

Soil Moisture Measurement by Using Seismic Wave

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Abstract - The work proposes an accurate, on-site and real-time method to measure the moisture content of agricultural soils; the idea is to estimate the moisture measuring the velocity of propagation of seismic waves in the medium applying a new model based on the use of both *compressional* and *shear* waves. In a previous paper the authors derived the relationship between the compressional wave speed and the moisture content for various kind of soils; they also derived the conditions for the actual validity of the proposed relationships and a suitable range of frequencies for the sound used as the input stimulus, for a wide range of agricultural soils in different physical conditions. In this paper, the use of shear wave velocity is proposed aiming to increase the accuracy of moisture estimation and to reduce the number of parameters affecting the measurement without increasing the computational charge. Finally, using the results obtained, they propose a portable, accurate and very cheap sensor suitable for direct use by farmers and/or not specialized personnel.

Keywords: Acoustic propagation, soil measurements, moisture measurements

1. INTRODUCTION

Nowadays there is an higher and higher interest in *precision agriculture*, roughly consisting in the scientific exploitation of an agricultural soil based on the detailed knowledge of its microclimatic characteristics. Precision agriculture assures the best crop growth and therefore the greatest economic return, with the lowest environmental impact; it is therefore, quite obviously, an issue of paramount economical and political importance. An accurate knowledge of the soil microclimate requires, of course, the application of suitable and innovative measurement technologies.

Generally speaking, analyzing the properties and the characteristics of soils is difficult, expensive and time-consuming; in particular measuring the *water content in a soil* is one of the most important but still most difficult task.

In the past decades several techniques have been developed for this purpose, e.g. the dated *gravimetric soil sampling*, the *neutron scatter* technique, the *dielectric constant* measurement, and so on; however, none of these methods is really accurate, low cost, user-friendly and reasonably quick at the same time [1, 2, 3].

Besides, it is well known that the velocity of propagation of an acoustic wave in an unconsolidated granular medium is a function of its porosity, its density and its moisture content; the authors propose the use of a compressional (or primary) wave, but also of a shear (or secondary) wave received at a known distance from a transmitter to measure the moisture content.

Applying a simplified moisture-velocity ($S-v$) model, they focus on the feasibility of a portable sensor based on a simple and cost effective technology; it is composed by a couple of piezoelectric actuators used to generate both a shear wave (that shakes the soil perpendicular to the direction of propagation) and a compressional wave (that shakes the soil in the same direction of propagation); finally they use a piezoelectric hydrophone to receive the transmitted signals at a known distance from the source. Starting from the Brutsaert's model [4, 5] the authors have previously obtained an approximate functional relationship between the moisture content and the velocity of propagation of the compressional acoustic wave v_c [6]; in this paper they present a simple model which allows also to

evaluate the velocity of propagation of seismic wave (that is a shear wave) v_s as a function of the degree of saturation of the soil.

2. THE COMPRESSIONAL VELOCITY

It is well known that if a soil specimen is stressed by an inner force, it generates three types of compressional waves but only one type of shear wave; it has been already proven that among the compressional waves, at low frequencies, only one of them prevails over all others [4], [7]. In the following we will call this wave *the primary wave* and we will use the symbol C to indicate it; instead we will use the symbol T to indicate the shear wave which will be called *the secondary wave*.

In a previous paper [6], the authors already found the following relationship for the velocity of a compressional wave in a soil:

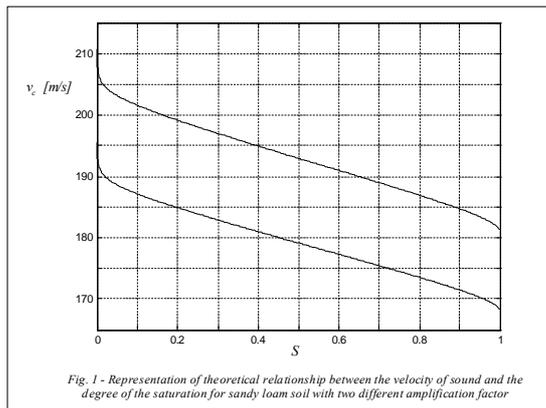


Fig. 1 - Representation of theoretical relationship between the velocity of sound and the degree of the saturation for sandy loam soil with two different amplification factor

$$v_c = \Psi \sqrt{\frac{0.306 \cdot p_e^{1/3}}{\rho \cdot f}} Z \quad (1)$$

where Ψ is an factor depending on the kind of soil, f is the soil porosity, p_e is the effective pressure, ρ represents the total bulk density and Z is a parameter which describes the effects of the interstitial fluids. Eqn. (1) is very useful for soil microclimatic characterization because the parameter f is related to the *degree of saturation with liquid* S by the expression:

$$S = \frac{u}{f} \quad (2)$$

being u the *soil moisture* i.e. the percentage of water in the soil. The quantity Z in (1), which accounts for the air and water influence on the velocity, can be expressed as a function of the effective bulk modulus k_e [8] as:

$$Z = \frac{\left[1 + \frac{30.75 \cdot k_e^{3/2} \cdot b}{p_e^{1/2}} \right]^{5/3}}{\left[1 + \frac{46.12 \cdot k_e^{3/2} \cdot b}{p_e^{1/2}} \right]} \quad (3)$$

k_e depending on S as:

$$k_e = \frac{k_a \cdot k_w}{k_a (1-S) + k_w \cdot S} \quad (4)$$

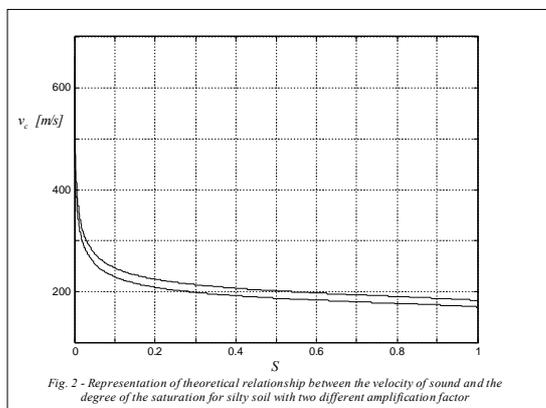


Fig. 2 - Representation of theoretical relationship between the velocity of sound and the degree of the saturation for silty soil with two different amplification factor

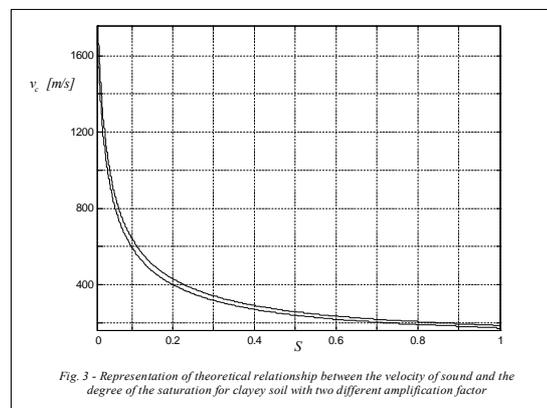


Fig. 3 - Representation of theoretical relationship between the velocity of sound and the degree of the saturation for clayey soil with two different amplification factor

being $k_a \cong 1.4 \cdot 10^5$ Pa and $k_w \cong 2 \cdot 10^9$ Pa the bulk modules of air and water, respectively [9]; the authors shown that Z can be considered close to one under suitable hypotheses [6] when b varies in the range $[10^{-12}, 10^{-10}]$ Pa⁻¹. In this case v_c can be approximated as:

$$v_c = \Psi \sqrt{\frac{0.306 \cdot p_e^{1/3}}{\rho \cdot f}} \quad (5)$$

and three different types of curves are possible, depending on the different kind of soil:

- almost linear for $S \in [0.2, 0.7]$ for greatly sandy soils (Fig. 1);
- almost linear in $S \in [0.3, 0.6]$ for greatly silty soils (Fig. 2);
- approximately exponential for $S \in [0, 1]$ for greatly clayey soils (Fig. 3).

Moreover they shown that the validity of both (1) and (5) is assured only when the frequency for the transmitted stimulus belongs to the range $[150, 900]$ Hz; these boundaries were obtained for the greatest value of hydraulic conductivity and for intermediate distances between transmitter and receiver (in the order of a meter); these hypotheses assure the applicability of the model to almost all kind of soils. Unfortunately, the relationship between v_c and S is non linear and requires the measure of some other soil parameters to produce an estimation of water soil content even when a suitable simplification of the relationship can be used.

3. THE SHEAR VELOCITY

To enlarge the information deriving by the acoustic propagation waves and to increase the accuracy of the soil moisture estimation the shear wave must be considered; in this section a simplified moisture-shear velocity relationship will be derived. For clearness' sake, a brief recall of some basic concepts of elastic wave theory is necessary.

It can be shown that in a homogeneous and isotropic medium the velocity of the compressional wave can be written in a very exhaustive form as:

$$v_c = \sqrt{\frac{\lambda + 2c_{sg} + 2c_{sw} + c_g + c_w + 2\mu}{\rho}} \quad (6)$$

where λ and μ are, respectively, the first and the second Lamé's parameters, which relate stress and strain according to the Hooke's law, and c_{sg} , c_{sw} , c_w and c_g are the elastic coupling coefficients; under the same hypotheses, the shear velocity is given by the following expression:

$$v_i = \sqrt{\frac{\mu}{\rho}} \quad (7)$$

Expressing the Lamé's coefficients in terms of the soil parameters:

$$\begin{aligned} \lambda &= (0.0765 a p_e^{1/3}) / f b^{2/3} \\ \mu &= (0.115 a p_e^{1/3}) / f b^{2/3} \end{aligned} \quad (8)$$

and expressing the total bulk density in terms on both soil and the water density, ρ_s and ρ_w , respectively:

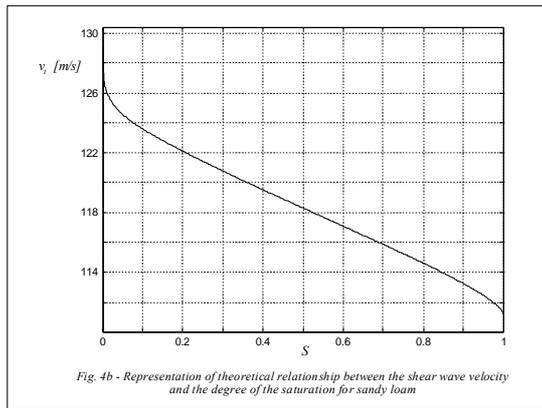
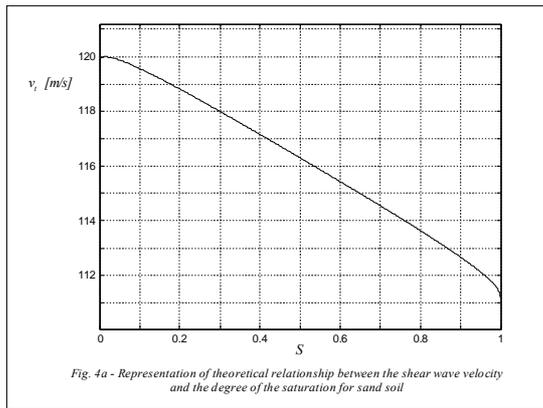
$$\rho = (1-f)\rho_s + f S \rho_w \quad (9)$$

eqn. (6) reduces to (1) and (7) can be rewritten as:

$$v_i = \Psi \sqrt{\frac{0.115 \cdot p_e^{1/3}}{f \cdot \rho}} \quad (10)$$

According to the Gassmann's theory [10], at low frequencies, the shear modulus is not sensitive to fluid content if the medium is considered approximately isotropic i.e. $\mu = \mu_{sat}$ when the degree of saturation with liquid changes, while λ is elastically dependent on fluid properties. In this case, the ratio $0.115 p_e^{1/3} / f$ in (10) is practically constant when both the effective pressure and the soil porosity are fixed, so the quantity v_i decreases when S increases according to (9). From a brief analysis of (10) it can be seen that v_i depends on the amplification factor Ψ defined as $\Psi = a^{1/2} / b^{1/3}$ and it is therefore linked to the granular properties of the material. It can be also shown (Figures 4a and 4b) that the

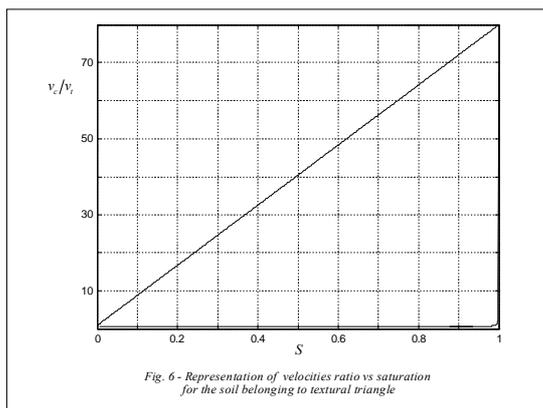
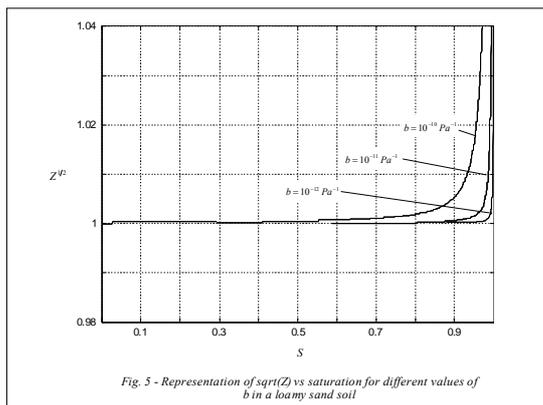
curves $S - v_t$ are approximately linear when S varies in the range $[0.1, 0.9]$ and that, differently from the case of v_c , there is always a bi-univocal correspondence between S and v_t .



Now, considering Eqn. (1) and (10), it is possible to express the ratio of the two velocities as:

$$\frac{v_c}{v_t} = 1.63\sqrt{Z} \quad (11)$$

which reduces to the constant value 1.63 when the quantity Z is close to one. This theoretical result is very interesting because it agrees with the previous experimental results [11] which show that, under suitable hypotheses, the shear wave velocity is about 40% lower than those for associated C waves.



4. THE Z FACTOR

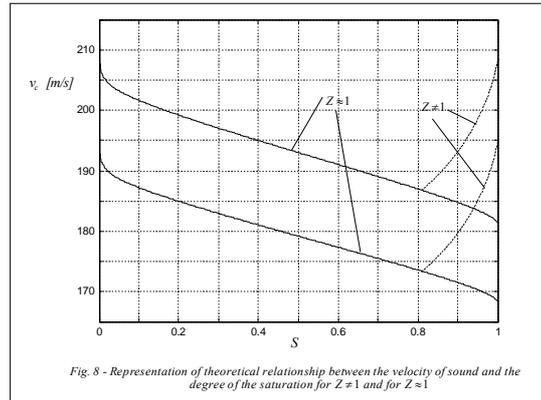
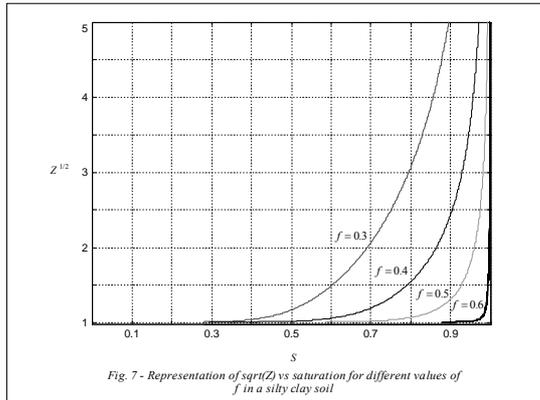
The behaviour of the acoustic waves in the soil is strongly dependent on the value of Z which accounts for the fluids influence in the granular medium. It affects the compressional wave velocity (1) but not the shear wave velocity; this effect is chargeable to dependence of λ on S and the independence of μ on S .

Eqn. (3) carries out that Z depends on S via effective modulus k_e defined in (4); a careful analysis shows that it is quite insensitive to S and very close to one when the parameter b varies in the range $[10^{-10}, 10^{-12}] Pa^{-1}$ and p_e is uniform in the soil (Fig. 5).

In this case the velocity v_c in (1) reduce to (5) and the ratio v_c/v_t is constant and close to 1.63 (Fig. 6). For different value of porosity the curves show that the Z parameter increasing with the degree of saturation with liquid (Fig. 7) so that the sound compressional velocity differs to approximate curves (Fig. 8) and the v_c/v_t ratio increases with S (Fig. 6).

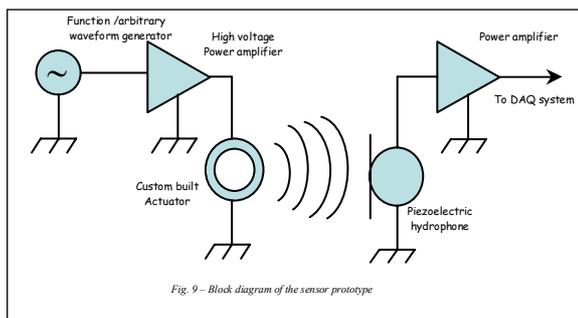
This effect is caused by the different behaviours of shear and compressional wave velocities when S increases: in fact v_c decreases linearly with S

and continues its downward trend when the full saturation is approached (i.e. when $S \rightarrow 1$), while v_t is linked to Z , so it decreases non linearly with S and increases for large values of S reaching the theoretical value of ∞ when the full saturation is approached ($S \approx 1$). This is a very interesting results because the ratio v_c/v_t increases with S only when water content in the soil is non uniformly distributed (i.e. when $Z \neq 1$) whereas the ratio is constant with S and close to 1.63 when the water and air are homogenously distributed (i.e. when $Z \cong 1$).



5. PROTOTYPE DESCRIPTION

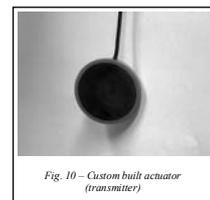
Building on a previous working prototype of the moisture sensor (already built in cooperation with a specialized electronic industry [7]), the authors produced some constructive modifications and so they built a new prototype able to measure both compressional and shear wave's velocities.



The new prototype of seismic sensor (Fig. 9), able to measure the degree of water saturation of the agricultural soil by measurement of the velocity of propagation of both compressional and shear waves (seismic waves), is made up of various elements, that is a transmitter, a receiver and a DAQ acquisition system.

In detail the prototype is composed by:

1. a transmitter (Fig. 10), driven by a high-voltage amplifier, to send the seismic stimulus in the soil; in particular this element is constituted by two custom built piezoelectric actuators, specially designed to generate the primary and the secondary wave and developed by Sensor Technology Limited; the first actuator is mounted so to produce a longitudinal wave (i.e. shaking the soil in the same direction of propagation). The second actuator must generate a transversal wave, therefore it is able to vibrate perpendicularly to propagation direction. The transmitter must be inserted in the soil at a depth in the order of 30-40 cm.
2. a receiver (Fig. 11), composed by two elements:
 - a piezoelectric hydrophone type *SQ26* (by Sensor Technology Limited), able to receive the primary wave. It is a general-purpose low-cost hydrophone, and has good sensitivity, wide bandwidth and good stability.
 - a custom built piezoelectric hydrophone designed and developed to receive the secondary wave.
 The receiver is located at a know distance from transmitter.
3. the feeble signal is amplified by a high gain differential amplifier type *SA03* (Sensor Technology Limited), then digitized by a common PC based data acquisition system and processed by a custom software developed using National Instruments' LabVIEW™ and/or MATLAB



6. CONCLUSIONS

In this paper the applicability of the acoustic-based method to measure both moisture and properties of the soil has been analysed. The results produced encourage to use this technique for obtaining soil

classification, moisture estimation and fluid distribution. The authors shown as the $S-v_c$ curves determines the soil characteristics, the $S-v_t$ curves draws the soil water content and the ratio v_c/v_t gives information about homogeneous water-air mixture in the soil.

The only restriction to validity of the proposed method is the frequency for the transmitted stimulus which must belong to the range $[150, 900]$ Hz; these boundaries, obtained for the greatest value of hydraulic conductivity and for intermediate distances between transmitter and receiver, assure the applicability of the developed theory to any kind of soil.

With the aim of verifying the theoretical results obtained, the authors are currently working to the arrangement of a working prototype of the sensor useful to measure both the compressional and shear waves velocities.

7. REFERENCES

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