Measurement of soil water content by percometer

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Abstract

A percometer (an instrument for simultaneous measurements of soil dielectric constant ε_r, electrical conductivity EC and soil temperature) was tested on soils under potato crop to investigate contents of soil volumetric water for eventual use in a field crop model. To approximate dependence of θ on ε_r, a logarithmic equation was chosen. Satisfactory results were obtained on stone-free areas, with the mean relative variance between θ values determined by percometer and by a gravimetric method remaining within the limits of measuring error. However, variances were higher for stony soils, with ε_r values at the same θ being considerably higher. To reconcile data from stony and stone-free soils, a formula was composed.

Keywords: soil water content, dielectric constant, moisture sensor

1. Introduction

Soil moisture is one of the most important characteristics in agrometeorology. Since its great variability both in time and space, a great amount of data on soil water content is required in various disciplines. Traditional volumetric and gravimetric methods for determination of soil moisture are very labour-intensive, therefore contemporary instruments apply soil electrical properties to describe different soil conditions.

A percometer (from PERmittivity and Conductivity) - an instrument for simultaneous and non-destructive *in situ* measurements of soil dielectric constant, electrical conductivity and soil temperature, has been tested in field experiments. This paper reports the measurement by percometer of soil moisture under potato crop, with the aim of determining water content for a production process model (Kadaja, Tooming, 2004).

2. Material and Methods

The dielectric constant (ε_r), more accurately named the real part of relative complex permittivity, is determined mainly by the water content in the soil, thereby indicating soil volumetric moisture content. Today, all different dielectric soil sensors on the market base on the soil interaction with the electromagnetic field. In our research, the dielectric constant was measured by percometer, which is a frequency domain instrument for measuring soil dielectric constant and conductivity. Frequency domain instruments measure electrical impedance of sensor arrangement on frequencies over 10 MHz (Sun et al., 2005, Ma et al., 2006). The electromagnetic theory used to describe ε_r measurements for widely used Hydra Probe (Hilhorst, 2000) and SigmaProbe (Seyfried et al., 2005) sensors; can also be applied for percometer sensor, but the measurement method of the impedance capacitive component (real part of relative complex permittivity) is different. The metal electrodes of percometer sensor form an electrical capacitor, which impedance depends on electrical properties of surrounding media. Dielectric constant of the soil is thereby determined from the change of electrical capacitance due to influence of the soil close to sensor electrodes. The specially designed electronic circuitry is placed in the vicinity of electrodes to measure the change of sensor capacitance on 40-50 MHz, independently from sensor conductivity (Plakk, 1990). This approach enables to make probes of different shape. Percometer is realised as a single tube sensor enabling to operate easily in different depths (Fig. 1). Percometer's active measuring electrode is located on the tube surface to minimize the compaction effect by the tip of the probe on the measured soil volume (about 2 dm^3).

Figure 1. Percometer pressed to the depth 50 cm and the lower end of tube with sensor between conic tip and plastic ring.

Soil electrical conductivity is measured by the same metal electrodes as dielectric constant but in different time interval. Percometer measures electrical conductivity in $\mu S\ cm^{-1}$ with 1 KHz alternating current signal using two electrode measurement scheme.

The temperature sensor is enclosed into the percometer probe for temperature correction of electrical conductivity to the temperature 20 °C. The dielectric constant values are not corrected, because the temperature error of ε_r is small.

Measurements were carried out during the growing periods of 2005-2007 in two Estonian localities: at Kuusiku Experimental Station (58°59'N: 24°42'E) and on the experimental fields of the Plant Biotechnological Research Center EVIKA at Saku (59°17'N; 24°40'E). At Kuusiku the measurements took place within a long-term trial of different soil tillage methods with a 6-year rotation (Viil, Nugis, 2002). Six different soil tillage techniques were investigated under the potato crop: minimum, conventional and deep tillage, both without (zero version) and with ploughing in of the straw of the pre-culture wheat as fertilizer in double amounts (compared with straw yield from the plot). Trials were on practically stone-free sandy loam, Calcic Luvisol (WRB).

At Saku, two fields of potato crops, grown from tubers and meristeme cultures respectively, were examined. Both fields had a corresponding trial of different fertilizer treatments (Cropcare 10-10-20 at 0, 250, 500 and 1000 kg ha^{-1}). In addition, a trial was under way to determine the leaf area index dynamics of differently multiplied meristeme plants. Tubers were planted in the middle of May, meristeme plants a month later. The soil type of Saku fields is sandy loam, Sceletic Regosol (WRB) and very break stony even in the tilled layer.

The relationship between dielectric constant and volumetric soil water content was investigated by parallel measurements by percometer and soil sample ring kits. At Kuusiku, one series of measurements was carried out in 2005 and two series in 2006. In both years, 100 cm^3 Eijkelkamp soil sample rings with diameter 50 mm were used to determine volumetric soil water content. Additionally, in 2005 the soil volumetric water content was simultaneously determined by ThetaProbe moisture meters (Delta-T Devices Ltd). Although the ThetaProbe converts the measurement results to units of volumetric soil water content, these do not agree sufficiently with directly (volumetrically) measured data. Therefore, a linear calibration equation (r=0.87) for calculation of real volumetric water content from the ThetaProbe measurement data was used. At Saku, two series with Eijkelkamp ring kits were accomplished in 2005 and three series in 2006, using additionally 50cm^3 Litvinov rings (d=40 mm) and 500 cm^3 soil sampling cylinders (d=80mm). Soil stoniness was calculated as the ratio between stones and dry soil (including stones) mass in 500 cm^3 soil samples. Mean stoniness ranged from 2-3% at the soil surface up to 17% in deeper layers. Stoniness determined in this way is not representative of the overall quantity of stone in the soil volume, since the larger stones do not fit into the cylinder; however, it is an indicative estimate that is easily achieved.

To compare earlier results determined by a gravimetric method to newer data collected by percometer, parallel measurements were performed. The comparable data were collected from the same hole, first by percometer, then by auger. Measurements were made in 10-cm layers at five depths in 2005. At Kuusiku the parallel measurements were carried out on three dates, with 12 measurement points in each. At Saku measurements were made on two different dates in eight points in each. Mean soil bulk densities determined for each layer of these fields were used for conversion from gravimetric to volumetric water content. To characterize the variance between water contents determined by different methods, the mean of differences (bias) was calculated. The mean difference in a single pair of measurements is described by mean absolute error.

3. Results and Discussion

3.1. Soil dielectric constant by percometer and volumetric water content

Data from parallel measurements of the dielectric constant and volumetric soil water content (Fig. 2) show significant deviations on three dates at Saku. Anomalously higher values for volumetric moisture were measured on 5 August after heavy rain from the surface layer when it was wetter than the lower ones. This anomaly stems from the *modus operandi* of the percometer in top layer measurements, since some of the generated electric field also covers the air space above the soil, while shifting the sensor deeper rather reflects lower moisture values below the waterlogged surface layer. On 6 and 14 June 2006, the percometer displayed higher ε_r values than would be expected from reference to the directly measured volumetric moisture in layers below 30 cm, where the degree of stoniness is quite high in this field. On the stone-free field of Kuusiku, data from surface and deeper layers matched well. Hence, the data mismatch at Saku may be attributable to the higher water content below the bigger stones and between limestone layers not involved in soil sampling cylinders at this stony site.

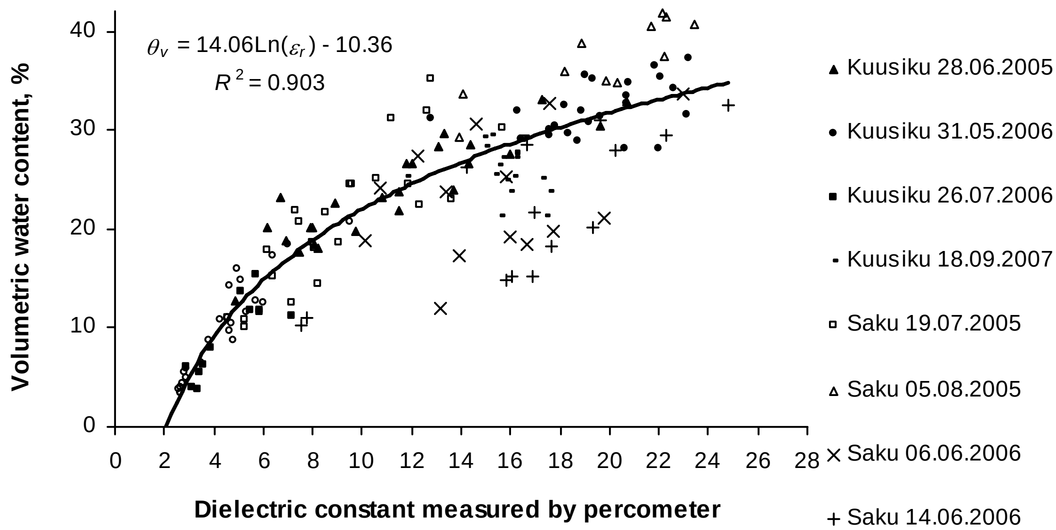

Figure 2. Relationship of soil volumetric water content θ_v with dielectric constant ε_r by logarithmic calibration curve. The curve excludes data from the 5th August 2005 and the separate group of data points below the main distribution measured from the layers deeper than 30 cm at Saku.

When these anomalous data are excluded, there is good relationship between dielectric constant and volumetric soil moisture. Although an empirical relationship between ε_r and *Θ,* introduced by Topp et al (1980), is widely used, in our case, the logarithmic curve gave the highest correlation to the remaining samples (Fig. 2). The mean absolute difference between directly measured and calculated volumetric water content is 2.2 for logarithmic equation compared to 8.6 for Topp equation.

An equation minimizing the root mean square error was established to approximate the dielectric constant values recorded in stony soil to the calibration curve:

$$\varepsilon_c = \frac{\varepsilon_r}{1 + 52S^2} \quad (1)$$

where *S* indicates stoniness (fraction by mass) assessed by extracting stones from the 500 cm^3 soil samples, ε_r is the measured dielectric constant and ε_c is its corrected value. In elaboration of this formula the volumetric water content was calculated concerning all volume of the sampling including stones. Subtracting the volume of stones decreased the correlation between calculated water content and measured dielectric constant. Corrected by equation (1), points are plotted against the background of the calibration curve (Fig. 3).

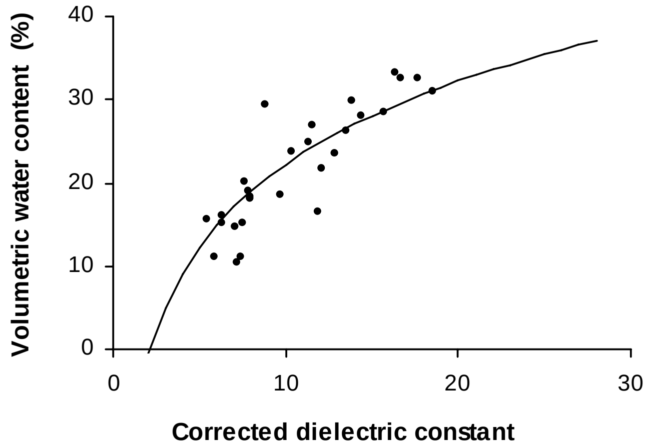

Figure 3. Values of dielectric constant corrected by equation (1), against calibration curve from Fig. 2.

3.2. Comparison with results recorded by ThetaProbe

The linear correlation between volumetric soil water contents calculated by percometer and ThetaProbe data (Fig. 4) proved reliable (r=0.92, p<0.01). Correlation of the data measured directly by the two devices was slightly lower because of the nonlinear relationship between dielectric constant and soil water content.

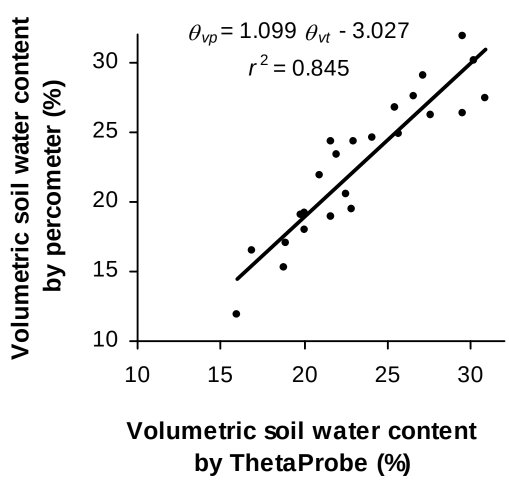

Figure 4. Comparison of volumetric soil water contents (%) determined by calibration curves from data measured by ThetaProbe (θ_{vt}) and percometer (θ_{vp}).

It can be concluded that the two devices measure soil water content with approximately the same accuracy. For measurements in the top layer of a stone-free soil the two devices were similar in terms of convenience. Data recording in deeper layers necessitates auger holes for the ThetaProbe, whereas the conical tip of the percometer can easily be pressed deeper into the ground unless soil is very dry or heavily compressed. It is possible to avoid bigger stones by probing with a spike. The advantages of the percometer are particularly obvious in gravelly soils, because the probe of the ThetaProbe, consisting of four parallel tines, is quite fragile among stones and gravel

3.3. Comparison of percometer and gravimetric results

At Kuusiku the mean difference (bias) for all layers between water contents determined by percometer and gravimetric method is -0.022 m^3 m^{-3} (Table 1). The differences are calculated by subtracting gravimetrically determined volumetric water content from the value recorded by percometer; consequently the gravimetric method gives higher values than the percometer. The bias remains negative from the surface to 40 cm and its value increases slowly with depth. Only for the deepest measured soil layer (40-50 cm) does the bias become positive. The mean absolute difference over all layers is 0.033 m^3 m^{-3}. Similar comparison results (standard deviation 0.035) were achieved by Miyamoto et al (2001) for TDR probes. The difference decreases to 0.024 m^3 m^{-3} if the overall water contents for the whole 0-50 cm layers are compared. Considering the great variability in soil properties, these results can be judged to be quite good.

The compatibility is not so good in the case of gravelly soils at Saku, where the bias for all layers is -0.048 m^3 m^{-3}. For the two upper layers the soil moisture values converted from percometer data (taking into consideration the layer's mean stoniness) are lower than the values obtained by the gravimetric method. For the third layer the relative difference becomes positive, only to change back to negative in two deepest layers. The mean value of the absolute difference over all layers reaches 0.061 m^3 m^{-3}.

The variability of measurements by the different methods is relatively similar – standard deviations of Θ determined by percometer are 0.021 m^3 m^{-3} at Kuusiku, 0.030 m^3 m^{-3} at Saku; by gravimetric method 0.024 and 0.029 m^3 m^{-3}, respectively. Coefficients of variation are 8.3% and 8.7% at Kuusiku and 16.1% and 12.5% at Saku for the percometer and gravimetric methods, respectively.

Table 1. Bias and absolute difference between soil volumetric water contents measured by percometer and gravimetric method

Depth of layer (cm)	Mean difference (bias) ($m^3 m^{-3}$)		Mean difference (bias) Relative to gravimetric method (%)		Mean absolute difference ($m^3 m^{-3}$)		Mean absolute difference Relative to gravimetric method (%)	
	Kuusiku	Saku	Kuusiku	Saku	Kuusiku	Saku	Kuusiku	Saku
0 – 10	-0.022	-0.025	-9.57	-10.04	0.032	0.033	15.45	15.88
10 – 20	-0.025	-0.059	-7.89	-19.28	0.038	0.064	13.06	20.84
20 – 30	-0.030	0.0002	-9.16	3.29	0.033	0.042	10.22	17.54
30 – 40	-0.034	-0.118	-10.44	-44.69	0.034	0.118	10.50	44.69
40 – 50	0.002	-0.051	1.43	-23.53	0.027	0.051	8.91	23.53
Average of layers	**-0.022**	**-0.048**	**-7.17**	**-17.10**	**0.033**	**0.061**	**11.61**	**23.90**
Overall for 0–50 cm	**-0.022**	**-0.042**	**-7.34**	**-18.60**	**0.024**	**0.044**	**8.32**	**20.04**

4. Conclusions

The percometer, an instrument that measures soil dielectric constant, electrical conductivity and temperature, has been used to determine soil moisture, and proved more convenient than other available instruments and methods. For stone-free soil the calibration curve, determined on the basis of parallel measurements by a volumetric method, is well described by logarithmic approximation. Differences appear on stony and gravelly soils, where additional correction, e.g. on the basis of soil stoniness, is necessary.

Comparison of the percometer and the ThetaProbes moisture meter gave similar results, but the construction of the percometer was more able to cope with deeper soil layers and gravelly soils. Comparisons of the percometer with a traditional gravimetric method gave satisfactory results with stone-free soils; substantially higher differences were recorded in gravelly soil.

Acknowledgment

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