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IMPROVEMENTS OF SEISMIC SENSOR DESIGN FOR SOIL MOISTURE MEASUREMENT

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Abstract: The main aim of the work is finding a general mathematical model to estimate the moisture content in the soil using seismic waves propagation, when the composition of the media is unknown. Using the new mathematical model here presented, the authors are developing a prototype of the sensor that will be able to measure the moisture of the soil using both compressional and shear waves velocity measurements.

Keywords: soil measurements, water content, seismic wave

INTRODUCTION

It is well know that the scientific exploitation of agricultural soils is based on the detailed knowledge of its microclimatic characteristics. An accurate knowledge of both the properties and the characteristics of soils is difficult and requires the application of suitable innovative measurement technologies.

In particular, the measure of the water content in soil is one of the most important, but still most difficult, task; several techniques have been developed for measuring the soil moisture, but no method, is really accurate, low cost, user-friendly and reasonably quick at the same time. The authors focuses on a method for agricultural soil moisture measurement; the paper presented consists of five parts: theoretical analysis of the mathematical model, model limits, prototype description, experimental results presentation, and conclusions. In the first part the general model valid for any type of soil is presented; in this section attention is focused on the *Lamè's coefficients* and on the physical factors that influence, in different ways, the velocities of propagation of seismic waves, as effective and capillary pressure, overall density and so on. In the second part the limits of applicability of the analysis that will be presented are discussed.

The third part is dedicated to the sensor prototype; here the hardware and the software specially designed for this project are both described. The experimental results and a brief summary about the model and prototype of sensor will conclude the paper.

1. THEORETICAL FOUNDATIONS

For elastic and isotropic materials there are two bulk elastic waves (compressional and shear) which propagate in the medium with the following velocities:

$$v_c = \sqrt{\frac{\lambda + 2\mu}{\rho}}, \quad (1)$$

$$v_t = \sqrt{\frac{\mu}{\rho}} \quad (2)$$

where ρ is the overall or *bulk density*, and μ and λ are the Lamè's parameters that appear in Hooke's law relating strain and stress in an isotropic medium; μ gives the dependence of shear stress on shear strain in the same direction, while λ gives the dependence of any compressional or tensional stress on extensional or dilatation strains in orthogonal direction.

The overall density of the sediment, defined by:

$$\rho = \rho_{fl} \cdot f + (1 - f) \cdot \rho_s \quad (3)$$

describes the relationship among the fluid density ρ_w, grain density of the sediment or rock matrix ρ_s, and the porosity f.

The following equation gives the density of the fluid mixture:

$$\rho_{fl} = \sum_{i=1}^{n} S_i \cdot \rho_i \quad (4)$$

where S_i is the degree of the liquid saturation of the individual components and ρ_i is the density of the individual components; to our aims only two components (air and water) must be considered, so the previous equation becomes:

$$\rho_{fl} = \rho_w \cdot S + (1 - S) \cdot \rho_a \quad (5)$$

only when liquid and gas are uniformly distributed in all pores as can be reasonably guessed for agricultural soils.

The air density ρ_a is negligible, therefore, for a porous system with porosity $f \in]0,\ 1[$ and liquid saturation $S \in [0,\ 1]$, the overall density is given by:

$$\rho = (1-f)\rho_s + f\,S\rho_w \tag{6}$$

This equation states that S influences the bulk density ρ, hence also the velocities of propagation of both compressional and shear waves; the following equation describes the relation between moisture content *u* and S:

$$S = \frac{u}{f} \tag{7}$$

Gassmann's equation [1] states that, *for quasi-static isotropic elasticity* and *low frequency wave propagation*, *the shear modulus μ is not sensitive to fluid content* in the medium, being *μ* mechanically indipendent from the properties of any fluid present in the pores; for instance, when the degree of saturation with liquid changes it is possible to consider $\mu=\mu_{sat}=\mu_{dry}$; on the contrary λ is elastically dependent on fluid properties.

In our studies we obtained that in equations (1) and (2) only *λ* and *ρ* depend on *S*; more specifically we express λ and *μ* in terms of the soil parameters as [2]:

$$\lambda = \frac{\left(0.0765 a p_e^{1/3}\right)}{\left(f \cdot b^{2/3}\right)} + \left(2c_{csg} + 2c_{sw} + c_g + c_w\right) \tag{8}$$

$$\mu = \frac{\left(0.115 a p_e^{1/3}\right)}{\left(f \cdot b^{2/3}\right)} \tag{9}$$

where c_{sg}, c_{sw}, c_w and c_g are the elastic coupling coefficients between the various mediums, p_e is the effective pressure and *a* and *b* are the constants introduced by Brandt [3].

In a previous paper [4], starting from the Brutsaert's theory, we already derived the relationship between the compressional wave velocity and the soil parameters:

$$v_c = \Psi \sqrt{\frac{0.306 \cdot p_e^{1/3}}{\rho \cdot f} \cdot Z} \tag{10}$$

In the same conditions and following the same procedure, we have obtained the velocity of the shear wave as:

$$v_t = \Psi \sqrt{\frac{0.115 \cdot p_e^{1/3}}{\rho \cdot f}} \tag{11}$$

where

$$\Psi = a^{1/2} / b^{1/3} \tag{12}$$

The factor Z in (10) accounts for the influence of air and water content in the soil on the compressional velocity.

Observing Eqns. (10) and (11), we immediately notice that Z is to be considered the discriminating factor for the propagation of the two kind of waves; Z can be expressed as a function of the *effective bulk modulus* k_e, of the *effective pressure* p_e and of the *b* constant as:

$$Z = \frac{\left[1 + \frac{30.75 \cdot k_e^{3/2} \cdot b}{p_e^{1/2}}\right]^{5/3}}{\left[1 + \frac{46.12 \cdot k_e^{3/2} \cdot b}{p_e^{1/2}}\right]} \tag{13}$$

Since the variety between different kinds of soils is represented in p_e, this is the parameter that needs most of our attention for this analysis. The effective pressure is defined in terms of atmospheric pressure p_a, of total pressure p_t and of capillary pressure p_c, as:

$$p_e = p_t - p_a - S \cdot p_c \tag{14}$$

that reduces to:

$$p_e = p_t - S \cdot p_c \tag{15}$$

if we assume that the atmospheric pressure can be neglected, the total pressure is given by the following equation:

$$p_t = \rho \cdot g \cdot H \tag{16}$$

where *ρ* represents the bulk density, *g* the acceleration due to gravity and *H* the depth of burial. So, to obtain a large total pressure, in comparison with capillary pressure, it is necessary to increase the depth of placement of the sensor.

Brutsaert's and Luthin's analysis [5] proves that, when the total pressure becomes very large in comparison with the capillary pressure, the effective pressure remains nearly constant for all values of S; under these conditions, v_t depends only on *S* by means of density *ρ*. In other terms, there is a one-to-one correspondence between *S* and v_t; while, as shown in Eqn. (12), v_c depend on S via both density *ρ* and *Z*.

When a soil is represented as a mixture of sand, silt and clay, also the the capillary pressure of the particular soil must. be considered. In this way Z , which accounts for the influence of air and water content in the soil on the compressional velocity, depends on parameters and microclimatic characteristics of the soil by mean of p_c.

The following equation highlights the relationship between the capillary pressure p_c and soil parameters obtained considering the Van Genuchten's model [6]:

$$p_c = -\frac{\rho_w \cdot g}{\alpha}\left(S^{-1/m} - 1\right)^{1/n} \tag{17}$$

where the values of *n* and *α* are calculated by Carsol and Parrish [7]. *m* is a dimensionless parameter calculated as:

$$m = 1 - \frac{1}{n}$$

These values have validity for all the twelve different kinds of soil represented in the textural triangle.

2. MODEL LIMITATIONS

The method described in this paper applies under the following limitations:

1. propagating waves have low frequencies so that pore pressure is equilibrate throughout the pore space; this is required to grant the validity of Gassmann's relationship. Moreover this limit has been obtained [4] imposing that the propagation of seismic wave takes places without dissipation in all kinds of soil,;
2. wave propagation must be approximately plane. This condition imposes an adequately high distance between actuators and transducers at the moment of the measurement (in the order of meters);
3. effective pressure must be nearly constant for all degrees of saturation; this ensures that v_t depends only on S by means of density. This condition requires the minimum depth of burial at the moment of measurement;

and assumptions:

1. the material is considered isotropic;
2. the soil model used consists of a frame of a randomly staked spheres of different size;
3. the pore spaces are filled by a mixture of water and air.

However, we must not forget that, the seismic properties are affected in complex ways by many factors as pressure, fluid type, porosity, and so on. So the theoretical results obtained approximate very well the experimental results for a fixed range of frequencies, [1-20] Hz, for a minimum distance between transmitter and receiver and for a minimum depth of placement.

3. SENSOR PROTOTYPE

To generate the compressional and shear waves at low frequencies two electromechanical actuators have been designed. The shear waves actuator is composed of a moving plate external to the actuator protective case and in direct contact with the soil; when the coil is excited this plate shakes the soil and generates a shear wave that propagates in it. In the compressional wave actuator, instead, the moving elements are completely contained inside a protective case; for this kind of actuator when current is supplied to the actuator coil, the moving element simply collide with the face of the protective case, generating the compressional wave in the soil. The protective cases of the two actuators are filled with acoustic absorbent material to minimize spurious effects due to mechanical vibrations.

The receiver sensors are highly sensitive directional geophones that respond only to one kind of wave (compressional or shear ones).

Fig. 1 and Fig. 2 show, respectively, the spectral content of the transmitted and received signal; both spectrum are estimated using the Welch's method. From these figures it is possible to see that the transmitted signal is similar to received signal, though this last one has been amplified.

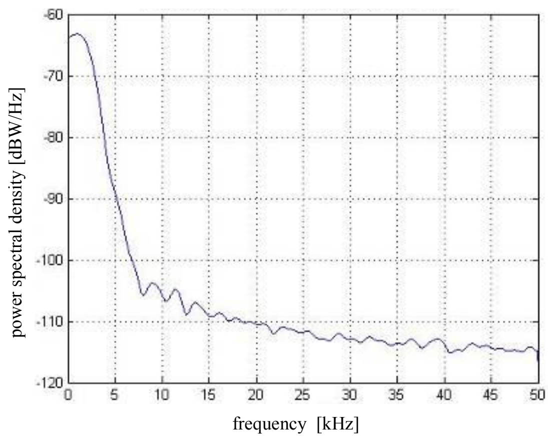

Fig. 1 - Power spectral density of the transmitted signal

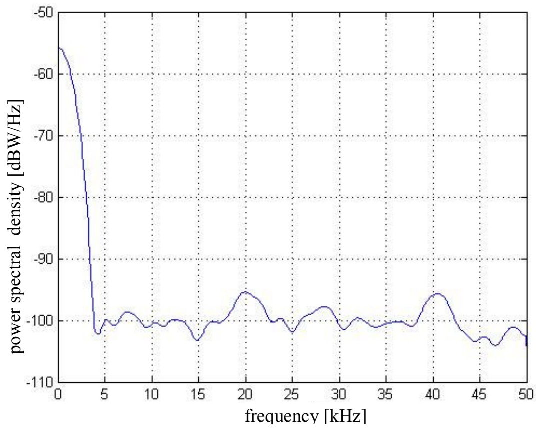

Fig. 2 - Power spectral density of the received signal

3.1 Hardware description

In the following figure the block diagram of the hardware prototype is illustrated.

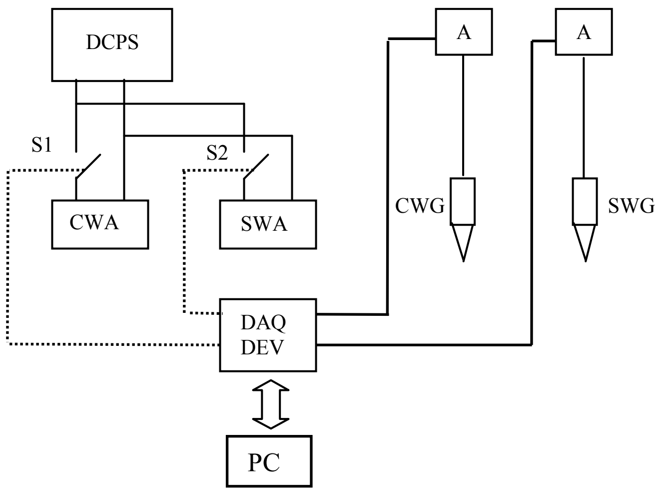

Fig. 3 - Block diagram of the hardware prototype

Where:

- DCPS : DC Power Supply;
- CWA: Compressional Wave Actuator;
- SWA: Shear Wave Actuator;
- S1, S2: Control relays;
- A: High gain, low noise preamplifiers;
- CWG, SWG: vertical and horizontal geophones;
- DAQ DEV: general purpose DAQ device (National Instruments DAQCard6024E);
- PC: personal computer.

The electromechanical actuators are DC supplied (24V DC) in order to remove the 50Hz vibration noise that the high sensitive geophones were capable to detect.

Control relays are necessary to drive the actuators under PC control; this solution also makes it possible to acquire data in two different ways, i.e. simultaneously or in alternate mode.

We have used two preamplifiers with high gain and low noise to amplify the received signals detected by the two geophones.

These preamplifiers requires a +/-12V split power supply, so that a stabilized amplifier must be used.

3.2 Method of measure of the velocity of propagation

The measure of velocity of propagation of wave trought the soil is obtained from the measure of time of fly:

$$v = \frac{d}{T_f}$$

where T_f is the time of fly (s) and d is the distance between the actuator and the geophone (m).

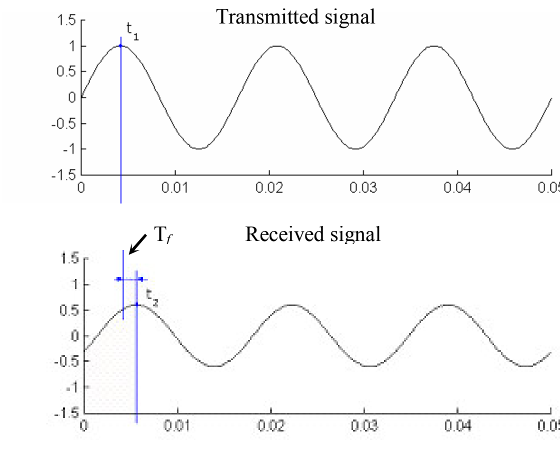

Fig. 4 - Computing the time of fly using the cross-correlation technique

We use the cross-correlation method to obtain an accurate estimation of time of fly (Fig. 4).

This method is suitable for our application because the accuracy guaranteed is sufficient for our purpose. In fact the measurement accuracy for T_f cannot be better than +/- $T_c/2$ (T_c being the used sampling interval) not making other data processing; a simple and cost effective method to improve the measurement accuracy is then to increase the sampling frequency f_c.

4. EXPERIMENTAL RESULTS

To verify the theoretical results developed in the previous sections, an experimental setup has been realized; the acoustic waves have been applied to a parallelepiped shaped specimen of soil, 0.8 m in height, 1,7 m in length and 0,9 m in depth. The transmission of acoustic pulses (both compressional and share wave) is measured in a horizontal plane 0.20 m below the soil; the compressional and shear velocities are measured for three different values of the saturation (0%, 30% and 50%) once the homogeneous saturation is obtained. Although the acoustic pulses energy are absorbed and scattered to the medium, the acoustic coupling of the transducers to the soil assure a good signals reception. The soil specimen tested in the experiment is a ordinary sand with porosity $f = 0.4$ and total density $\rho = 1.53$ *g/ml*. Figs. 5 and 6 show the transmitted and received pulse for both compressional and shear waves when the distance *d* from the actuators is equal to 1.30 m. The time of fly of both the waves is calculated using the cross-correlation techniques (Figs. 7 and 8).

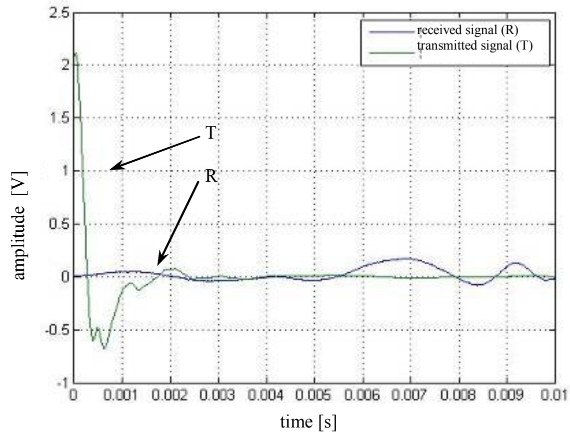

Fig. 5 - Transmitted and received compressional waves

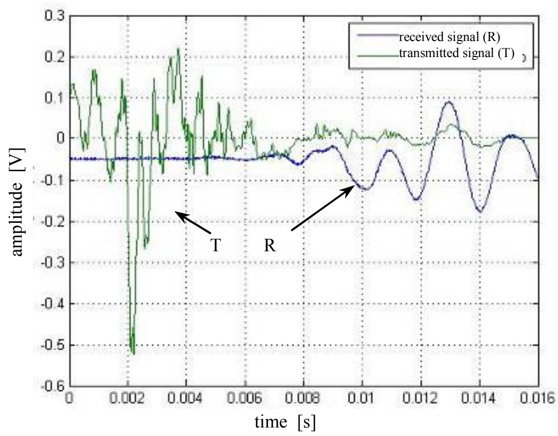

Fig. 6 - Transmitted and received shear waves

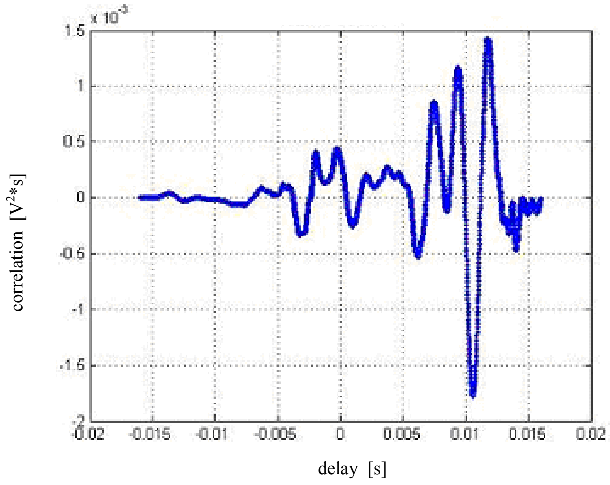

Fig. 7 - Cross-correlation of signals in Fig. 6

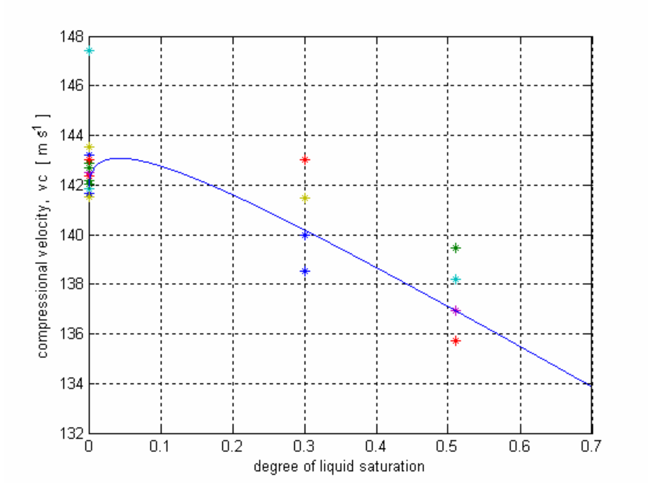

Fig. 9 – Comparison between experimental and theoretical results for compressional waves propagation

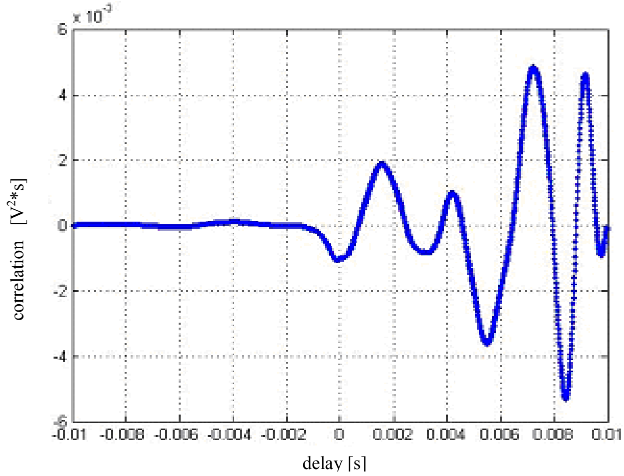

Fig. 8 Cross-correlation of signals in Fig. 5

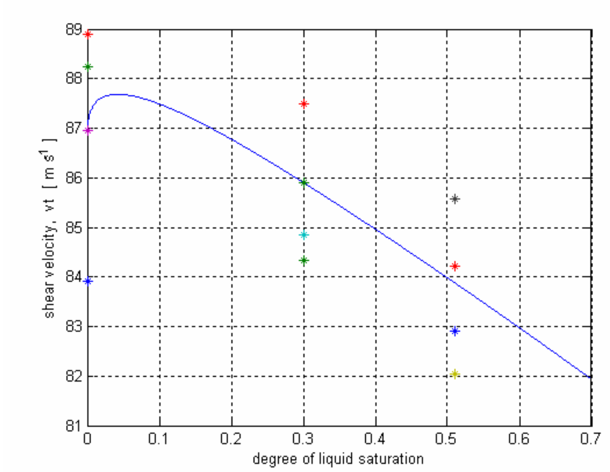

Fig. 10 – Comparison between experimental and theoretical results for shear waves propagation

The first series of measures made using the above illustrated system and method are encouraging; Fig. 9 shows the comparison between the theoretical compressional velocity (solid line) and the values obtained with 100 measurements for each value of the degree of liquid saturation (stars); the dispersion of the experimental values is caused by alignment loosing between transmitter and receiver sensor and the environmental noise. The maximum error in both compressional and shear velocities are been lower than 3%; these dispersion is caused by the uncertainty of the time estimation (about 1%) and the uncertainty in length estimation (about 2%). The experimental values of the velocities agree with typical values reported in literature [8], where the effective modulus k_e is defined via bulk moduli of air and water according to [9].

5. CONCLUSIONS

In this paper we have presented the state of the work about the theory of propagation of seismic waves through different kinds of soil for moisture measurement and the seismic sensor prototype based on the theory till now developed.

The results show a very good agreement between the theoretical velocities - calculated through the (10) and (11) - and the values measured with the sensor prototype and encourage us to a more in-depth experimentation with different kinds of soil.

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