Soil 2	0.10–0.35	8.78	9.56
Soil 3	0.10–0.30	4.95	4.05
Soil 4	0.10–0.35	9.32	9.34

* The average offset of the σ_a–K_a relationship for the three σ_w levels.
** Measured using the method described in the WET sensor manual.

remove all salts in the soil by leaching. Thus, the results from Soil 5 were removed from Table 3.

The averaged values of K_0 were used with the measured K_a and σ_a in equation (3) for the calculation of σ_p, revealing a good correlation between the measured and calculated σ_p (e.g. Fig. 4). In Table 3 the K_0 values determined by the method described in the WET sensor manual are also presented. The K_0 values agreed well with the others, except the one for Soil 1. This soil had higher silt and clay content compared to soils 2–4. When fine-textured soils settle after mixing with water, they will not have the same structure as undisturbed soil. Thus, the sensor manual's method of determining K_0 cannot be recommended in fine-textured soils.

In the leaching experiment, both the σ_a and K_a measurements decreased with the amount of leachate (Fig. 5). The WET sensor consistently gave larger measurements compared to the TDR. Since both instruments gave similar readings in the fluids, the discrepancy is probably due to the different sampling volumes of the two sensors. The TDR probes have a measurement volume which can be described as a cylinder with the same diameter as the distance between the outer rods (0.05 m) and a length equal to the rod length (0.1 m). The WET sensor has an unknown sampling volume due to the partially coated central rod. This also makes the sampling volumes for σ_a and K_a different for the WET sensor. It is likely that the sampling volume for σ_a is much

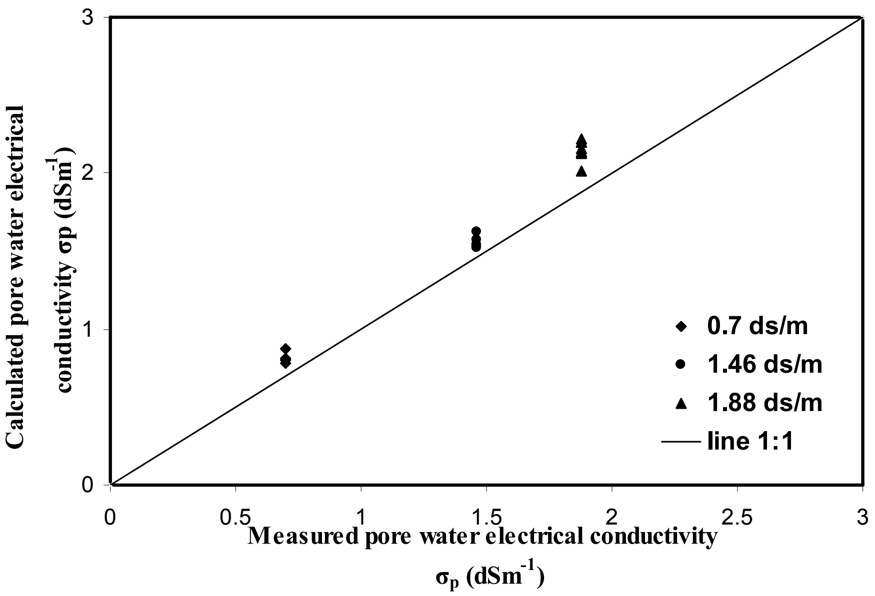

Fig. 4 The pore water electrical conductivity (σ_p) calculated using equation (3) *vs* the measured (σ_p) in Soil 3.

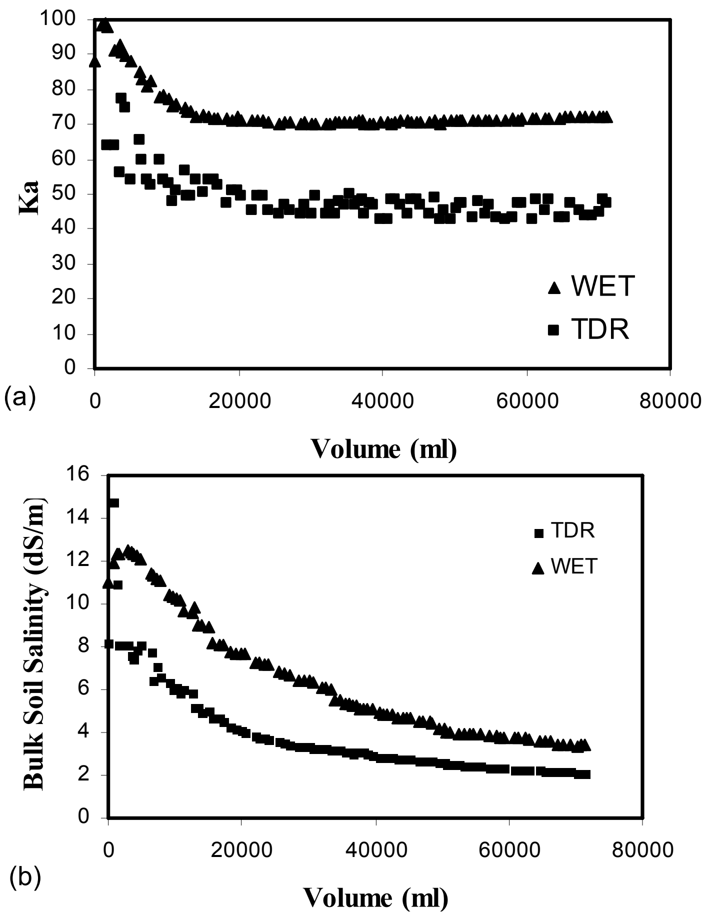

Fig. 5 Measurements using TDR and WET sensor in an undisturbed soil sample during leaching: (a) the dielectric constant (K_a) and (b) the bulk soil electrical conductivity.

smaller compared to the one for the TDR probe. Thus, heterogeneities like cracks or voids near the WET sensor will likely affect the readings to a great extent. Karlsson & Winqvist (2005) showed that, under field conditions, the σ_w readings of the WET probe had a coefficient of variability of 0.10 when it was inserted 30 times in a soil with constant salinity; thus, it is sensitive to placement of the sensor. In the undisturbed soil sample, readings of K_a were overestimated due to the large value of σ_a. For the WET probe, K_a measurements were overestimated for σ_a values larger than about 8 dS m^{-1}. The same limit for the TDR was about 4 dS m^{-1}. These limits were lower than those found in the saline solutions. Clearly, the dielectric properties of the smectite clay makes the K_a readings more sensitive to large σ_a, a fact that previously has been noted by Persson *et al*. (2004). The differences in the K_a measurements of the WET and TDR probes in Soil 5 can be explained by the different measuring frequencies (Kelleners *et al*., 2005).

SUMMARY AND CONCLUSION

This paper concentrates on the experimental calibration of a rapid, non-destructive FDR-based sensor to investigate the dielectric properties of soil. Results are compared to TDR measurements. The parameters of the water content and soil solution electrical conductivity calibration for different soil types in the region under consideration have been determined. Furthermore, the paper studies also the effect of the conductivity of the moistening solution (σ_w) on the calibration parameters.

From the calibration experiments in salt solutions it was evident that the WET sensor gave highly accurate K_a and σ_a measurements when compared to TDR. In the salt solutions, the WET sensor was less affected by large σ_a compared to the TDR probe used.

From the measurements in the soil samples, the results revealed that the calibration coefficients of water content and the soil parameter are significantly dependent on the soil type, and slightly affected by electrical conductivity of the moistening solution. The method for determining the soil parameter K_0 suggested in the WET probe manual works well in coarse-textured soils, whereas in fine-textured soil it can give erroneous values when used for σ_p measurements. In the clay soil, σ_p measurements were not possible using the WET sensor, probably an effect of the smectite clay mineralogy.

In one soil sample, containing high amounts of smectite clay, extremely high K_a values were found (higher than 100). TDR measurements in the same soil gave more feasible values. The difference can be explained by the different measuring frequencies as previously noted by Kelleners *et al*. (2005). However, if a soil-specific calibration is conducted, the WET sensor will give accurate θ values also for smectite clays (Table 2).

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