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COMPARING GPR AND TDR FOR SOIL WATER CONTENT MONITORING IN AGRICULTURAL MEDIUM

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The advantage of using GPR method for monitoring of soil moisture in the agricultural medium, is specially the possibility of carrying out measurements without permanent installation in the plot and therefore acting as obstacle for farming labours.

The experimental work has been carried out measuring gravimetric humidity from undisturbed samples, the apparent distance measured with the TDR and GPR at depths ranging from 0 to 20 cm and the apparent dielectric permitivity. Field surveys have been carried out using different instruments, frequencies and antenna configurations.

In this paper, a relationship between soil water content measured in the field by the TDR and thermogravimetric humidity is proposed. This relationship can be used to determine the best conditions (K_s and α) for GPR parameters.

1 INTRODUCTION

Monitoring soil moisture content in plots (productive or experimental) requires non-destructive techniques that allow repeated measurements. Nowadays, the Time Domain Reflectometry (TDR) is the most used technique that measures soil water content in different sites. Ground Penetrating Radar (GPR) and TDR techniques are based on the reflection of an emitted electromagnetic pulse. There are correlations between the volumetric soil moisture and the ratio between apparent and real length of the TDR probes. Likewise, there is a correlation between the volumetric soil water content and the time travel difference between the first two electromagnetic waves.

Ground Penetrating Radar has been used for the last 20 years in many different issues (i.e.: glaciology, archaeology, engineering, etc.). In this paper GPR has been applied to detecting water content in soils. Two equipments have been tested in Torre Marimon (Spain) catchment.

The aim of this paper is to use the first direct wave travelling through the ground to measure the water content in topsoil (0 to 20 cm). Dielectric constant (Ka) is measured using TDR and GPR techniques, and comparing them to the thermogravimetric method.

2 BASIC PRINCIPLES

In GPR system a very short (a few nanoseconds) electromagnetic pulse is radiated into the ground by an emitter antenna. The pulse travels through the ground until it reaches a change in the electric properties of the medium. At this moment, a part of the energy is reflected back to the surface and the rest continues its way to greater depths. The reflected energy reaches the receiving antenna and is processed, filtered and finally displayed as a profile. The record shows the total traveltime for a signal to pass through the subsurface [1].

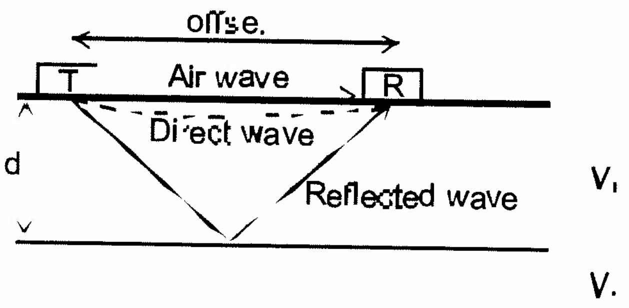

Fig. 1 The electromagnetic waves follow different paths in their way from the transmitter to the receiver unit.

The electromagnetic pulse follows different paths in its way to the receiver antenna. There is the direct wave through the air (the first one), the direct wave through the soil (the second one) and the ones that have been reflected from boundaries between different materials of the soil (fig. 1).

A horizontal axis, which indicates the antenna position along the profile and a vertical axis that corresponds to the two-way traveltime compose the profile. The radar unit will then plot a mark on a vertical scale based on the time it took for each signal to return. The radar unit will also analyse the characteristic properties of the waves, mainly the amplitude.

The first arrival through the ground can be altered by changes in the velocity due to changes in the dielectric permitivity. This mainly occurs when there are changes of the soil moisture content of the first layer [2].

The electromagnetic waves' emission, transmission, reflection and refraction are defined by the Maxwell's equations. These equations describe the electric and magnetic fields of a wave, which travels through a medium with determined electric and magnetic properties. The speed of the radiowaves in a material (v_m) is given by (1):

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$$V_m = \frac{c}{\frac{\varepsilon_r \mu_r}{2}\left[\sqrt{(1+P^2)}+1\right]} \quad (1)$$

Where

c is the speed of light in free space

ε_r is the relative dielectric permitivity

μ_r is the relative magnetic permitivity (1 for non magnetic materials)

P is the loss factor such (2)

$$P = \sigma / \omega\varepsilon \quad (2)$$

In low loss materials, P is approximately 0 and the speed of the radiowave is (3)

$$v_m = \frac{c}{\sqrt{e_r}} = \frac{0.3}{\sqrt{\varepsilon_r}} \quad (3)$$

The electromagnetic properties depend on different parameters: angular frequency (ω), magnetic susceptibility (μ) conductivity (σ) and the relative dielectric permitivity (ε).

The amplitude reflection coefficient is (4)

$$R = \frac{(v_1 - v_2)}{(v_1 + v_2)} \quad (4)$$

Where v_1 and v_2 are the radiowave velocities in layers 1 and 2 respectively and also $v_1 < v_2$. Also (5):

$$R = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}} \quad (5)$$

where ε_1 and ε_2 are the respective dielectric permitivities (ε_r) of layers 1 and 2, applicable for incidence at right-angle to a plane reflector.

The electrical properties of geological materials are primarily controlled by the water content [3]. Variations in the electrical properties of soils are usually associated with changes in volumetric water content which, in turn, give rise to radar reflections.

Radar signal velocities in low-loss geological materials, which are amenable to radar sounding, are related to the real part of the dielectric constant by (6)

$$v = \frac{c}{\sqrt{k'}} \quad (6)$$

where c = $3x10^8$ m/s, the propagation of electromagnetic waves in free space.

The real part of the dielectric constant of water is temperature dependent (aprox. 80) and the driest geological materials are in the range of 4-8. This large difference explains why the radar signal velocity is strongly dependent on the water content in soils.

3 GPR METHODOLOGY

There are three devices that can be used working with GPR. The first one is the reflection mode, the second is the CMP-WARR sounding and the third one is the transillumination mode. GPR is normally used in the reflection-profiling mode that gives a section showing traveltime to reflectors versus position. The

CMP or WARR, sounding mode is used to determine the signal velocity in the soil or rock. The transillumination mode is mainly used in civil engineering and forms the basis of tomographic image construction.

3.1 Reflection sounding

The profiles are usually measured using a fixed offset between the antennas and a constant step along the profile. Normally the horizontal scale is in meters and the vertical scale is based on two-way travel time (nanoseconds). Data is acquired only on a narrow line directly below where the profiles are taken. It is very similar to that used in seismic reflection surveys.

3.2 Common Mid Point and Wide Angle Reflection and Refraction sounding

CMP and WARR soundings are measured varying the antenna spacing from a central point and measuring the change of the two-way traveltime to the reflections produced at any interface and defined by a hyperbola. Velocity analysis can be performed in a similar way that for the reflection seismic method. The used display is the square of antenna separation versus the square of two-way time.

Typically, within the range of GPR antenna frequencies, the lower the frequency of the pulse, the deeper the signal penetration, but at a lower data image resolution. On the other hand, the higher the frequency, the greater the image resolution, but at a lower signal penetration. The type of antenna used will depend on the particular targets-of-concern.

Experience in many geological environments indicates that radar systems with a centre frequency of about 100 MHz frequently offer the best compromise between range, resolution and system portability [4]. The range and resolution of GPR decreases with the presence of conductive materials like clays, silts or wet soil.

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4 EXPERIMENTAL DESIGN

The experiment was performed at the ESAB's (Escola Superior d'Agricultura de Barcelona) Experimental Station in Torre Marimon (30 km in the North of Barcelona, Spain) on a calcareous sandy loam (53% sand, 40% silt and 7% clay) pre-planting tilled topsoil.

Soil moisture was measured in thirty-two points placed along a profile at intervals of one meter. At each point, volumetric water content was measured with a TDR cable tester and a GPR equipment. Soil temperature was measured at each point. Values of apparent dielectric constant (Ka) were converted to volumetric water content using (7). In all the points, water content was measured in laboratory conditions by means of thermogravimetric method, too. The water content is expressed as a volume ratio.

$$\theta = 0.0000043\,K^3 - 0.00055\,K^2 + 0.0292\,K - 0.053 \quad \text{Topp et al (1980)} \tag{7}$$

Where

θ is the soil moisture content (m^3/m^3)

K is the calculated dielectric permittivity

Bulk density was measured in five points using undisturbed samples (metallic cylinders, 100-cm^3 capacity).

On the other hand, soil moisture calculated by means of the mixing law relations proposed by [5] (8), was used to determinate the best K_{soil} and alfa parameters.

$$\theta = (K^\alpha - (1-\eta)\,K_s^\alpha - \eta \cdot K_g^\alpha)/(K_w^\alpha - K_g^\alpha) \quad \text{Roth et al (1990)} \tag{8}$$

$$K_w = 78.54\left[1 - \left(4.579 \times 10^{3}(T-25) + 1.19 \times 10^{-5}(T-25)^2\right) - 2.8 \times 10^{-8}(T-25)^3\right] \tag{9}$$

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Where
θ is the soil moisture content (m^3/m^3)
K is the calculated dielectric permittivity
K_w is the dielectric permittivity for the aqueous phase
K_s is the dielectric permittivity for the solid phase
K_g is the dielectric permittivity for the gaseous phase
α is the anisotropy
η is the soil's porosity
T is the temperature in °C.

5 EQUIPMENTS

TDR equipment used was 1504 model of Techtronic using a three-wire probe of 20-cm long stuck vertically into the soil.

GPR instruments used in this work were a Pulse Ekko IV from Sensors & Software and a RAMAC from Måla Geoscience. Both instruments were used with a 100 MHz antennas and one-meter offset. Field parameters of GPR measurements can be seen in table 2.

Offset (m)	Antenna Frequency(Mhz)	Step (m)	State	Lenght (m)
1	100	0.5	dry	40

Table 2 Field parameters used for field data collection

6 RESULTS

Bulk density measures in the experimental area are variable. Extreme values were 1,264 and 1,651 kg m^{-3}, average is 1,467 and the standard deviation is 163.

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In figure 3 (a and b), values of soil moisture obtained using thermogravimetric method (Θ_G) are compared with results from TDR (Θ_TTDR) and GPR (Θ_TGPR) calculated by [3].

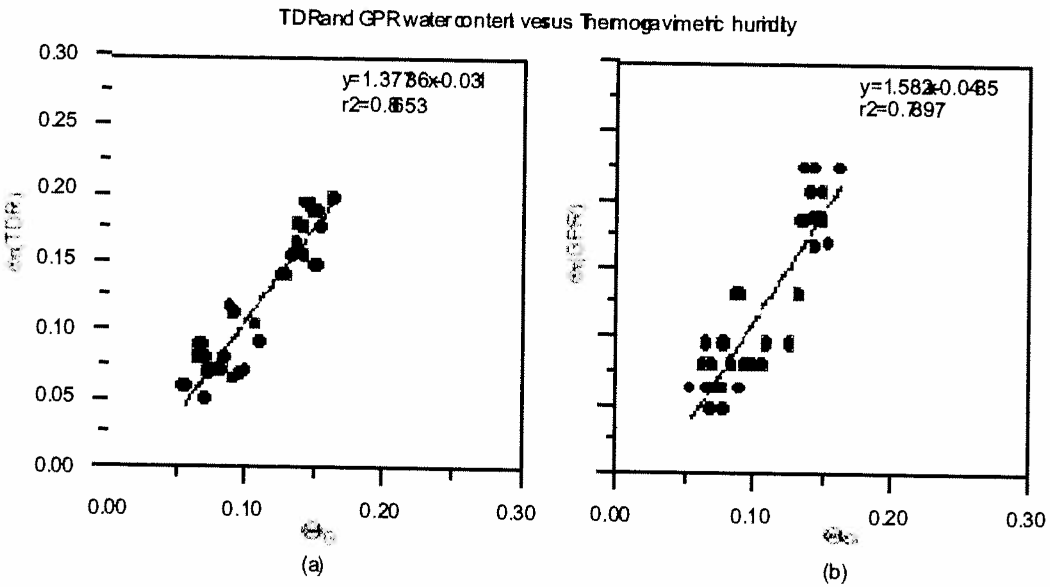

Fig. 3 Comparison of thermogravimetric humidity versus TDR (a) and GPR (b) values calculated by Topp et al, 1980 (7).

The correlation coefficient between thermogravimetric method (Θ_G) and TDR method (Θ_T) is R = 0.93. This high value indicates that empirical adjustment of measured apparent dielectric permitivity furnishes a correct value of soil moisture in those calcareous sandy loam soils. In this case a unique local calibration was established in order to minimise the measurement errors in the future. The best-fit equation was found to be:

$$\Theta_T = \Theta_G * 1.3774 - 0.031 \ (R^2 = 0.8653) \qquad (10)$$

Likewise, using GPR data the correlation coefficient is R=0.8886. For the practical uses the regression equation for these variables was found:

$$\Theta_T = \Theta_G * 1.582 - 0.0485 \ (R^2 = 0.7897) \quad (11)$$

In figure 4 (a), the mixed approach of [5] allows us to establish a regression with the thermogravimetric values (Θ_G) in order to select the optimum values of Ksoil and the geometric factor (alfa) to be applied for GPR method.

The best regression obtained using K=4.29 and alfa =0.6 from TDR data was:

$$\Theta_R = \Theta_G * 1.135 - 0.0173 \ (R^2 = 0.8407) \quad (12)$$

After applying these parameters to GPR calculated by [5], the linear regression formula achieved was (13)

$$\Theta_R = \Theta_G * 1.3388 - 0.0348 \ (R^2 = 0.763) \quad (13)$$

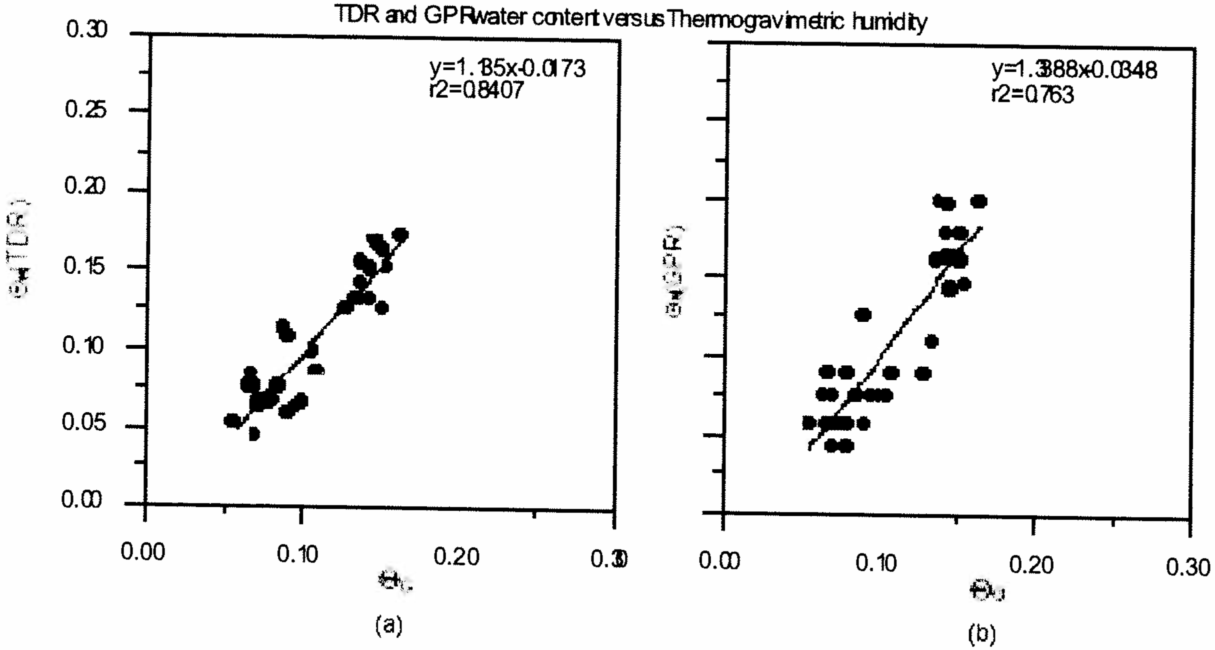

Fig. 4 Comparison of thermogravimetric humidity versus TDR (a) and GPR (b) values calculated by Roth et al, 1990 (8).

The correlation coefficient between Ka measured by GPR and thermogravimetric values was R = 0.8977. In order to find a similar relationship to the one presented in [3] for the TDR, Ka and GPR values have been compared (fig.5). The equation of regression obtained was (14):

$$\Theta_G = -0.00025\,Ka^3 + 0.005115\,Ka^2 - 0.0208\,Ka + 0.092 \quad (R^2 = 0.8058) \qquad (14)$$

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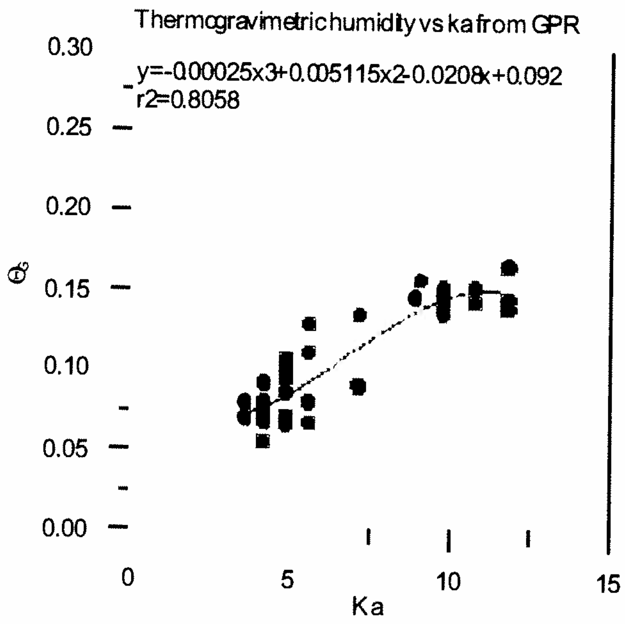

Fig. 5 Comparison of thermogravimetric humidity versus Ka calculated from GPR.

Finally, in figure 6, a correlation between TDR and GPR soil water content values obtained by equations (7) and (8) has been presented. The correlation coefficient was R = 0.9256 for equation (7) and R = 0.9083 for equation (8).

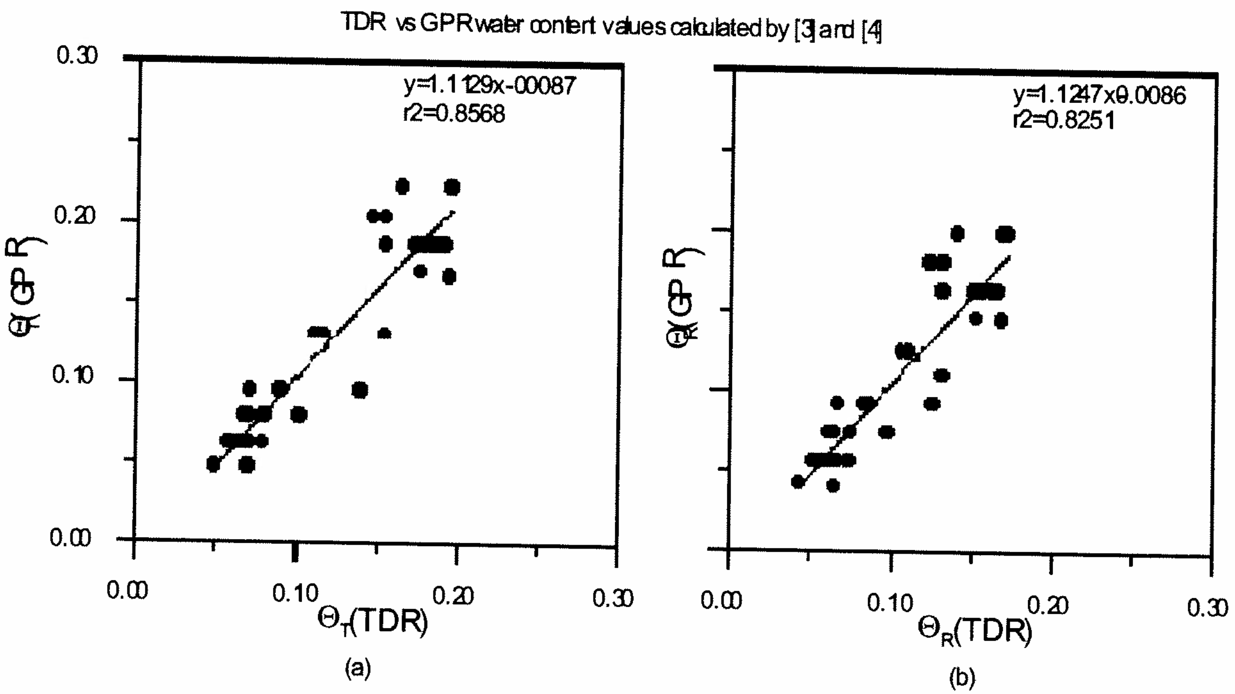

Fig. 6 TDR vs GPR water content values calculated by (7) (a) and (8) (b).

7 CONCLUSIONS

GPR has proved to be a useful tool in determining toplayer soil water content when the first two waves are used. The correlation with thermogravimetric values, using [3] is high (R = 0.8886).

Soil moisture values calculated by GPR and TDR have a high correlation coefficient using both (7) (R = 0.9256) and (8) (R = 0.9083) approaches. The radar values reliability ([3] and [5]) is minor than the one of TDR after the correlation coefficient from figures 3a and 4a.

In these experimental conditions (sandy loam soil and agricultural use) it makes no difference whether GPR or TDR is used for soil moisture content in toplayer horizons.

The model [3] does not require other data than K (dielectric permitivity). This is advantageous in front of the use of [4] model.

When monitoring soil humidity, frequently measurements through time are required. These are carried out in a very large range of temperature and bulk density conditions. In this case the use of [4] can be necessary to obtain more consistent results.

Due to the narrow range in soil water content values presented here GPR must be tested in moister conditions to better define the validity range.

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