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Soil moisture assessment by means of compressional and shear wave velocities: Theoretical analysis and experimental setup

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ABSTRACT

In previous works, the authors presented the outline of a method for measuring the moisture content in agricultural soils via elastic waves, along with experimental results obtained on a specimen of sandy soil. This work illustrates other aspects and results of the research, regarding both the underlying theory and the design and realization of an improved measurement system. Firstly, the derivation of the simplified equations which are at the basis of the moisture measurement is thoroughly illustrated and discussed, starting from the more complex (and generally unmanageable) equations of elastic waves in unconsolidated porous media. The analysis suggests that by measuring the velocities of low-frequency compressional and shear waves in soils, it is possible not only to measure the water content, but also the uniformity in the water distribution. Secondly, the design and the practical realization of an experimental setup, which is able to measure the velocity of compressional and shear waves in soils, is illustrated in detail. The use of custom-built compressional and shear waves electromechanical actuators, together with geophones, low noise preamplifiers, and suitable signal processing techniques, brought to the realization of an effective and reasonably accurate measurement system.

1. Introduction

Several techniques have been developed to detect and measure the water content in agricultural soils, e.g. the *gravimetric soil sampling*, the *neutron scattering,* the *nuclear magnetic resonance,* the *dielectric constant measurement* and so on [1]; each method has its own advantages and disadvantages. However, it is very difficult to obtain, for this kind of measurements, accuracy, low cost, ease of use and real-time results with a single method. For this reason the authors, in previous papers [2–4], have investigated the feasibility of a new method, based on the functional relationship between moisture content and elastic waves velocity in the soil.

In [2] the authors have shown that, by introducing suitable simplifications and hypotheses in the equations of elastic waves propagation in porous media, a simple relationship between the velocity of propagation of compressional waves and the moisture content of a soil can be obtained. The limit of this approach is that it requires a good knowledge of many parameters of the medium (e.g., porosity, density, granular composition, etc.), and, above all, that the water is, almost perfectly, uniformly distributed. In the paper, a method to obtain information about the soil composition by means of a series of experiments with compressional waves is suggested, but the main hypothesis of uniform distribution of water is maintained.

To overcome this difficulty, the authors have studied the possibility of using shear waves velocities, in conjunction with compressional ones. After a preliminary theoretical study [3], careful measurements have been executed on a specimen of a particular kind of soil (sandy soil) with accurately known characteristics; the relevant results, along with an uncertainty analysis, have been published in [4].

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In this work, which must be considered a companion paper of [4], the theoretical basis of the moisture measurement method via the velocities of shear and compressional waves is thoroughly illustrated and discussed, and the experimental setup needed to obtain the measurements reported in [4] is described in detail. The paper shows that, by using such a combination of both compressional and shear waves at very low frequencies (i.e., by operating in the seismic waves frequency range), it is possible to measure the moisture content of the soil even if the water is irregularly distributed in it, and, besides, it is possible to obtain information about the uniformity of distribution. In the particular case of perfectly uniform distribution of the water (which can be verified by preliminary velocities measurement), one can use only compressional waves, which implies more accurate measurements, due to the nature of the two kind of waves.

2. Theoretical relationships between moisture and wave velocities in soils

Modelling and analyzing dynamic phenomena in soils is a very complex and difficult subject of geophysics, even if one restricts the analysis to the class of agricultural soils. In developing a practical application, such as the one presented in this work, it is necessary to take into due account the complications of the theory, but also to introduce suitable simplifying hypotheses (which has not general validity) and to make choices about controversial theoretical issues. The present work uses mainly theory and equations derived by Brutsaert [5]. The main hypothesis is that the agricultural soil under observation can be considered an homogeneous and hysotropic medium (on a large scale, i.e. when any considered volume includes a large number of grains), and a granular and porous unconsolidated medium (on a small scale). Multi-layer soils, totally dry and compressed soils, etc., are excluded from the analysis. Moreover, many soil phenomena, such as colloidal effect, solute movement, evaporation, contact angle hysteresis, role of organic matter and so on, are purposely neglected; details on these issues are available, for example, in [6,7].

The soil model used for the analysis consists of randomly stacked spheres of different sizes with interstices filled by a mixture of water and air; the solid frame is composed by sand, silt and clay particles of different sizes. The percentage of these three kinds of particles determines the *granulometry* of the soil. It is customary to discriminate twelve different classes of soils, depending on sand, silt and clay percentage; all classes are represented in the soil textural triangle (Fig. 1).

The theoretical discussion can start from the definition of some simple parameters related to the air and water content in soil. Let V_s be the volume of soil particles, V_a the volume of the air content, V_w the volume of water content, and $V_v = V_a + V_w$ the volume of voids. The soil *porosity*, *f*, is:

$$f = \frac{V_a + V_w}{V_a + V_w + V_s} = \frac{V_v}{V_{tot}} \quad (1)$$

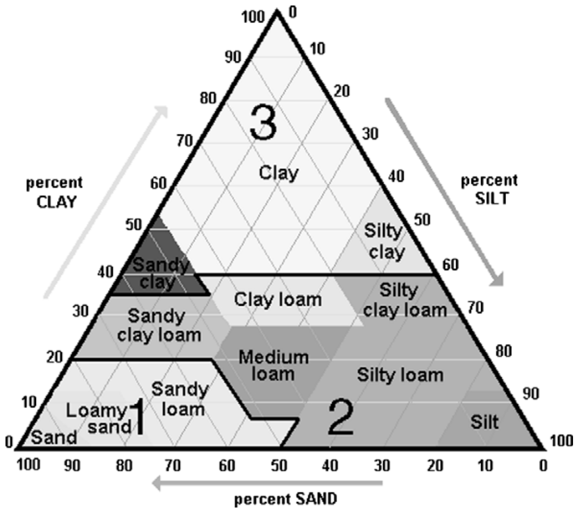

Fig. 1. Soil texture triangle [8].

The degree of saturation with liquid, *S*, is defined as:

$$S = \frac{V_w}{V_v} \quad (2)$$

The saturation *S* of course varies with the water content, and can be actually identified with the humidity of the soil. The porosity *f*, instead, can be considered approximately constant, at least if the percentage of clay in the soil is small [8].

If the medium is stressed by an inner force, *three types* of compressional waves and *one type* of shear wave are generated [5]. Besides, at low frequencies (approximating the Gassmann's assumption of an infinite wavelength [9]) only one type of compressional wave prevails over all others [5]. In [2] the problem of establishing a practical limit frequency is discussed, obtaining the approximate value of 900 Hz.

In the classical work [5], expressions for the velocity of the primary and the secondary wave are given; in [2] the authors have suitably transformed and used the expression of the compressional wave, and in [3] they have introduced in the model a similar expression for the shear wave. The expressions are:

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

$$v_s = \Psi\sqrt{\frac{0.115 \cdot p_e^{1/3}}{\rho_{tot} \cdot f}} \quad (4)$$

where the terms Ψ, ρ_{tot}, p_e, Z have distinct meaning which are here separately discussed. Since the aim is measuring the saturation *S* from measurements of one (or both) the velocities, the analysis will focus on the dependency of each of these terms on *S*.

The multiplicative term Ψ depends only on the kind of soil, and therefore *not* on the saturation *S*. It can be expressed as $\Psi = a^{1/2}/b^{1/3}$, where *a* and *b* are two constants of the soil introduced by Brandt [10], and experimentally