A Dual Sensor for Simultaneous Investigation of Soil Cone Index and Moisture Content

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A dual sensor combining dielectric and mechanic principles was developed. The geometric structure of this sensor has been designed according to the ASAE- standard for penetrometer cones, and the sensor can provide a pair of output signals when inserted into soil. By analyzing both signals, one can determine the correlation among cone index, soil bulk density, and moisture content. Some preliminary experiments were performed in a laboratory environment, and the sensor will be ready for use in the field in the near future.

Keywords
Cone index, soil moisture, bulk density, dielectrics, measurement

Introduction

Soil water content is a valuable hydrologic parameter that is commonly used in agricultural and water resources research. Since Topp et al. found an empirical equation to describe the relationship between soil moisture and permittivity of moist soil, a variety of measurement methods based on dielectric properties of moist soil, such as TDR (Time Domain Reflectrometry), FD (Frequency Decomposition) and SWR (Standing Wave Ratio), have become increasingly popular [1, 2, 3]. However, these instruments can attain high accuracy in the laboratory but not in the field. The main reason is that the readouts of these instruments are not only dependent on soil water content, but to a certain degree also on bulk density. For instance, the universal calibration functions for TDR instruments (TRIME, Micromodultechnik GmbH, Germany) were established at a dry bulk density of 1.4 Mg m^{-3}. Once dry bulk density in field is significantly higher (>1.7 Mg m^{-3}), the readout of the TDR will overvalue moisture, whereas moisture content will be undervalued if dry bulk density in field is considerably lower (<1.0 Mg m^{-3}) [4]. In order to eliminate the influence of soil bulk density, the term volumetric water content should be employed. It refers to a measured value of soil moisture in terms of a known bulk density [5]. Because soil is a mixture of air, solid, and water, a three-phase mixing model presented by Roth et al. for investigating how the three components contribute to the dielectric behavior of soil mixture was used [6].

$$\varepsilon^{\alpha} = \varepsilon_a^{\alpha} f_a + \varepsilon_s^{\alpha} f_s + \varepsilon_w^{\alpha} \theta \quad (1)$$

where ε_a , ε_s and ε_w denote the relative permittivities of air (ε_a=1), soil solid (6>ε_s>3, depending on different soil types) and water (ε_w =80) respectively; f_a, f_s and θ are their volume fractions and α has a value between 0 and 1 depending on different soil types. Gardner et al. brought this model into a simple form [2],

$$\sqrt{\varepsilon} = 1 + \frac{(\varepsilon_s - 1)\rho}{\rho_p} + 8\theta \quad (2)$$

where ρ is the dry bulk density of soil and ρ_p is the particle density of soil. Variability in moisture content among soil samples can be significantly reduced by using the volume method, but this requires that the volume of the soil sample is known [5]. Thus, an ideal way is to measure θ and ρ simultaneously. A conventional tool for evaluating ρ is the penetrometer. As a direct measurement result of the penetrometer, the cone index is closely related to soil particle size distribution, bulk density, and moisture content [5, 7, 8, 9, 10, 11, 12]. On this basis, Ayers and Perumpral gave the following equation to approach soil density on the basis of cone index and soil moisture content for different soil types [7].

$$DD = \left[(CI / C_1)C_2 + (MC - C_3)^2\right]^{\frac{1}{C_4}} \quad (3)$$

where:
DD = dry density (g cm^{-3})
CI = cone index (kPa), which is defined as penetration resistance divided by cone cross-sectional area
C_1, C_2, C_3, and C_4 = constants to be estimated depending upon the soil type
MC = moisture content, percent of dry weight.

According to their report, the model fitted the data from soil samples in the laboratory with a correlation coefficient R^2 of 0.94 for sand and 0.98 for clay soil. Hence, they concluded that with additional research, the penetrometer was a promising instrument for determining subsurface soil density in situ. Hereafter, Lüth developed a horizontal penetrometer and checked this model in the field [12]. His results demonstrated that the model was suited for clay quite well but needed improving for loamy and sandy soil.

Over the past decade, a few trials for the simultaneous measurement of soil penetration resistance and water content with a combined penetrometer-TDR moisture probe have been conducted [13, 14, 15, 16, 17]. The main idea of these trials was to design a probe with a TDR sensor integrated into a cone penetrometer. In fact, the TDR technique is not a real-time method, and therefore it is not suited to working in synchronism with a penetrometer. For instance, a newly developed probe in [16] is operated by impact way since a measurement cycle of TDR sensors is at least 10 seconds. In addition, a cone integrated with a TDR sensor is relatively expensive but not robust in use.

The objective of this study is to design a dual sensor for the simultaneous determination of soil cone index and moisture content. Both the configuration and the measurement principle of the dual sensor differ from those of the above-mentioned sensors. In particular, the new dual sensor can simultaneously provide a pair of signals, which are sensitive to ε and CI respectively at real time. A preliminary trial to assess soil water content and bulk density by using the pair of signals was conducted under laboratory conditions with a non-saline clay-loam soil.

Measuring principle

As shown in **figure 1**, the new dual sensor is based on a rod together with a cone designed according to the ASAE recommended standard [18]. A dielectric transducer, which consists of a brass cone and a brass ring, is embedded at the bottom of the rod, and a force transducer is mounted at the top of the rod. In most cases, the penetration resistance and thus the cone index increases as the silt and clay content increase, soil moisture decreases, depth increases, and bulk density increases [8, 10, 12]. In addition to the above, the value of the cone index is proportional to the velocity of penetration [12, 19]. Assuming the speed of penetration to be a constant during the measurement process, each output value from the dielectric or the force transducer can be expressed as

$$S_{Dielectrics} = f_1(\theta, \rho, \alpha) \tag{4}$$

$$S_{force} = f_2(\theta, \rho, \alpha) \tag{5}$$

where:
- $S_{Dielectrics}$ = output value of the dielectric transducer
- S_{force} = output value of the force transducer, so-called penetration resistance
- θ = volumetric soil water content
- ρ = soil bulk density
- α = a parameter depending on different soil types

Once the soil type is chosen, α will become a constant. Under this assumption, there remain the two unknown terms θ and ρ in each equation. Furthermore, a necessary condition should be taken into account to ensure that there is no linear dependency between both equations. In other words, if there is a dimensionless constant C, so that

$$f_2(\theta, \rho, \alpha) = C \cdot f_1(\theta, \rho, \alpha) \tag{6}$$

there exist infinite solutions for both equations, and a pair of output values of the dual sensor will become identical. Thus, the characteristics of the dielectric transducers were deliberately designed to fulfill

$$(\theta^{\uparrow} \cup \rho^{\uparrow}) \rightarrow S_{dielectrics}^{\uparrow} \tag{7}$$

since the characteristics of the force transducers are known by

$$(\theta^{\downarrow} \cup \rho^{\uparrow}) \rightarrow S_{force}^{\uparrow} \tag{8}$$

As a required result, both output signals are linear independent of each other and it is possible to investigate soil moisture and bulk density by using the pair of signals.

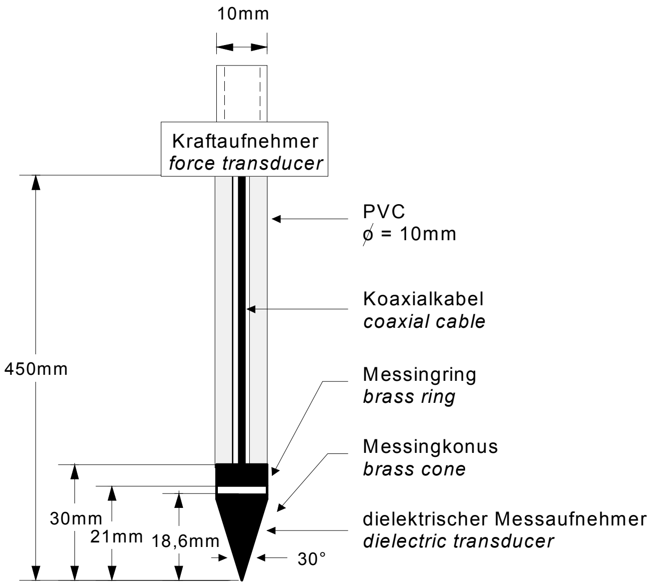

Figure 1: Schematic diagram of the dual sensor

Design of the dielectric transducer and the experiment system

Figure 2 illustrates a schematic diagram of the dielectric transducer. The principle of the transducer is to measure the value of the impedance of the probe since it depends on the probe's physical dimensions and on ε. Actually, the brass ring and the cone at the probe tip are equivalent to two electrodes of a capacitance. If soil moisture or bulk density around the probe tip changes, it will cause the impedance of the probe to vary. Thus, by means of soil samples with different moisture contents and bulk densities, the properties of the dielectric transducer can be characterized by calibration in the laboratory. In figure 2, Z_p stands for the impedance of the probe. In order to eliminate an error factor arising from the output impedance of the oscillator, an additional impedance Z_o is introduced to this circuit so that Z_p can be determined by equation 9:

$$Z_p = \frac{Z_o}{U_a - U_b} U_b \tag{9}$$

where:
- U_a = output voltage of the wave detector referring to point a
- U_b = output voltage of the wave detector referring to point b

Since the presence of salts in soil water may directly influence the dielectric behavior of moist soils, several researchers suggested that the measurement frequency should be greater than 30 MHz [20, 21, 22]. In particular, according to the report from Gashin and Miller [20], the output signal of their sensor, based on a measurement frequency of 100 MHz, was reduced to around 15-20 mV with respect to soil conductivity between 0 and 1500 µs across a range of 1100 mV. Thus, 100 MHz was chosen as the measurement frequency of our dielectric transducer.

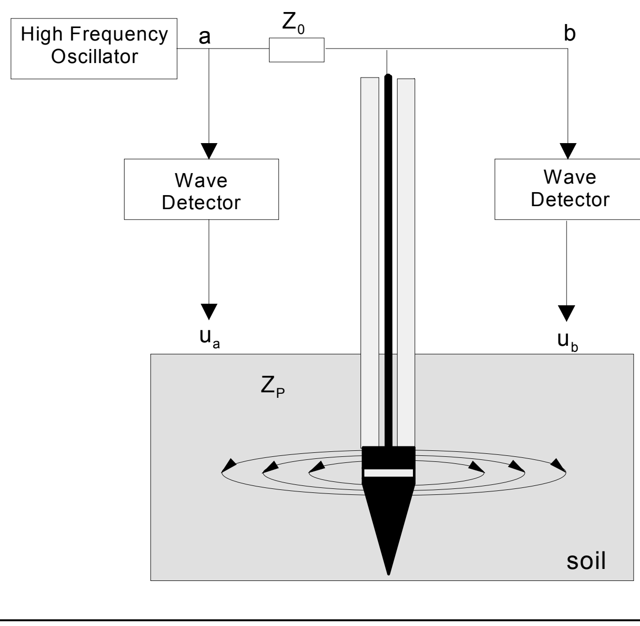

Figure 2: Schematic diagram of the dielectric transducer

The designed probe weighs 110 g and was installed in a penetrometer as presented in **figure 3**. **Figure 4** shows a block diagram of the experimental measurement system. The type of force transducer used is HBM-C9B/500N (Hottinger-Baldwin-Messtechnik), and the maximal value of measured force is 500 N. In addition, a linear amplifier (HBM-MC3, analogue output 0-5V) is employed to enlarge the signal amplitude

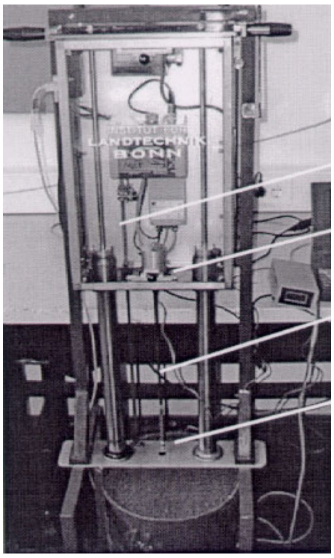

Figure 3: The experiment system of the dual sensor

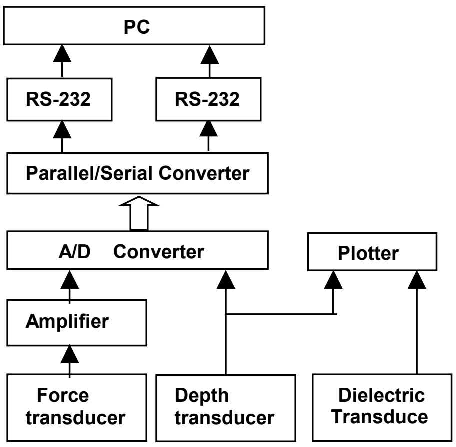

Figure 4: Block diagram of the experimental measurement system

of the force transducer. After being converted into a digital signal, the output of the force transducer is fed into a notebook computer via a RS-232 interface. The depth transducer (10-turn, 10 kΩ potentiometer with ± 0.25 % linearity) is mounted in a housing which rests on the soil surface. As the rod moves vertically, the potentiometer is rotated by a rack and pinion adjustment. The output signal of the depth transducer is also an analogue signal varying within 0-5V. Because both the PC and the plotter need a synchronous signal from the depth transducer, the analogue signal of the depth is transmitted directly to the plotter and is converted into a digital signal for the PC. The maximal vertical movement of the cone is 420 mm.

Experiment procedure

In this experiment, soil samples were collected from the experimental field in Endenich, Bonn. According to their different volumetric water contents ranging from 0 ~ 42.5 m^3 m^{-3}, i.e. from oven dry to saturated, these samples were packed into seven plastic cylinder containers. The height of the container was 400 mm, and the diameter of the container was 340 mm. The tested soil sample is clay-loam and its textural composition was: clay 36 %, silt 53 %, sand 11 %. The measurement process was controlled by running a program stored in the PC. Signal reading for penetration resistance was conducted at 5 mm intervals. After each test, a curve relating penetration resistance to depth was displayed on the screen of the PC. Meanwhile, another curve associating the output signal of the dielectric transducer with depth was drawn by the graph plotter.

Results and discussion

A set of calibration data at a dry bulk density ρ = 1.4 Mg m^{-3} and the correlation between volumetric soil water content and the output signal of the dielectric transducer are illustrated in **figure 5**. The calibration curve fitted a linear equation with R^2 of 0.93. Figure 5 presents in addition a cluster of nonlinear regression curves to indicate the influence of different dry bulk densities on the output of the dielectric transducer. Since ε_w is considerably greater than ε_s and ε_a, it plays a major role in affecting the output behavior of the dielectric transducer in the vicinity of soil water saturation. Alternatively, when θ is close to air-dryness, the factor changing the value of ε arises mainly from dry bulk density. Between these cases, it is easy to note that the output behavior of the dielectric transducer depends strongly on the proportions of soil matrix, water and air. In order to quantify the influence of dry bulk density, the parameter Relative Deviation (RD) is defined as

$$RD = \frac{S_{dielectrics}\big|_{\rho=\rho_0} - S_{dielectrics}\big|_{\rho\neq\rho_0}}{S_{dielectrics}\big|_{\rho=\rho_0}} \times 100\% \qquad (10)$$

where, ρ_0 acts as a reference value of dry bulk density. **Figure 6** gives a set of data

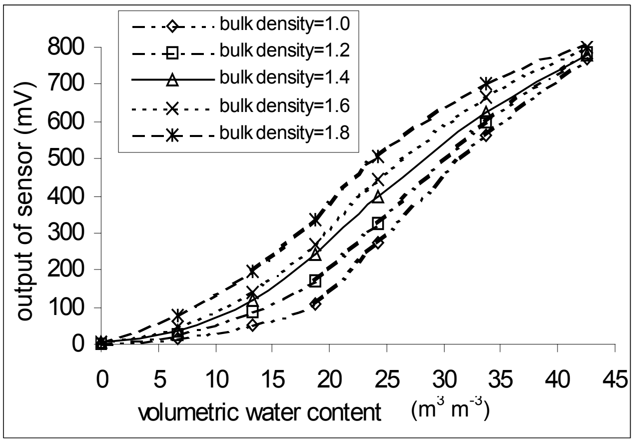

Figure 5: Signal of the dielectric transducer versus volumetric water content depending on different bulk densities

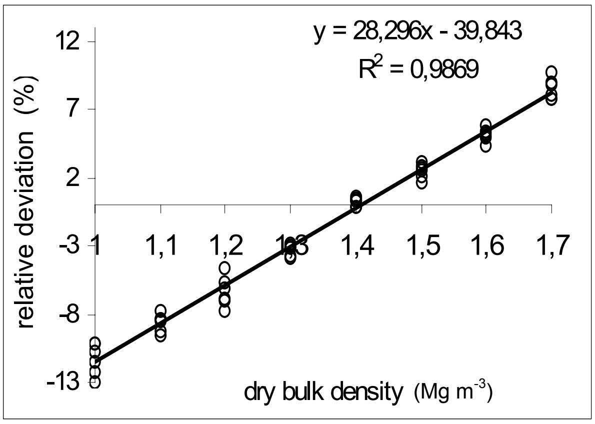

Figure 6: Relative deviation of the output of the dielectric transducer versus dry bulk density

and its regression analysis in terms of RD and ρ at θ =13.7 m^3 m^{-3}. Although here 1.4 Mg m^{-3} is chosen as ρ_0, it can be altered easily by moving the horizontal coordinate axis up or down when the influence of ρ_0 at an arbitrary value needs to be investigated. As a result of the comprehensive test of the dual sensor, the 3D curve in **figure 7** illustrates the relationship among volumetric water content, bulk density, and cone index for the tested soil samples. From this figure, it can be observed that the maximal value of the cone index occurs not always in the vicinity of $\theta = 0$. This fact had been found by Ayers et al. [2], and it has two main reasons. Firstly, the effect of moisture content on dry bulk density should be taken into account. According to the test results from Ayers et al. [7], the peak value of dry bulk density is strongly related to moisture content and soil types. Secondly, the interaction between soil sample and the surface of the cone tip varies significantly when either moisture content or dry bulk density changes. The results in figure 7 confirmed that one measured cone index can be the result of many different combinations of cohesion and friction [23]. Therefore, one cannot simply postulate that the cone index increases as moisture content decreases monotonously.

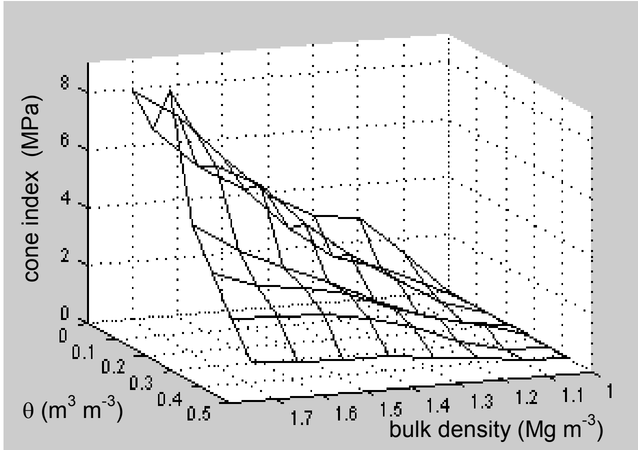

Figure 7: The relationship among cone indices, volumetric water content and bulk density

Conclusion

A new sensor for determining soil cone index and moisture content simultaneously and at real time was developed and tested under laboratory conditions. Compared with the TDR sensor, this sensor is much cheaper and more robust in use. The preliminary test result seems quite promising for its utilization in field. Commercialization of the dual sensor can significantly increase the value of the data from the soil penetrometer. Further research will aim at three aspects: (1) To calibrate the sensor for different soil types; (2) To seek an ideal model to interpret the correlation among cone index, soil bulk density, and moisture content for universal application; (3) To develop a mathematical approach for calculating the impedance of the dielectric transducer.

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