

SOIL MOISTURE MEASUREMENT WITH ACOUSTIC METHODS

Francesco Adamo, Gregorio Andria, Filippo Attivissimo, Nicola Giaquinto

Dipartimento di Elettrotecnica ed Elettronica, Politecnico di Bari
Via E. Orabona 4, 70125 Bari - Italy
Tel.: +39 080 5963 266/318/436/647
Fax: +39 080 5963 410
e-mail: [adamo, labmis, attivissimo, giaquinto]@deemis06.poliba.it

Abstract – The paper deals with the problem of measuring the soil moisture by an accurate and real-time method. Since no available measuring techniques provide both an accurate estimation of the soil water content and a user-friendly real-time system, the authors examine a method to assess the degree of the saturation with water in granular materials that use acoustic wave. Particularly, the influence of soil characteristics on velocity of wave propagation are analysed in systematic way. The final aim of the research is to carry out a simple and complete system for microclimate soil analysis.

Keywords: acoustic waves, soil measurements, water content

1. INTRODUCTION

Nowadays, an important aim pursued in agriculture is a prudent and eco compatible utilisation of the soil. The principle of differentiated management and the use of the so-called *precision agriculture* are the starting points of the considerable diffusion of innovative measurement technologies in this field.

With this aim, the measurement of water content in soil is an important task to carry out, *in situ*, an accurate and reproducible microclimate analysis. Several methods are available to obtain an estimation of soil moisture [1-3], but none of them offers satisfactory results.

The authors investigated the acoustic pulses transmission through the soil to obtain a functional relation between moisture level and both travel velocity and absorption of acoustic waves.

Many researchers have studied deeply the problem of elastic wave propagation in liquid-saturated granular of porous mediums [4], [5], but the theory introduced by Brutsaert [6] seems suitable for realising a portable and accurate moisture soil sensor. Even if these techniques present some problems, as the scattering due to different acoustic impedance of the air within the pores and the soil particles, or the limited applicable frequency range caused by non linear absorption of acoustic energy, they are non-invasive, simple to set up and very fast; these features are very desirable in a portable soil humidity sensor.

A careful analysis of these techniques suggests that the measurement of wave attenuation often produces an inaccurate and conflicting estimation of water content in soil [7]-[8], so that the moisture variation-wave velocity model will be investigated.

Really, the pulse transmission in unconsolidated and partially saturated porous media has received particularly attention, but the results are very often contradictory. These discrepancies are probably caused by various variables which contribute to the wave propagation velocity. All these considerations explain why there is the need, in the authors' opinion, of a systematic analysis of the model parameters and of their influence on travel velocity of acoustic pulse transmission through the soil.

2. THE MATHEMATICAL MODEL

To deal with the measurement of water content of soil it is profitable to drop the typical and accurate in layers model by considering a very simple model of soil as an unconsolidated granular medium. Really, the four different kinds of soil (clay, sand, silt and skeleton) are classified considering the relevant *granulometry*; related to this characteristic is the porosity which accounts for the water

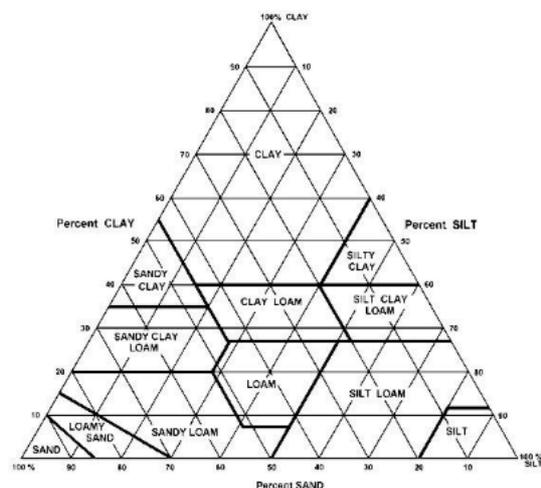


Fig. 1. Soil textural triangle.

content of the soil [9]; its value can be determined by considering the velocity variation of the transmitted acoustic wave. The first three elements are very interesting in agriculture and their combination determines the soil textural class (Fig. 1).

Really, it is the different rate of clay, silt and sand that determine the soil response at moisture variation. Particularly, has been experimentally shown [10] that the soil composition produces acoustic absorption and velocity variation when a sound wave is transmitted through unconsolidated granular mediums containing gas and liquid in their interstice.

A complete mathematical theory model for this case has been developed by considering the equations of a motion in a soil model consisting of randomly stacked spheres of different sizes containing both liquid and gas in their interstices [6]. The analysis shows that a rigorous solution of the equations yields three compressional waves and one type of shear wave, when the solid, water and air components are present.

Particularly, it has been proved that only the perfectly coupled compressional wave prevails whereas the magnitudes of the other ones are negligible, when the dimensionless parameter β , given by the following expression [10]:

$$\beta = R \left(\frac{2 \cdot \pi \cdot f_s \cdot \rho}{\eta} \right)^{\frac{1}{2}} \quad (1)$$

verifies the limitation:

$$\beta < 1 \quad (2)$$

Actually, in this case, the movement of the three phases is synchronized, the dissipation of the sound energy is negligible and the dominant wave is approximately elastic.

It is worth to underline that this factor accounts for both inertia and viscosity forces and influences heavily both the velocity and the attenuation of the wave sound.

In eqn. (1), R represents the pore radius, f_s is the wave's frequency, ρ and η are the density and viscosity of the water, respectively.

Under this constraint, the velocity of the perfectly coupled acoustic wave is given by the expression:

$$v = \sqrt{\frac{0.306 \cdot a \cdot p_e^{1/3} \cdot Z}{\rho_{tot} \cdot f \cdot b^{2/3}}} \quad (3)$$

where f is the porosity of the soil, a and b are constants depending on the granular properties material.

It is worth to underline that the model given in (3) applies very well when the soil moisture is homogeneously distributed, whereas a deviation from the theoretical curves is possible during rapid infiltration [8]. This expression accounts for the sound velocity which depends on:

(i) the degree of the saturation with liquid S through the effective pressure p_e defined as:

$$p_e = p_t - p_a - S \cdot p_c \quad (4)$$

where p_t is the total pressure, p_a is the air pressure and p_c is the capillary pressure;

(ii) the total density ρ_{tot} given by the expression:

$$\rho_{tot} = \rho_s (1-f) + \rho_w \cdot f \cdot S \quad (5)$$

with ρ_s and ρ_w soil and water density respectively; and

(iii) the parameter Z , which contains the effects of the interstitial fluids, evaluated by the following expression:

$$Z = \frac{\left[1 + \frac{30.75 \cdot k_e^{3/2} \cdot b}{p_e^{1/2}} \right]^{5/3}}{\left[1 + \frac{46.12 \cdot k_e^{3/2} \cdot b}{p_e^{1/2}} \right]} \quad (6)$$

which describes the influence of the air and the water content in the granular medium on velocity sound where, the effective modulus k_e in the eqn. (6), is defined by the following relation, corrected according to [8]:

$$k_e = \frac{k_a \cdot k_w}{k_a (1-S) + k_w \cdot S} \quad (7)$$

being k_a and k_w the bulk modulus of air and water, respectively [7].

The eqn. (3) is a very interesting model to realising a prototype of a soil moisture sensor since it connects the sound velocity with physical properties of the soil. Consequently, a careful analysis of the model it is necessary to investigate in more detail its performance, to simplify its expression and testing its accuracy.

3. MODEL ANALYSIS

3.1. The parameter β

In the previous section it has been shown that, under the hypothesis (2), the sound velocity v can be expressed according to eqn. (3).

To investigate the range of frequency signal which assures a propagation purely elastic and without dissipation of the compressional wave, i.e. the applicability of eqn. (3), it is necessary analysing the parameter β .

By determining the effective pore radius in terms on the hydraulic conductivity k_i :

$$R = \left(\frac{8 \cdot k_i \cdot \eta}{\rho \cdot g \cdot f} \right)^{\frac{1}{2}} \quad (8)$$

where g represents the acceleration due to gravity, and substituting in eqn. (1), a simplified expression for β is obtained:

$$\beta = \left(\frac{5.13 \cdot f_s \cdot k_i}{f} \right)^{\frac{1}{2}} \quad (9)$$

which point out that this parameter is practically dependent both on the hydraulic conductivity and the frequency of sound wave so that a suitable frequency range must be choice to assures, theoretically, a propagation purely elastic and without dissipation.

Tab. 1. Values of k_{is} , f and n for some different soil texture.

Soil	k_{is}	f	N
Sand	$8.2 \cdot 10^{-5}$	0.43	2.7
Loamy Sand	$4.0 \cdot 10^{-5}$	0.41	2.3
Loam	$2.8 \cdot 10^{-6}$	0.43	1.6
Silty loam	$1.2 \cdot 10^{-6}$	0.45	1.4
Silt	$6.9 \cdot 10^{-7}$	0.43	1.4
Silty clay	$5.7 \cdot 10^{-8}$	0.36	1.1
Clay	$1.7 \cdot 10^{-6}$	0.45	1.2

To investigate the influence on β of the first quantity, it has to be considered the Van Genuchten expression which describes the relationship between hydraulic conductivity and degree of the saturation with liquid:

$$k_i = k_{is} \cdot S^2 \left[1 - \left(1 - S^{\frac{1}{m}} \right)^m \right]^2 \quad (10)$$

where k_{is} is the hydraulic conductivity at saturation and $m = 1 - 1/n$ represents a parameter dependent on the soil textural class (Tab. 1).

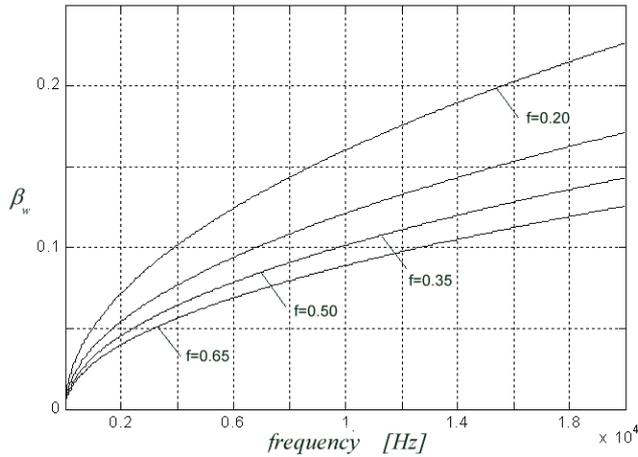


Fig. 2. Representation of theoretical values of β_w vs frequency for different typical values of f with $k_{is} = 10^{-7}$.

The eqn. (10) shows that the hydraulic conductivity reaches the maximum value $k_i = k_{is}$ when the degree of the saturation with liquid is maximum i.e. when $S = 1$.

Consequently, at worst the parameter β is given by the following expression:

$$\beta_w = \left(\frac{5.13 \cdot f_s \cdot k_{is}}{f} \right)^{\frac{1}{2}} \quad (11)$$

so that the constraint:

$$\beta < \beta_w < 1 \quad (12)$$

assures the validity of eqn. (3).

A careful analysis of the eqn. (12) point out that the β_w value decreases when the soil porosity increases; moreover, it can be shown that this relation is verified for each value of frequency when $10^{-5} < k_{is} < 10^{-8}$ (Fig. 2) whereas depends on frequency when $10^{-2} < k_{is} \leq 10^{-5}$ (Fig. 3).

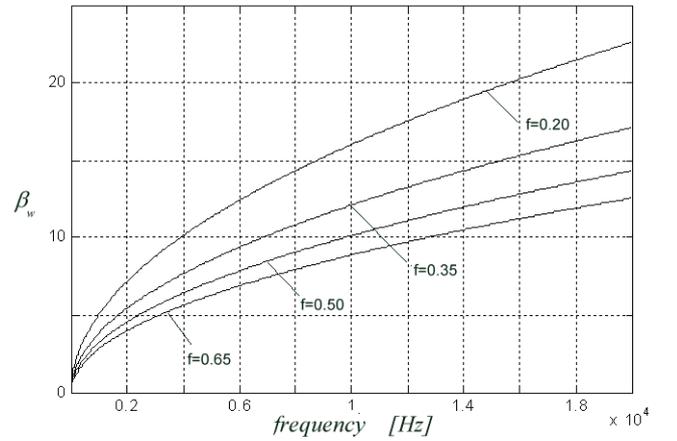


Fig. 3. Representation of theoretical values of β_w vs frequency for different typical values of f with $k_{is} = 10^{-3}$.

For example, if the hydraulic conductivity is $k_{is} = 10^{-3}$, the condition (12) is verified for $f_s < 120 \text{ Hz}$ when $f = 0.20$, and for $f_s < 50 \text{ Hz}$ when $f = 0.65$. Anyway, it is worth to underline that the soils porosity intended for cultivation generally varies from $0.30 \div 0.50$ and does not reach the limit values.

At this point it is worth to investigate a suitable range frequency of emitted acoustic signal; the condition to obtain reliable results is that the distance between transmitter and receiver should assure the hypothesis of plane wave but such as exclude too great attenuation.

By keeping in mind that the sound velocity v in the soil is certainly included in the range $300 \div 1500 \text{ m/s}$, it is possible to select the suitable frequency which carries out the smallest distance d_m that verifies the constraint of distant field and therefore the correct wave sound propagation (Fig. 4).

It is easy to see that the minimum frequency $f_{s_{\min}}$, which assures the hypothesis of plane wave without causing impracticable distance between transmitter and emitter,

decreases when the sound velocity in the soil decreases.

For example, d_m at $f_s = 500 \text{ Hz}$ is equal to 48 cm when $v = 1500 \text{ m/s}$, it is 35 cm when $v = 1100 \text{ m/s}$, it is equal to 23 cm when $v = 700 \text{ m/s}$ and reduce to 9 cm when $v = 300 \text{ m/s}$.

Consequently, it is obtained that the minimum suitable frequencies are reported in Table 2 for different values of the sound velocity and therefore of several kinds of soil.

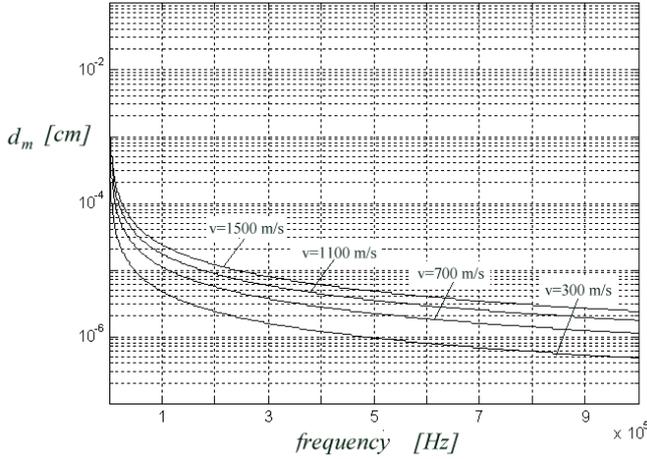


Fig. 4. Representation of minimum theoretical distance d_m vs frequency for different values of v .

The results carry out that the minimum frequency utilizable by the device is equal to $f_{s\min} = 1 \text{ kHz}$; really for $f_s < 1 \text{ kHz}$ the distance between transmitter and receiver could be more than 100 cm with great problems of attenuation and beam spreading.

Tab. 2. Values of $f_{s\min}$ and d_m for some different wave sound velocity.

wave sound velocity [m/s]	wave sound frequency $f_{s\min}$ [Hz]	distance [cm]
1500	1000	23.8
1300	900	22.9
1100	700	25.0
900	600	23.8
700	500	22.3
500	400	19.9
300	200	23.8

It is worth to underline that the medium will operate as a filter so that the maximum frequency utilizable will depend on kind of soil [8], [11]; because there is no agreement on a general trend a greater investigation it is advisable.

3.2. The velocity v

At this point, after analysing the parameter β , the

question arises whether the eqn. (3), which represents the velocity of the wave sound, can be simplified.

In previous section it is pointed out that this quantity is dependent on the three parameters p_e , ρ_{tot} and Z , which are tied the degree of the saturation with liquid S .

First, the analysis of the eqn. (4) shows that the effective pressure p_e is practically dependent on both p_i and p_c ; the first quantity is proportional to the depth where the sensor is situated, the second one can be written, by using the Van Genuchten model, as:

$$p_c = \frac{1}{\alpha} \left[S^{\frac{1}{m}} - 1 \right]^n \quad (13)$$

with α constant dependent on the kind of the soil (Tab. 3). To come to this point, the wave sound velocity is affected by the effective pressure at the rate $1/6$ th power and consequently it is strongly influenced by capillary pressure and soil texture.

Second, the relation between ρ_{tot} and S can be written as:

$$\rho_{tot} = \frac{\rho_s^2 - \rho_s \cdot \rho_l \cdot S + 2.65 \cdot \rho_l \cdot S}{2.65} \quad (14)$$

where this equation derives combining the eqn. (5) with the following relationship:

$$f = 1 - \frac{\rho_s}{2.65} \quad (15)$$

which makes a connection between porosity and real density of soil. The eqn. (15) is an adequate approximation for many soils; really, soil is composed of solid particles of different sizes (minerals and organic matter) and voids space distribution. Since, the mineral grains are quartz and feldspar a suitable average value for real density is 2.65 g per cm^3 [12].

By combining the eqn. (15) in the eqn. (14), it is possible to express the product $f \cdot \rho_{tot}$ in the eqn. (3) as a function of ρ_s and S as:

$$\Upsilon(\rho_s, S) = 0.1425 \left[(S + 2.65) \rho_s^2 - 5.3 \cdot \rho_s \cdot S + 7.0225 \cdot S - \rho_s^3 \right] \quad (16)$$

Tab. 3. Values of α and relative error per cent for some different soil texture.

Soil	α [cm ⁻¹]	e_r [%]
Sand	14.5	0.36
Loamy Sand	12.4	0.34
Loam	3.6	0.36
Silty loam	2.0	0.39
Silt	1.6	0.36
Silty clay	0.5	0.29
Clay	0.015	0.39

At last, a careful investigation of eqn. (6) highlights that essentially the quantity Z is dependent on both the effective pressure p_e and the effective modulus k_e ; really, using the eqns. (4) and (7) it is possible to carry out that this parameter is dependent on the degree of saturation with liquid S and the elastic properties of the solid particles b . By setting in the eqn. (7) the value of the air bulk modulus at $1.41 \times 10^5 \text{ N/m}^2$ and the value of the water bulk modulus at $2.01 \times 10^9 \text{ N/m}^2$, and considering about 50 cm deep in eqn. (4), it is possible to outline the Z trend, to different typical values of b .

A careful analysis of the curves, of which for sake of brevity it is reported only one (Fig. 5), shows that the parameter Z is little sensitive to saturation with liquid and increase when b decreases; however in many practical cases it is always closed to one.

However, the relative error caused by this approximation is less than $4 \cdot 10^{-3}$ when $b = 10^{-8} \text{ Pa}^{-1}$ (Tab. 3) and reduces to $4 \cdot 10^{-7}$ when $b = 10^{-11} \text{ Pa}^{-1}$.

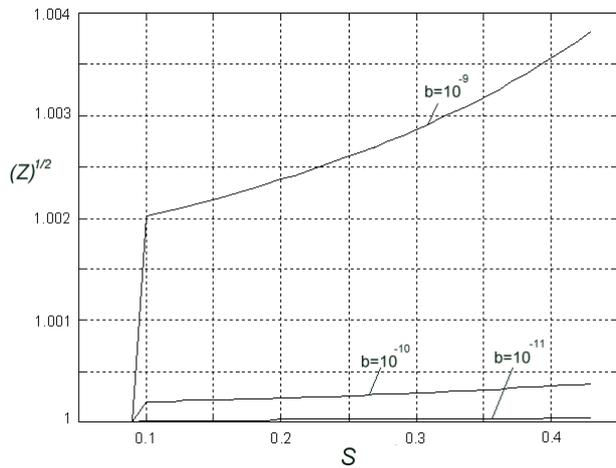


Fig. 5. Representation of the \sqrt{Z} vs saturation for different typical values of b in a sand soil.

Finally, by substituting eqn. (16) in eqn. (3) and setting $\chi = \sqrt{a/b^{2/3}}$, a simple expression of the sound velocity is obtained:

$$v = \chi \sqrt{\frac{0.306 \cdot p_e^{1/3}}{\Upsilon(\rho_s, S)}} \quad (17)$$

so that this quantity is dependent on moisture soil by a constant χ lied to kind of soil, which represents just an amplification factor. For example, χ is equal to 1.077×10^3 when $a = 1$ and $b = 8.1 \times 10^{-10}$, it is equal to 4.472×10^3 when $a = 0.2$ and $b = 1.0 \times 10^{-12}$. It is worth to underline that experimental results produce that the constant a is neighbourhood of unity and the constant b is variable in the range $10^{-8} \div 10^{-12}$ [6].

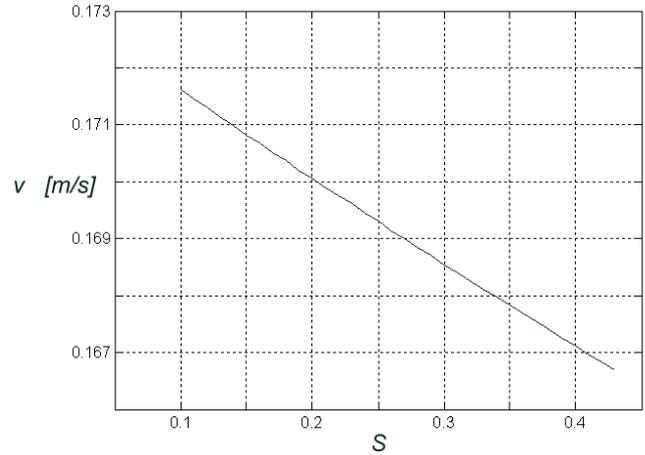


Fig. 6. Theoretical relationship between the velocity of sound and the degree of the saturation for sand soil when $\chi = 1$ with 50 cm deep.

The analysis of eqn. (17) carries out that, for a given value of effective pressure, the velocity of the sound in the soil is dependent on the saturation with liquid; it can be shown that different curves will be obtained in terms on the kind of the soil. Generally, three types of curves can be distinguished: the first one which includes loam sand, sandy loam and sand soil (Fig. 6); the second one characterized by low content of clay as sand clay loam, loam, silt loam and silt (Fig. 7); the third characterized by high content of clay, which includes silty clay, sandy clay, clay loam, silty clay loam and clay (Fig. 8).

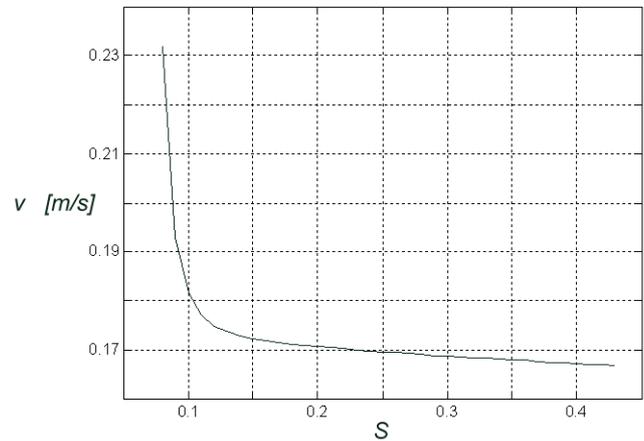


Fig. 7. Theoretical relationship between the velocity of sound and the degree of the saturation for silt soil when $\chi = 1$ with 50 cm deep.

The figures highlight that the sound velocity in the soil decreases when the saturation with the water increases, independently from the kind of the soil textural class. The curve trend is linear in the first case and approximately logarithmic for the second and third groups.

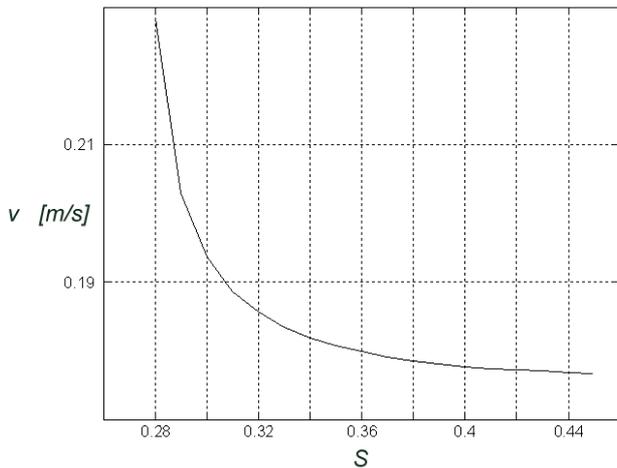


Fig. 8. Theoretical relationship between the velocity of sound and the degree of the saturation for clay soil when $\chi = 1$ with 50cm deep.

For example, in the first kind of curves, it reduces to about 1.2% for each 10% of S variation, whereas in the third kind of curves, it reduces to about 10% for each 10% of S . However, generally the degree of the saturation with liquid is variable generally in the range $0.30 \div 0.50$.

4. CONCLUSIONS

In this paper the applicability of Brutsaert theory to soil moisture measurement has been examined. It worth to underline that the velocity expression obtained applies well in equilibrium state.

The analysis carries out that, under suitable hypothesis, the sound wave velocity is proportional to the $-1/2\text{th}$ power of the degree of the saturation with water and the $1/6\text{th}$ power of the effective pressure; in this model, the kind of soil affects the velocity value by an amplification factor. The velocity sound equation obtained works good for a given frequency range and the approximation error is always less than 0.4% .

Considering that there is not full agreement on experimental results obtained by different researchers, it is in the author's opinion that investigation in more detail, firstly via simulation, nextly via experimental data processing is necessary.

Particularly, it is desirable to examine:

- i) the effects of both total density and effective pressure variation on velocity sound;
- ii) the soil absorption regarding pulse energy and its behaviour as filter with a given frequency band;
- iii) the acoustic coupling of sensor and the soil behaviour with the water presence.

Even if, the authors are currently working arranging a system based on both capillary pressure and total density with the purpose of realising a portable prototype of an accurate moisture sensor, this model should be applicable to moisture measurement in greenhouse where the soil characteristics are well known and in seismic wave propagation velocity.

REFERENCES

- [1] J. O. Curtis, "Moisture Effects on the Dielectric Properties of Soil", *IEEE Trans. on Geoscience and Remote Sensing*, 2001, pp. 125-128.
- [2] V. T. Kondratov, Y. A. Skripnik, "A Digital Device for Measurement of Physical and Chemical Parameters of Materials and Substances", *Proceedings of the IMTC/96 Conference*, Brussels, 1997, pp.981-986.
- [3] J. Curtis, R. Narayanan, "Effects of Laboratory Procedures on Soil Electrical Property Measurements", *IEEE Trans. on Instr. & Meas.*, 1998, pp. 1474-1480.
- [4] H. Brandt, "A study of the speed of sound in porous granular media", *Journ. of Applied Mech.*, 1955, pp. 479-486.
- [5] M. A. Biot, "Theory of propagation of elastic waves in a fluid-saturated porous solid", *Journ. of Acoustic*, 1956, pp. 168-191.
- [6] W. Brutsaert, "The Propagation of Elastic Waves in Unconsolidates Unsaturated Granular Mediums", *Journ. of Geophysical Researcher*, 1964, pp. 243-257.
- [7] S. Domenico, "Elastic Properties of Unconsolidated Porous Sand Reservoirs", *Geophysics*, 1977, pp. 1339-1368.
- [8] I. Flammer, A. Blum, A. Leiser, P. Germann, "Acoustic Assessment of Flow Patterns in Unsaturated Soil", *Journ of Applied Geophysics*, 2001, pp. 115-128.
- [9] L. Cavazza, "Fisica del Terreno Agrario", (in Italian), UTET, 1981.
- [10] W. Brutsaert, J. Luthin, "The velocity of Sound in Soil near the Surface as a Function of the Moisture Content", *Journ. of Geophysical Researcher*, 1964, pp. 643-652.
- [11] J. T. Geller, L. R. Myer, "Ultrasonic imaging of organic liquid contaminants in unconsolidated porous media", *Journ. of Acoustic*, 1995, pp. 85-104.
- [12] P. W. Birkeland, "Soils and Geomorphology", *Oxford Press*, New York, 1984.