Enhancement and Metrological Characterization of an Accurate and Low-Cost Method Based on Seismic Wave Propagation for Soil Moisture Evaluation

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Abstract—Monitoring soil moisture is a major interest for several practical applications. This task can be suitably performed through various methods; however, at the state of the art, there is not a single method that successfully combines ease of use, low cost, customization, possibility of measuring large volumes, and, most importantly, measurement accuracy. In this regard, seismic wave propagation (SWP)-based methods, which rely on the evaluation of the propagation velocity of a seismic wave \( v_c \) through the soil sample under investigation, hold considerable potential for practical implementation. On such bases, in this work, first the authors propose an enhanced version of a previously developed SWP-based system for soil moisture measurement. Successively, to provide an exhaustive performance characterization of the system, a specific comparative methodology, based on reference time-domain reflectometry (TDR)-based measurements, is addressed. More specifically, SWP- and TDR-based measurements are simultaneously performed on river sand for increasing levels of water content. The TDR-measured moisture levels are taken as reference values and are used to infer the theoretical propagation velocity values \( v_{c,\text{MEAS}} \). Then, these reference values are suitably compared with those directly measured through the SWP-based system \( (v_{c,\text{MEAS}}) \), thus allowing a consistent metrological assessment. The ultimate goal of this work is to validate and characterize the performance of the proposed SWP-based system in view of practical implementation for soil moisture evaluation.

Index Terms—Moisture measurement, seismic waves, soil measurements, time-domain reflectometry (TDR), uncertainty.

I. INTRODUCTION

MOISTURE evaluation of porous materials is a major interest in many fields, such as soil science and agriculture. In fact, in the former field, moisture content can be associated to several other properties of the investigated soil. Similarly, in agriculture, the accurate instantaneous knowledge of the amount of water content of soil is crucial, e.g., for an effective irrigation scheduling.

However, in spite of its importance, measuring the moisture content of soils is not a trivial task; in fact, there are many involved factors (e.g., granulometry, nonhomogeneity, and physical and chemical composition) that should be taken into account to accurately retrieve soil moisture levels. A wide variety of methods are commonly used to estimate soil water content, ranging from destructive (gravimetric) to nondestructive methods (gamma radiation probe, neutron probe, porous blocks, etc.). The gravimetric sampling for water content estimation is a highly accurate method; unfortunately, it becomes difficult to apply when large sample volumes are involved.

On the other hand, nondestructive methods for measuring soil water content, such as the neutron scattering method [1] and the gamma ray attenuation method [2], are also accurate; nevertheless, their higher costs and caution to avoid possible health hazards [3] limit their adoption. Electromagnetic methods, such as time-domain reflectometry (TDR), ground-penetrating radar [4], [5], or active microwave remote sensing [6], can estimate water content by performing permittivity measurements on the target medium. However, none of the aforementioned methods simultaneously guarantees low cost, ease of use, and high measurement accuracy.

In the last few decades, there has been a growing interest toward the seismic wave propagation (SWP)-based technique as an alternative low-cost method for measuring soil moisture [7]–[9]. This method is particularly attractive for applications where quickness of measurements, reliability, and, most importantly, low cost and customization possibility are prerogatives that are simultaneously required.

SWP-based methods rely on the fact that the propagation velocity of elastic waves is strongly dependent on the intrinsic properties of the material in which they propagate and, hence, on its moisture level [10]–[12].

Generally, the SWP-based method involves a seismic wave generation source and a specifically customized receiver that records the time of flight \( T_f \), which, in turn, leads to the estimation of the propagation velocity of the wave \( v_c \). Finally, knowing the propagation velocity, through a theoretical model, it is possible to estimate the corresponding unknown moisture level.

The theory of propagation of elastic waves in porous mediums was first developed by Gassmann [13] and Biot [14]; the relationship between Lamé’s constants and the velocity of compressional waves was derived by Brutsaert [10], who investigated the particular case of three-phase porous mediums (liquid, gas, and solid phases). Brown and Korriga [12]...
extended the validity of the Gassmann’s equation by analyzing the dependence of the elastic properties of a porous rock. Brown and Korriga formulation is still highly regarded.

Although the seismic wave propagation in porous mediums has deeply been studied, there are still several open issues related to the applications of the SWP method. One of the crucial aspects relates to the optimal choice of the signal form (i.e., sinusoidal, pulse, pulse train, etc.).

In previous works, the authors developed an SWP-based device that used a low-frequency pulse signal (with a frequency content on the order of hundreds of hertz) [15], [16]. Obtained results were promising and encouraging; nevertheless, some inherent aspects of the previous method (i.e., signal not perfectly repeatable, low sensitivity, spectrum concentrated at low frequency, presence of spurious peaks, etc.) limited the practical applicability.

In this paper, an enhanced version of this system is proposed, and the aforementioned limits are overcome by resorting to a different excitation signal, i.e., an amplitude-modulated (AM) signal. This strategy, as clearly demonstrated by the experimental results, successfully leads to three major improvements: 1) the substantial simplification of the data processing that is necessary for the retrieval of the desired information; 2) the reduction of the overall measurement uncertainty; and 3) the exclusion of the trigger source.

Starting from these considerations, this work aims at validating the newly proposed SWP-based system and at characterizing its performance in view of practical in situ applications. For these purposes, the authors address a specific comparative methodology that, starting from some reference TDR measurements, can successfully relate the SWP-measured propagation velocity to an accurate reference value of moisture.

It is worth mentioning that the state-of-the-art literature does not address a rigorous procedure for the validation of the SWP-based methods. Furthermore, although reference data for moisture measurements are traditionally obtained through the use of the gravimetric method, such a method becomes unsuitable when large sample volumes are tested (which is the case of the experimental conditions used in this paper).

The TDR technique is a well-established electromagnetic method for moisture measurements, and it has thoroughly been investigated in literature [3], [17]–[19]. Additionally, a specific metrological characterization of TDR methods in soil moisture evaluation has been addressed in [20] and [21]. In such a context, the adoption of the TDR technique for evaluating the reference moisture values provides several advantages and appears as a robust tool for the metrological characterization of the proposed SWP-based system.

To validate and metrologically characterize the SWP method, moisture content measurements are simultaneously performed through the TDR and through the TDR methods on sand watered at several different moisture levels.

On a side note, it is interesting to point out that the TDR- and SWP-based methods are based on very different concepts: the former takes into account the response (in terms of reflected signal) of the investigated material to an electromagnetic stimulus, whereas the latter considers the response (in terms of soil particles displacement) to a mechanical stimulus.

This paper is structured as follows: Section II provides a thorough description of the used experimental setup, of the theoretical background, and of the proposed approach. In Section III, the experimental results are reported and discussed. Finally, in Section IV, conclusions are drawn.

II. MATERIALS AND METHODS

In this section, after briefly addressing the sample preparation, the theoretical background of the SWP method is recalled, and the enhancements added to the SWP-based system are discussed. Successively, the performed experiments and the proposed validation methodology are described in detail.

A. Sample Preparation

The material considered for the measurements is river sandy soil, with density $\rho_s = 1500 \text{ kg/m}^3$ and porosity $\varphi = 0.39$.

The soil porosity was determined using an experimental method based on the assumption that the porosity is equal to the air percentage contained in a specimen of soil where the bulk modulus of water $k_w$ is 2.4 GPa and the bulk modulus of air is considered equal to $1.45 \cdot 10^{-4}$ GPa.

The soil was placed in an open-top box measuring $1.7 \text{ m} \times 0.8 \text{ m} \times 0.9 \text{ m}$. Starting from the sample at environmental moisture $s_0$, the soil was progressively watered at 11 different levels of unknown moisture content ($s_1, \ldots, s_{11}$). Water was added from the top of the box; therefore, to ensure a homogeneous distribution of water, measurements were performed after a waiting time of 24 h. For each moistening condition, both the SWP- and TDR-based measurements were performed on the same measurement plane (see Fig. 1), which corresponds to a distance from the top of the box of 0.3 m.

B. SWP-Based Measurements

The experimental setup used for the SWP-based moisture measurements includes a compressional wave actuator (CWA), a directional piezoelectric sensor, and a general-purpose digital acquisition (DAQ) device.

The actuator, which was appropriately designed and realized, generates the compressional waves that propagate in the soil. The propagated signal is collected by the piezoelectric sensor, which is placed at a known distance from the CWA. The output signal from the piezoelectric sensor is digitized by means of the DAQ device. Fig. 1 shows a scheme of the overall measurement setup.

The SWP system measures the propagation delay of waves through the soil. In particular, the operating principle used to assess $v_c$ is the estimation of the time of flight $T_f$ through the following expression:

$$v_c = \frac{d}{T_f}$$  \hspace{1cm} (1)

with $d$ being the known distance between the CWA and the piezoelectric sensor.
Then, $v_c$ can be related to the moisture level through a well-known theoretical model [10], [22]

$$v_c = \Psi \sqrt{\frac{0.306 \cdot p_e^{1/3} \cdot Z}{\rho \cdot \varphi}}$$

(2)

where $p_e$ is the effective pressure, $\Psi$ is a corrective parameter that depends on the kind of soil, $\rho$ is the total bulk density of the moistened soil, and $Z$ is a coefficient that accounts for the influence on the compressional wave velocity of the air and of the water content in the soil [23]. It is worth pointing out that the parameters involved in (2) can be related to the specific moisture content, as reported in [15].

From (1), it is apparent that the accurate estimation of $v_c$ depends on the uncertainty affecting $d$ and $T_f$, respectively.

In this regard, the newly proposed SWP method successfully overcomes a strong limitation that was intrinsic of the sensor proposed in [16] and leads to a more accurate estimation of $T_f$.

In fact, in [16], the shape of the used electromechanical signal (i.e., a voltage steplike pulse whose harmonic content was predominant at low frequencies) had three major limitations. First, the generated signal had to be triggered to accurately individuate the exact instant $t_0$ in which the wave propagation began. Additionally, it was necessary to account for the time lag between the wave generation instant and $t_0$; in [16], this issue was circumvented by placing a piezoelectric sensor in contact with the electromechanical actuator. Finally, even when $t_0$ was accurately known, the evaluation of the instant when the piezoelectric sensor received the signal was affected by a significant uncertainty: this was particularly troublesome when dealing with low moisture levels. In fact, in these experimental conditions, the amplitude of the received signal was often comparable with noise and frequently presented spurious peaks of moderate size, thus leading to some ambiguities in the evaluation of $T_f$ and, consequently, in the final estimation of $v_c$.

On the other hand, the SWP-based device proposed herein successfully overcomes the aforementioned limitations by using a damped digital sinusoid (synthesized through a specific digital technique) in place of the low-frequency pulse. The used signal was synthesized through an HP 33250A. The used signal is described by the following equation:

$$t(nT) = A_t(nT)^m e^{-nT/\mu} \cos(2\pi f_t nT + \psi_t)$$

(3)

where $A_t$, $f_t$, and $\psi_t$ are the signal amplitude, frequency, and phase, respectively; $m$ determines the initial finite slope of the signal; the parameter $\mu$ models the final one; and $T$ is the sampling period. In the measurements reported herein, these parameters were set as follows: $T = 10 \mu s$, $A_t = 500$ mV, $f_t = 500$ Hz, and $\psi_t = 0$, where the characteristic of the carrier was selected to assure that the propagation of the acoustic wave would practically be elastic with a negligible dissipation factor. As for the optimal values of $m$ and $\mu$, experimental results confirmed that, when they are assumed to be equal to 2 and $3.5 \cdot 10^{-2}$, respectively, the beginning and the end of the received signal are simply identified.

Finally, the estimation of $T_f$ is based on the search of the relative maximum of the correlation function

$$C(hT) = \sum_n t(nT) r[(n + h)T]$$

(4)

according to the cross-correlation method [24], with $r(nT)$ being the signal received by the piezoelectric sensor and expressed as

$$r(nT) = \alpha A_t(nT - T_f)^m e^{-(nT-T_f)/\mu} \cos[2\pi f_t (n(T-T_f)+\psi_t)]$$

(5)

with $\alpha < 1$ being the attenuation coefficient.

Fig. 2(a) shows an example of the generated signal that was used in the experiments reported herein; similarly, Fig. 2(b) shows the corresponding received signal. Finally, Fig. 3 shows the cross correlation between the generated and received signals.

### C. TDR Measurement for the Performance Assessment

The experimental setup used for the reflectometry measurements includes a TDR unit (Campbell Scientific TDR100), a
Fig. 2. (a) Signal generated by the CWA. (b) Signal received by the piezoelectric sensor.

Fig. 3. Cross correlation between the generated and received signals.

30-cm-long three-rod probe (Campbell Scientific CS610) [25], and a 3.5-m-long 50-Ω-matched coaxial cable that connects the probe to the TDR unit. The TDR100 generates a step-pulse signal with a rise time of 200 ps, which corresponds to a frequency bandwidth of 1.7 GHz. The generated signal propagates along the probe immersed in the material under test; the reflected signal coming from the probe is recorded by the same TDR unit and is displayed in terms of reflection coefficient, as a function of apparent distance.

As previously mentioned, to validate the proposed SWP method, reference TDR measurements were performed on all the sand samples \( s_1, \ldots, s_{11} \).

To these purposes, the TDR probe was horizontally buried in the sand (at a depth corresponding to the measurement plane), and it was not removed until all the experiments were performed.

It is worth pointing out that this last aspect represents a major advantage of using TDR for gathering accurate reference values for the moisture level of the sand samples. In fact, although other standard methods for evaluating reference moisture levels (i.e., the gravimetric method) should virtually provide more accurate results, in the present case, such a method is not practically feasible. As a matter of fact, resorting to the gravimetric method would require that, for each moistening condition \( (s_1, \ldots, s_{11}) \), a number of test samples should be removed from the area corresponding to the measurement plane. Such a procedure, besides being extremely time consuming, may also not guarantee the expected accuracy. Indeed, the very removal of different test samples all along the measurement plane would not allow an easy check of the homogeneity condition; additionally, it would alter the initial experimental conditions. Conversely, the adoption of the TDR technique quickly fulfils both the aforementioned tasks and preserves the experimental conditions.

The preliminary analysis of the TDR traces allows verifying the homogeneity of moistening along the \( x \)-direction of the measurement plane (see Fig. 1). As an example, Fig. 4 shows the TDR waveform corresponding to the sample \( s_4 \): the stable response, in terms of steadiness of the reflection coefficient values, indicates the homogeneity of moistening along the considered direction.

The second and most important aim of the TDR measurements was to determine the values of the unknown moisture levels of the sand contained in the box. The procedure for performing these measurements is described in detail in [21]. However, for the sake of completeness, an overview of the basic principles for the practical evaluation of the moisture levels and of the corresponding uncertainty values is briefly addressed herein.

The first step before performing the TDR-based measurements was to derive the so-called calibration curve for the specific type of sand. The calibration curve describes the empirical relationships between the moisture level \( \vartheta \) and the
corresponding dielectric constant $\varepsilon$. This way, when dealing with an unknown moisture level, it is enough to measure the dielectric constant, and the corresponding moisture level is simply retrieved from the calibration curve.

The $\varepsilon-\vartheta$ calibration curve is typically assessed as follows: samples of the considered material are moistened (through the volumetric method) at prefixed values of moisture $\vartheta_{\text{REF}}$, and the corresponding dielectric constant $\varepsilon$ is measured through the TDR method. The $(\varepsilon, \vartheta_{\text{REF}})$ points are fitted through the nonlinear regression method [21], [26]: additionally, lower and upper confidence limits (corresponding to a confidence level of 95%) are associated to the regression curve.

This procedure was specifically adopted to identify the $\varepsilon-\vartheta$ curve for the river sand used in this work. The uncertainty on the evaluation of $\varepsilon$ can be expressed as $\varepsilon_c = 2.26\sigma$ (obtained from repeated averaged measurements), where $\sigma$ is the standard deviation corresponding to the Gaussian probability distribution (which was verified through the $\chi^2$-square test). The expanded uncertainty was thus evaluated, considering the $t$-distribution of student, and 2.26 is the $t$-score that corresponds to a confidence level of 95%.

Fig. 5 shows the $\varepsilon-\vartheta$ calibration curve, along with the associated confidence levels for the tested river sand. This way, referring to this calibration curve and performing the TDR measurements, it was possible to associate a reference value to each moisture content of the sand ($s_1, s_2, \ldots, s_{11}$).

From the evaluation of $\vartheta$, the corresponding saturation degree ($S$), which is the parameter that is typically considered for the SWP measurements, can easily be derived according to the following expression:

$$S = \frac{\vartheta}{0.39}$$  \hspace{1cm} (6)

where 0.39 is the porosity $\varphi$ of the considered river sand.

The procedure for assessing the performance of the SWP-based systems is summarized in the functional scheme in Fig. 6. For each moisture level (from $s_1$ to $s_{11}$), the following steps were followed. First, a TDR measurement was performed and was used to verify that a homogeneous moistening had been reached over the measurement plane. Then, $\varepsilon$ was evaluated through this TDR measurement and was used to retrieve the corresponding moisture level $\vartheta$ from the calibration curve in Fig. 5. This value of $\vartheta$ was used to calculate the value of the corresponding saturation degree ($S_{\text{REF}}$) according to (6). Successively, $S_{\text{REF}}$ was used in a well-known model [10], [11] to infer the corresponding value of $v_c,\text{REF}$ according to (2). This value of $v_c,\text{REF}$ was compared with the value of the propagation velocity of the seismic wave directly obtained from the SWP method ($v_c,\text{MEAS}$). Finally, to provide a metrological characterization of the proposed SWP method, the experimental uncertainties associated with $v_c,\text{MEAS}$ were estimated, along with the deviation of these data from the reference values predicted by the theoretical model.

III. RESULTS AND DISCUSSIONS

The propagation velocities were measured, at a fixed depth of 0.3 m from the top surface of the box, for the 11 different values of moisture level. To evaluate the experimental uncertainties in the measured $v_c,\text{MEAS}$, 100 repeated measurements were performed for each moistening condition, thus eventually considering the average value $v_c,\text{MEAS}$. After verifying the hypothesis of normality for sample function distribution (applying the $\chi^2$-square test with a significance level of 5%), the extended uncertainties $U_{v_c,\text{MEAS}}$ associated to a confidence level of 95% and 99 DOFs were calculated, considering the $t$-student distribution.

Simultaneously, the reference moisture level was evaluated through the TDR technique. The corresponding value of $S_{\text{REF}}$ was calculated from (6), substituted in the model described by (2) and discussed in [23]. This way, the reference value of the propagation velocity $v_c,\text{REF}$ was derived.

As previously mentioned, the uncertainty on $v_c$ depends on the uncertainty affecting $d$ and $T_f$, respectively.

Since $d$ is measured with a highly accurate infrared sensor (whose relative measurement uncertainty is 0.4%), the related uncertainty is practically negligible; therefore, the critical point in obtaining accurate values of $v_c,\text{MEAS}$ is mostly related to the evaluation of the $T_f$.

In this regard, it is important to note that the uncertainty components that contribute to the overall uncertainty budget of $T_f$ are those due to the processing algorithm $U_{T_f,\text{al}}$, the instrumental setup $U_{T_f,\text{in}}$, and, most importantly, the nonidealities of the sample under test $U_{T_f,\text{sa}}$. As a matter of fact, $U_{T_f,\text{al}}$ and $U_{T_f,\text{sa}}$ are strictly dependent on the specific experimental conditions, whereas $U_{T_f,\text{in}}$ can simply be reduced by choosing $T \ll T_f$.

Indeed, the $t(t)$ signal is a narrow-band signal, but its correlation function is highly oscilatory; as a result, it is difficult to discriminate the actual maximum from the other peaks having similar amplitudes. In this case, considering the index $h_{\text{max}}$ of the peak of the correlation function, the time of flight is estimated as $T_f = h_{\text{max}} \cdot T$. This guarantees a worst case uncertainty on $T_f$ no better than $T_f/2$, which, however, is considered adequate for the intended purposes. This technique ensures that the time error will be zero only when $T_f$ is a multiple of $T$.  

Fig. 5. TDR experimental calibration curve ($\varepsilon-\vartheta$) for the considered sand. Related confidence limits, which are associated to the 95% of probability occurrence, are also reported.
Table I shows the comparison between the theoretical values \( (v_{c,REF}) \) and the average measured values \( (\bar{v}_{c,MEAS}) \), which were obtained for each value of saturation degree; the theoretical curve is obtained for \( \Psi = 1.21 \cdot 10^3 \, \text{dyn/cm}^2 \). The experimental expanded uncertainty on \( \bar{v}_{c,MEAS} \) is also reported.

To highlight the improvements of the proposed SWP-based system, measurements on the same sand samples were also performed using the “old” SWP system, which involved a steplike signal as stimulus. Indeed, measurements with the “old” system were limited only to the samples \( s_1, s_2, s_3, s_4, \) and \( s_5 \); in fact, for higher moisture levels, the received signal became less repeatable, presented spurious peaks, and did not allow correct data processing. The values of the propagation velocities measured with this system and the corresponding uncertainties are reported in Table II.

The comparison between the “new” and “old” SWP methods clearly demonstrates the introduced accuracy enhancement since the uncertainty associated with \( \bar{v}_{c,MEAS} \) when the AM signal is used is approximately halved.

To provide a rough idea of the agreement between the measured data and the theoretical values predicted by the considered model, a specific parameter \( D \) is specifically introduced, i.e.,

\[
D = \frac{\bar{v}_{c,MEAS} - v_{c,REF}}{v_{c,REF}} \cdot 100. \tag{7}
\]

Nevertheless, \( D \) should not strictly be considered as the systematic error since the values of \( v_{c,REF} \) are not true values; on the contrary, they represent the best estimate made by substituting the TDR-measured value of saturation degree \( S \) into the theoretical model. The continuous line in Fig. 7 shows the theoretical behavior predicted by the considered model of \( (2) \). It can be noted that, for lower levels of \( S \), the theoretical
The increasing interest in measuring moisture content in many fields, such as soil science and agriculture, motivates the development of inexpensive, reliable, and customizable systems. In previous works, the authors had developed an SWP-based system for soil moisture measurements. In this paper, the authors have further enhanced the measurement method by adopting a modulated signal as the electromechanical stimulus for the SWP measurements: this solution has effectively overcome several drawbacks related to the previously proposed methodology. Results have demonstrated that the newly proposed method guarantees higher measurement accuracy. Furthermore, the agreement between measurement and theoretical prediction has been confirmed through a comparative approach that relied on TDR-based measurements as reference data, thus providing useful information leading to the compensation for the systematic error contributions. On such bases, the proposed system can be regarded as a viable solution that successfully optimizes the tradeoff of reliability, ease of use, low cost and, most importantly, customization possibility.

IV. CONCLUSION

The increasing interest in measuring moisture content in many fields, such as soil science and agriculture, motivates the development of inexpensive, reliable, and customizable systems. In previous works, the authors had developed an SWP-based system for soil moisture measurements. In this paper, the authors have further enhanced the measurement method by adopting a modulated signal as the electromechanical stimulus for the SWP measurements: this solution has effectively overcome several drawbacks related to the previously proposed methodology. Results have demonstrated that the newly proposed method guarantees higher measurement accuracy. Furthermore, the agreement between measurement and theoretical prediction has been confirmed through a comparative approach that relied on TDR-based measurements as reference data, thus providing useful information leading to the compensation for the systematic error contributions. On such bases, the proposed system can be regarded as a viable solution that successfully optimizes the tradeoff of reliability, ease of use, low cost and, most importantly, customization possibility.

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