Comparison of GPR and Capacitance Probe laboratory experiments in sandy soils

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Abstract — **The integration of different techniques for the estimation of the volumetric water content θ in low-loss sandy soils may allow to obtain more reliable measure, after a proper evaluation of the techniques limits and their pros and cons. In particular, the integration of direct laboratory measurements performed on samples (θ values measured) with geophysical data collected on a soil column using a Ground Penetrating Radar (GPR) as well as a Capacitance Probe (CP), allowed us to compare the results and evaluate their accuracy. Our experimental measures, performed on two typical sandy soil outcropping in Central Italy, show that the GPR reflected pulses provide similar permittivity (ε_r) values for both soils at very low θ. The measured ε_r values seem to progressively differ by increasing the soil moisture of the two sands. The CP shows a clear difference of measured permittivity already at lower soil moisture. As θ values in the media increase approaching the soil saturation, the CP ε_r values measured on both the two soils show a larger difference. In conclusion, the comparison between GPR and CP measures in two selected sands under controlled condition ($0.05 < \theta < 0.3$), shows that the latter tends to overestimate ε_r on the entire range investigated. Nevertheless, if a specific laboratory calibration is carried out, as in the present work, reliable θ values estimations can be obtained by both methods. Other measurement techniques will be tested and compared in further experiments; moreover, the calibration and integration of GPR and CP is advised not only in laboratory studies, but also to better constrain possible field applications.**

Keywords — Water content; GPR; PR2/6 probe; dielectric permittivity; sandy soils.

I. INTRODUCTION

An accurate estimation of the Soil Water Content (θ) is nowadays required in many fields and applications: assessments of landslide susceptibility, slope stability analysis, civil engineering, in the recharge of aquifers, in the remediation of contaminated lands and other hydrogeological applications.

The estimation of the Volumetric Water Content (θ_v) which is related to gravimetric water content (θ_g) by the water unit weight (γ_w) and soil dry unit weight (γ_d) is evaluated by different techniques both in the laboratory and in the field [1-3].

Among the field sensors, dielectric soil-moisture probes are used in unsaturated soil conditions [4]. These probes include Time Domain Reflectometers (TDR), Frequency domain reflectometers (FDR) and Capacitance Probes (CP). Over the last years many efforts have been spent to integrate several techniques to perform non-invasive and areal measures at intermediate scales. The latter include electromagnetic induction (EMI), ground-based radiometers, electrical methods [5-7], often combined with other equipments such as the Ground Penetrating Radar (GPR) [8]. The latter measures the reflections of an electromagnetic (EM) pulse probing the underground materials, in a frequency range generally between 1 MHz and 3 GHz. Changes in dielectric properties (ε_r) are responsible for the EM wave reflections. The GPR is a high-resolution geophysical technique often used to study the shallow subsurface [9-11], using 2D or 3D surveys in many applications [12-17]. GPR has been also used by itself to provide estimations of the θ_v in soils [18-22], e.g. computing θ_v from the well-known and widely used Topp equation [23], that relates θ_v and the apparent ε_r.

Among the CP probes, the PR2/6 (Delta-T Devices, Cambridge, UK) allows to measure θ_v at different depths by measuring the relative dielectric constant (ε_r) of the damp soil. The PR2/6 probe emits a signal of 100 MHz using six pairs of stainless steel rings (0.10, 0.20, 0.30, 0.40, 0.60 and 1.00 m depth), which transmits an electromagnetic field within the soil across a distance of about 0.10 m surrounding the probe. The change in the circuit output (in volts—V) is related to the square root of soil permittivity ($\sqrt{\varepsilon_r}$) by a sixth-order polynomial fit (Delta-T Devices Ltd., 2016), from which the θ values can be estimated [24-25].

II. METHODS

A. Soil characteristics and laboratory measures

Laboratory experiments were carried out on two sandy soils of Central Italy: a calcareous sand from *Conca Ternana* alluvial plain (S_A – 42° 33' 23" N, 12° 33' 35" E) and a flyschoid sand from recent fluvial deposits of Tiber River (S_B – 43° 7' 32" N, 12° 26' 4" E). The materials can be considered as representative of recent and ancient fluvial-lacustrine deposits widely outcropping along alluvial plains and hillslopes in Umbria Region and in other places in Central Italy [26-28]. Both sands were characterized at the Laboratory of Applied Geology of Perugia University by using the following ASTM standards:

- particle size distribution (ASTM D422-631998);

- specific gravity Gs (CEN ISO/TS 17892-3 2004);
- Atterberg limits (CENISO/TS 17892-12 2004);
- compaction properties (standard Proctortest, ASTM D698-12e2);
- organic matter (ASTM D2974-14).

The amount of sands is 83% and 95% for S_B and S_A, respectively. Soils are not plastic and the main mineralogical components are carbonates with subordinate minerals (muscovite, gypsum) for soil S_A and quartz, biotite, muscovite, pyrite, biotite, carbonaceous frustules for soil S_B. In order to test both GPR and CP equipment at the same experimental conditions, both soils were mixed with tap water and left for 24 h to moisten at controlled temperature conditions (T = 22 ± 1 °C). Then, the soils were placed and manually compacted in a cylindrical PVC container (soil column, diameter 0.50 m, and height 1.30 m). Different gravimetric water content (Θ_g) and dry density values (γ_d) were used which allowed testing soils with volumetric water content (Θ - eq. 1) from 0.05 m^3/m^3 to 1.25 m^3/m^3.

$$\Theta = \Theta_g \cdot \frac{\gamma_d}{\gamma_w} \qquad 1)$$

B. <u>*Experiment description (data collection and processing)*</u>

Ground Penetrating Radar (GPR) and Capacitance Probe (CP) data were collected on soils S_A and S_B compacted – at different water content conditions – in the cylindrical PVC container. The study goal was an evaluation of the relative dielectric permittivity ε_r, in controlled conditions, for the two sampled soils by integrating different techniques and datasets. We have compared the results of both such indirect techniques with the lab measurements performed on soil samples (from gravimetric method). In order to define the proper acquisition parameters and to aid the experimental data interpretation we first analyzed the results provided by GPR simulations.

Table 1 - Parameters used in the FDTD simulation.

Split step model parameters	
Frequency	***1000 MHz***
Source wavelet	Gaussian centered on the nominal frequency
Source–receiver offset	Zero offset
Length (m)	0.40
Depth (m)	0.31
dx (x-spacing)	0.004
dz (z-spacing)	0.002
Source start - end positions	0 – 0.38
Number of traces	100
dt (sampling time interval)	0.008
Time window [ns]	20

We used a finite difference forward modelling split-step (SS) algorithm implemented in MATGPR software [29].

The model was built with two polygons, with physical properties respectively representing the Sand Medium and a Perfect Electric Conductor (PEC [30], Fig. 1). The input parameters used in the simulation are summarized in Tab. 1.

The synthetic data like the example reported in Fig. 1, show that the reflection generated by the metal plate is located between 4-6 ns in case of $\varepsilon_{rsim} = 4$. As expected the TWT (ns) of such a reflector increases in case of higher ε_r values, simulating a higher θ (reflector TWT_{sim} between 8-9 ns with $\varepsilon_{rsim} = 15$).

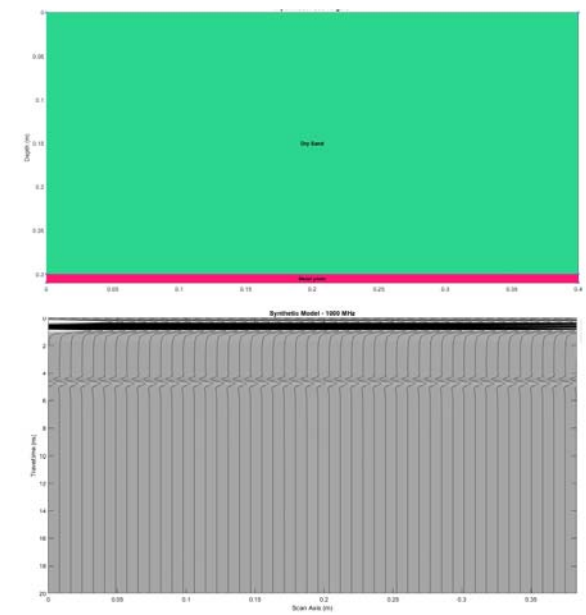

Figure 1 – SS simulation built to aid the experimental interpretation of the radargrams; a) two later model, medium 1 = sands and medium 2 = PEC; b) Synthetic radargram obtained modelling dry sands (ε_r=4; h=30 cm) showing the PEC reflection between a time interval of 4-5 ns.

The physical model we built up was made by a cylindrical PVC soil column of with a diameter of 40 cm and 43 cm height. The latter was filled up at different stages with the sandy soils and through a cylindrical standardized hammer (mass = 13.5 kg; diameter = 0.15 m) repeatedly dropped from a height of ~0.20 m and, using a regular sequence of blows in a circular motion, we compacted the sands to obtain a thickness of 30 cm (Fig. 2). The repeatability of the experiments has been guaranteed by deploying and compacting damp sand intervals about 10 cm thick in order to reach a similar soil unit weight. The workflow was repeated by increasing at different stages the θ values of the two soils in separated experiments.

The GPR measurements were carried out using a GPR in laboratory to evaluate the variation of the dielectric constant (ε_r) due to a higher θ water (larger TWT of reflections).
We used a Zond 12-e GPR and a high frequency antenna (1 GHz central frequency). We positioned a metal plate beneath the soil column as an excellent reflector (PEC) with the aim to clearly detect the maximum peak of its two-way-travel-time arrival on the radargrams (Fig. 2a).
The laboratory data collection encompassed 11 different tests (n°6 on S_A and n°5 on S_B, respectively). For each experiment we recorded n° 14 radargrams so that a total number of 154 GPR Common Offset (CO) profiles were collected on the same position at the center of the soil column. Several traces were recorded for each radargram, testing different parameters like the total number of samples (512 or 1024), the time window (from 25 to 100 ns), the stacking (128 traces max), the frequency filters, and also different heights from the top sand layer (every 5 cm up to 30 cm above). The radargram with the best S/N ratio was finally chosen to compute ε_r.
The processing flow of the raw data encompassed a trace cut (100 traces/profile) and computation of the "time-zero" correction on the first arrival (positive peak). Then, we picked the reflector (e.g. red line between 4-6 ns, in Fig. 3) interpreted as the horizon generated by the bottom side of the soil column, where the metal plate was located.

Figure 2 – Laboratory data acquisition on the soil column. The small box on the top illustrates a phase of sampling for direct θ measurements; a) 1 GHz GPR antenna used in reflection mode, with a metal plate located at the bottom of the soil column; b) 100 MHz FDR probe used to measure the soil moisture.

The picked TWT arrivals allowed us to compute the EM velocity (low-loss medium [9]) by using the eq. (2):

$$v = \frac{c}{\sqrt{\varepsilon_r^{'}}} \quad 2)$$

ε_r: relative dielectric constant;
c: propagation velocity in the air (3*10-8 m/s);
t: travel-time in ns;
h: thickness of the material;
By using the eq. (3) [31]:

$$\varepsilon_r = \left(\frac{c * t}{2 * h} \right)^2 \quad 3)$$

We computed the dielectric permittivity using the TWT values picked on each trace (then averaged) in correspondence of the metal plate reflector. As expected, our measures show that the progressively higher soil θ produced a decrease of the EM velocity, and therefore an increase of the ε_r values.
Such obtained experimental ε_r values are comparable with the GPR ranges reported by several authors (ε_r = 2-6) [9-11] in case of dry sandy soils. For higher θ_v contents the maximum value we measured is $\varepsilon_r = 14$, therefore again within the range $10 < \varepsilon_r < 30$ reported in literature in case of humid/web sands [9-11].

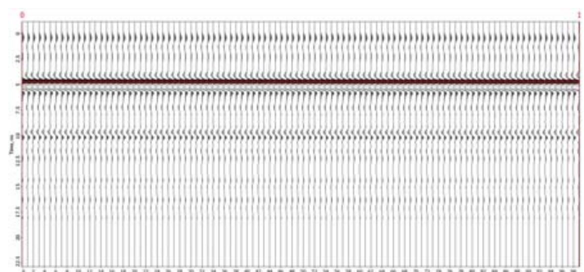

Figure 3 – Experimental GPR data collected on the soil S_A in natural (dry) condition. The PEC reflection is visible in the interval 2.5-5 ns and the red line represents the TWT picking done on the max reflection amplitude of each trace.

The CP device we used in the laboratory experiments is a profile probe PR2/6 (Delta-T Devices, Cambridge, UK) that allows to measure the relative dielectric constant (ε_r) of the damp soil down to 1 m depth. In the PR2/6 probe, a signal of 100 MHz is applied to six pairs of stainless steel rings: the change in the circuit output (in volts—V) is related to the square root of soil permittivity ($\sqrt{\varepsilon}$) by a sixth-order polynomial fit. According to the Topp equation [23] there is a simple linear relationship between the $\sqrt{\varepsilon}$ and θ. The manufacturer proposes the eq. 4, in case of mineral soils. Recently, Di Matteo et al. [25] carried out a calibration for the PR2/6 probe, proposing two specific equations for soils S_A and S_B (equations 5 and 6):

$$\sqrt{\varepsilon} = 1.6 + 8.4 \cdot \Theta \qquad \text{(mineral soils)} \quad 4)$$

$$\sqrt{\varepsilon} = 1.7 + 9.5 \cdot \Theta \qquad (S_A, R^2 = 0.997) \quad 5)$$

$$\sqrt{\varepsilon} = 1.9 + 10.6 \cdot \Theta \qquad (S_B, R^2 = 0.995) \quad 6)$$

The use of eq. 4 produces an overestimation of θ, particularly appreciable for $\sqrt{\varepsilon_r}$ higher than 3. As an example, for $\sqrt{\varepsilon} = 4.5$, the eq. 5 overestimates θ values of about 5 and 10 percentage points for soil S_A (calcareous sand) and soil S_B (flyschoid sand), respectively.

III. Data integration and results

The comparison between the results obtained using the 100 MHz CP and the 1000 MHz GPR antenna vs θ the values obtained through direct laboratory analyses (Fig. 4), shows different ε_r values from each technique within the studied interval ($0.05 < \theta < 0.30$). In detail, The GPR reflected pulses provide similar permittivity (ε_r) values for both soils ($\varepsilon_{r\text{-}SA}$ = 3.2 and $\varepsilon_{r\text{-}SB}$ = 3.6) at very low θ (0.05-0.07 m^3/m^3). The measured ε_r values seem to progressively differ by increasing the soil moisture ($\theta >$ 0.15% m^3/m^3) of the two sands (see trends of the GPR_S_A and GPR_S_B lines in Fig. 4). The CP data show, already at low soil moisture contents, an important difference in the ε_r values measured on both the two sandy soils ($\theta = 0.05$ m^3/m^3, $\varepsilon_{r\text{-}SA}$ = 4.6 and $\varepsilon_{r\text{-}SB}$ = 5.7). As θ values in the media increase close to the soil saturation, the ε_r values measured by the CP on both the two soils show a larger difference (see trends of the CP_S_A and CP_S_B lines in Fig. 4: e.g. if θ = 0.25 m^3/m^3, $\varepsilon_{r\text{-}SA}$ = 16.9 and $\varepsilon_{r\text{-}SB}$ = 21.2). Our results for the two selected sands analyzed in controlled condition shows the CP tends to overestimate ε_r on the entire range investigated. Nevertheless, this work illustrates that if a specific calibration is carried out in laboratory, reliable θ values estimations can be obtained using both methods even in field applications.

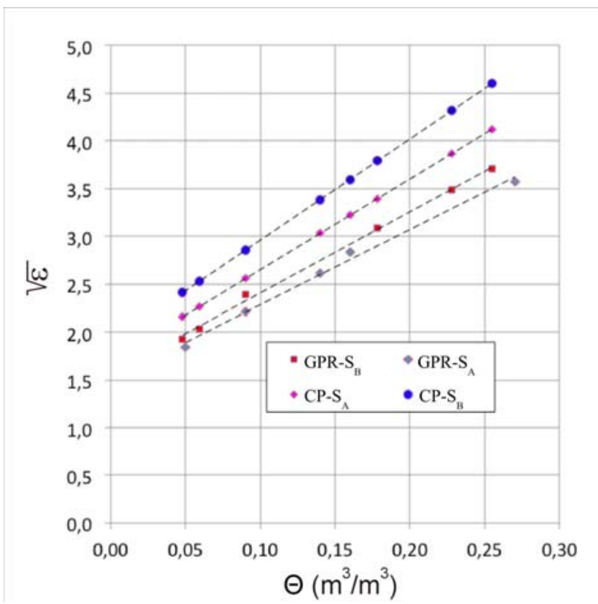

Figure 4 – Results of the ε_r laboratory measurements performed on the sandy soils S_A and S_B using GPR and CP techniques.

IV. Conclusions

We have provided a comparison between laboratory measures of relative dielectric permittivity ε_r, performed on two sandy soils outcropping in Central Italy, at different volumetric soil water contents. Our methodological approach and results suggest that integrated analyses are mandatory to better determine the limits of each method and to provide calibration relations necessary for obtaining reliable θ estimation on sandy soils in different moisture contents. The ε_r values presented in the framework of this project, are the first available reference permittivity values for typical sandy soils outcropping in Central Italy, considering a degree of saturation ranging from 5% to 92%. The comparison between GPR and CP measures in two selected sands under controlled condition ($0.05 < \theta < 0.30$), shows that the latter tends to overestimate ε_r on the entire range investigated. Although GPR and CP gave different ε_r values for the same soil moisture condition and sand type, the specific equations here used allow reliable θ values estimations with both methods. In other words, after a proper calibration, water content estimates from GPR were similar to those from CP measurements for the homogeneous tank experiment. In conclusion, the applications of some additional techniques (resonant cavity, parallel plates, etc.) will be evaluated to provide and compare ε_r measures, but the FDR and GPR integration, if properly calibrated, already represents a valuable method for the study of the physical properties and soil moisture conditions of sandy materials.

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