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Dielectric properties of a tilled sandy volcanic-vesuvian soil with moderate andic features

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ABSTRACT

The apparent dielectric constant, ε, of many agricultural soils, measurable with the Time Domain Reflectometry (TDR) method, may be used to estimate soil water content, θ, with the Topp's empirical model. However, organic soils and those of volcanic origin do not obey this model, which has been termed "universal". In particular, volcanic soils have singular physical properties in terms of bulk density, porosity, surface area, and variable charge essentially arising from the state of structural aggregation of particles of the solid mineral phase. After drying and/or intensive long-term tillage in arid and semi-arid climate, properties of these soils tend to change irreversibly. These modifications affect pore-sizes distribution and more stable larger size aggregates are formed. This in turn modifies porosity, surface area, variable charge, thus changing the dielectric characteristics and the relationship $\theta(\varepsilon)$ of the porous system. In this paper we compare the dielectric properties of two horizons of a volcanic-vesuvian soil profile. $\theta(\varepsilon)$ experimental relationships were measured in the laboratory on 16 undisturbed soil samples taken from Ap and Bw horizons of the soil profile. The subsoil Bw has kept its physical characteristics, typical of a volcanic soil having better expressed andic features. By contrast, topsoil Ap has been intensively cultivated and has altered its properties, partially losing its andic features. Physically based dielectric approaches explicitly taking into account the contribution of the changed properties are necessary for comparing the dielectric properties of the two soil horizons. The experimental $\theta(\varepsilon)$ were thus interpreted by using Maxwell–De Loor's approach and the so-called α-model which both consider soil as a multiphase system. The Topp's model was also used for evaluating its interpretative capability for the two soil horizons. By using the multiphase models in their three- and four-phases (including the effect of the bound-water) configurations on both the unaltered subsoil and the altered topsoil, it was possible separating the contribution of the different physical factors mainly involved in determining the singular dielectric properties of volcanic soils. In terms of model comparisons, we found no major differences between the three- and four-phase versions of the Maxwell–De Loor's and α-models, thus demonstrating the substantial irrelevance of the bound-water on the dielectric properties of the investigated volcanic soils. Besides, this confirms the strength of the completely physically based Maxwell–De Loor's model for interpreting soil dielectric properties without using any fitting parameters.

1. Introduction

The status of soil water content in the vadose zone is a key parameter to many aspects of agricultural, hydrological and meteorological research. In agriculture, extensive knowledge of soil moisture is essential for efficient water resource management, irrigation scheduling, crop production and chemical monitoring. In hydrology and meteorology, soil moisture plays a significant role in the partitioning of available energy at the earth's surface into sensible and latent exchange with the atmosphere, as well as in the partitioning of rainfall into infiltration and runoff.

A variety of methods have been traditionally used for measuring or estimating volumetric soil water content (θ), ranging from destructive (gravimetric) to non-destructive methods such as gamma ray radiation and neutron thermalization (Hillel, 1998). Over the last 30 years, electromagnetic-wave techniques such as

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Time Domain Reflectometry (TDR) and Ground Penetrating Radar (GPR) have become widely used for measuring water content and its dynamics, and represent a valuable and useful tool to support hydrological research (Topp et al., 1996; Noborio, 2007; Robinson et al., 2003; Ferrè and Topp, 2002).

These techniques estimate volumetric water content from measurement of the apparent dielectric constant (ε). Topp et al. (1980) found that the $\theta(\varepsilon)$ relationship follows, to an extent, a unique curve for sandy and clay-loam soils with dry bulk density ranging between 1.04 and 1.44 g cm^{-3}. These findings make TDR a popular method for measuring water content. However Topp's calibration curve is only partially suitable for organic soil (Roth et al., 1990), for fine textured soil (Dasberg and Hopmans, 1992; Coppola et al., 2012), for stony soil (Coppola et al., 2013) and for soils formed in volcanic area. (Vogeler et al., 1996; Weitz et al., 1997; Tomer et al., 1999; Regalado et al., 2003; Stenger et al., 2007). Soils of volcanic regions are unique natural resources. These soils formed in volcanic areas cover only 1–2% of the world's land surface but they are often among the most fertile soils and therefore are the foundations for some of the most densely populated areas of the world. When volcanic materials are exposed to weathering, short-range order minerals, such as allophane, imogolite and ferrihydrite are formed, as well as specific types of humic substances. These colloidal materials give the soils distinctive properties, collectively termed andic properties, which separate volcanic soils from other types of soils. Particularly, they are strongly structured showing specific surface areas as high as 600 m^2 g^{-1} and large volume of micropores (intra fabric unit pores) and macropore (inter fabric unit pores) as well (Yong and Warkentin, 1975). These properties are responsible for the low natural bulk density, high water retention capacity and water permeability as well. These kinds of soils are named Andosols (FAO-WRB).

All these distinctive properties contributing to very different dielectric properties from other mineral soils. According to Regalado et al. (2003) and Bartoli et al. (2007), the singular dielectric behaviour of such soils might be principally ascribed to: (1) the high dielectric constant of the solid phase, which can even be closer to 15; (2) the larger proportion of rotationally hindered water bound to the mineral phase in presence of high surface area and electrical charge of the soil particles (Jones and Or, 2003); (3) the low bulk density; (4) in allophanic soils, rotationally hindered water trapped within allophane spherules could have some important effects on dielectric behaviour at low water contents and, from a dielectric point of view, may behave as bound water, as suggested for example by Wada (1980) and Regalado et al. (2003). Understanding the actual (if it exists) contribution of each of these factors may only be possible if simultaneous measurements of specific surface, bulk density, dielectric properties of the solid phase and bound water are available or, can at least be indirectly deduced. In this sense, Regalado et al. (2003) analyzed the origin of the atypical dielectric behaviour of volcanic soils by fitting the experimental $\theta(\varepsilon)$ relationship to the physical models accounting for the contribution of these factors. Nevertheless, only some of these parameters were actually measured, while the dielctric constant of the solid phase was fitted along with the exponent of the α model. This somewhat limits the representativeness of the analysis since, as Regalado et al. (2003) themselves also mentioned, the two parameters are highly inversely correlated so that high values of one may be accomodated reducing the values of the other. This way, no physical meaning may be really ascribed to any of the two parameters.

Long term intensive tillage of volcanic soils, along with intense drying often occurring in arid and semi-arid regions, may change some soil characteristics (Dorel et al., 2000; Basile and Coppola, 2004; Dorner et al., 2009, 2010, 2012; Neris et al., 2012). The elementary clay-sized unit particles, forming the intra fabric unit porous system, are weakly bonded together; they come sufficiently close one each other to be strong bonded during a drying process (Yong and Warkentin, 1975). In such a way some micropores disappear and larger grain-sizes are induced (Kubota, 1972) modifying several physical properties like water retention, hydraulic conductivity, solute transport parameters (Basile and De Mascellis, 1999; Bartoli et al., 2007). These aggregates are unchanging and are not broken up on rewetting. In such a case, their dielectrical behaviour will be closer to those shown by typical "Topp-type" porous medium, whose characteristics may be well described by the Topp's universal calibration equation. In this sense, comparing the altered (because of tillage and drying) topsoil and the unaltered subsoil may provide useful additional information on the characteristics mainly involved in determining the specific behaviour of volcanic soils.

With these premises, the objective of this paper was mainly establishing the role of the solid phase and surface characteristics (porosity, dielectric constant, bound water, surface area) on the dielectric properties of a typical volcanic-Vesuvian soil in the Campania plain (southern Italy). All these properties were directly measured in the laboratory for two soil horizons (Ap, in the following topsoil and Bw, in the following subsoil) of the same modal soil profile. Physically based dielectric models, explicitly accounting for all the measured properties were used for separating the contribution of each on the bulk dielectric properties of the two horizons. Specifically, we considered two different physically based descriptions of the $\theta - \varepsilon$ relationship including the theoretical model based on the Maxwell's equation proposed by De Loor (1964) and the α model of Dobson et al. (1985). These descriptions were compared to the third-order polynomial represented by Topp's equation (1980). Finally, a relationship between θ and ε specifically developed by Regalado et al. (2003) for volcanic soils was also tested.

2. Theory

2.1. Interpretative models of soil dielectric response

We briefly review the TDR theory in relation to the calibration methods presented in this paper. Volumetric water content determined by TDR involves measurement of the propagation velocity (or time delay) and attenuation of an applied electromagnetic (EM) wave along a transmission line in the soil. Time Domain Reflectometry generates an electrical pulse, which propagates as an electromagnetic wave through the soil via a transmission line (wave-guide = TDR probe).

The propagation velocity (v) corresponds to the time (t) it takes for a step pulse to travel forward and backward along a wave-guide of assigned length L. According to the Maxwell's equation, the velocity of propagation of the EM wave can be expressed as:

$$v = \frac{2L}{t} \tag{1}$$

The time interval t is the variable quantity measured by the TDR technique and used to determine apparent dielectric properties and therefore estimate soil water content. As the soil water content increases, the time required for the wave to travel along the transmission line also increases.

The apparent dielectric constant ε, may be expressed as follows:

$$\varepsilon = \left(\frac{c}{v}\right)^2 \tag{2}$$

where c (=3×10^8 m s^{-1}) is the velocity of an electromagnetic wave in free space.