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A prototype measuring system of soil bulk density with combined frequency domain reflectometry and visible and near infrared spectroscopy

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ABSTRACT

A combined-penetrometer sensor prototype (CPSP) for the measurement of topsoil bulk density (BD) was developed and tested under field conditions. The prototype consisted of a standard penetrometer, equipped with a near infrared spectrophotometer (NIRS) (1650–2500 nm) to measure gravimetric moisture content (ω) and a frequency domain reflectometry (FDR) to measure volumetric moisture content (θv), while BD was assessed by the combination of both sensors' data. The CPSP was tested *in situ* at five arable and two grassland fields of different soil texture classes in Silsoe, Bedfordshire, UK, during the period from August to December 2013. Artificial neural networks (ANN) were used to predict ω and θv based on data fusion of NIRS diffuse reflectance spectra and FDR output voltage (V), and the predicted values were substituted in a model to predict BD. The CPSP showed more accurate BD assessment in grass fields with root mean square error of prediction (RMSEp) of 0.077 g cm^{-3}, compared to arable fields (RMSEp = 0.104 g cm^{-3}). A collective BD model produced for arable and grass fields provided a moderate accuracy with a RMSEp of 0.102 g cm^{-3}. It can be concluded that the new CPSP can be used successfully to measure BD in the topsoil by combining the NIRS and FDR techniques through ANN-data fusion approach.

1. Introduction

Soil compaction created by different human and natural factors causes multiple environmental and agronomical problems. It has attracted scientists' attention to carry out intensive research to understand the occurrence and propose solutions for avoidance and management for more than a century. Soil compaction is mainly occurred by the intensive use of the heavy agriculture machinery, repeated ploughing at the same depth in addition to the trampling of animals. However, soil compaction can also be found under natural conditions without human or animal intervention (Batey, 2009). Many studies indicated increases in soil strength, bulk density (BD), and tillage draught requirement as a result of soil compaction, while decreases in soil total porosity, soil aeration, water infiltration and saturated hydraulic conductivity were evidence of soil compaction (Hamza and Anderson, 2005). Understanding therefore how and to what extent soil compaction may be eliminated seems of vital importance to the future wellbeing of agricultural systems. A key requirement to manage soil compaction is by accurate measurement of associated parameter/s that should be done quickly and cost effectively in the field without the need for laboratory analyses that are time consuming, difficult and costly procedures.

In situ measurement of soil compaction is a tricky task to accomplish rapidly, easily and cost effectively, because of the complex nature of agricultural soils (Aragón et al., 2000; Horn et al., 2000; Mouazen and Ramon, 2006). Due to this fact, many scientists have developed various devices for measuring soil compaction. Apart from the traditional Kopercki rings and standard penetrometers commonly used to measure BD and penetration resistance, respectively, new approaches based on multi-sensor and data fusion approach were recently introduced. This was essential to avoid the shortcomings of Kopercki rings method (i.e., time consuming, difficult, and prone to error in dry conditions) and standard penetrometers (i.e., combined effects of moisture content, texture and BD on penetration resistance readings) reported earlier (Mouazen and Ramon, 2006). Therefore, there are now examples of penetrometers equipped with multi-sensors for the measurement of soil compaction.

Vaz et al. (2001) reported the development of a combined sensor consisting of a penetrometer and a time domain reflectometry (TDR) to measure soil strength and volumetric moisture content (θv) simultaneously. Peter and Yurui (2004) designed a combined capacitance sensor with a cone penetrometer, to measure θv and penetration

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resistance, respectively. Hummel et al. (2004) presented a combined probe consisting of a cone penetrometer and a near infrared spectrophotometer (NIRS) to measure penetration resistance and gravimetric moisture content (ω), respectively. Sheng et al. (2011) developed a combined penetrometer sensor kit consisting of two impedance soil moisture sensors, two soil temperature sensors, and an electrical conductivity (EC) sensor to monitor moisture dynamics in the soil. All these combined-penetrometer sensor porotypes (CPSP) were not implemented to predict BD. Quraishi and Mouazen (2013a) introduced a multi-sensor platform, which enabled the assessment of BD from the fusion of data on penetration resistance measured with a load cell and ω, clay content and organic matter (OM) measured with a NIRS sensor. This multi-sensor does not measure θv, necessary for the direct assessment of BD using the following equation (Wijaya et al., 2004):

$$BD = \theta v/\omega \quad (1)$$

where BD is the soil bulk density in g cm^{-3}, θv is the volumetric moisture content in $cm^3\ cm^{-3}$ and ω is the gravimetric moisture content in g g^{-1}.

Therefore, there is a need for a modified penetrometer sensing kit that enables simultaneous measurement of both θv and ω, and then derive BD values using Eq. (1). The aim of this paper was to design and evaluate a CPSP, consisting of a NIRS and a FDR sensor. The developed CPSP kit will be tested for the measurement of the top soil BD under field measurement conditions.

2. Materials and methods

2.1. Development of the combined-penetrometer sensor prototype (CPSP)

Al-Asadi and Mouazen (2014) introduced a proof of concept of a new measurement system of BD, based on measurement of θv and ω values with a FDR and NIRS, respectively, which are then substituted into Eq. (1) to assess BD. In a recent work, Mouazen and Al-Asadi (2018) studied the effect of moisture content on the accuracy of BD measurement. These two studies enabled understanding the requirements for designing a new CPSP for the measurement of BD based on a standard penetrometer. The new design to be reported in this work consists of a NIRS, a dielectric (FDA) sensor, a standard penetrometer, a global positioning system (GPS) a battery and a laptop.

The NIRS used was Avantes® portable model NIR200-2.6 (Avantes, Eerbeek, the Netherlands), which has a dual stage thermo-electrical Peltier-cooled InGaAs single detector with 256 pixels, with a spectral range of 1650–2500 nm and 7 nm resolution. This spectrometer was connected to a laptop through a high-speed USB2.0 interface and AvaSoft 7.7 software (Avantes, Eerbeek, the Netherlands). The spectrometer was also connected to an assembly of a rod and a 30 degree, 1.26 cm^2 base-area cone through two optical fibres (Quraishi and Mouazen, 2013a). An electronically stabilized 20 W halogen lamp is used as a light source, and light was transferred to the soil profile through an illumination fibre connected at one end to the spectrometer and at the other end to a sapphire window (Fig. 1). The diffuse reflected light passing the sapphire window was collected back to the spectrometer by a detecting fibre. The system operates *in situ* using 24VDC and 20 Watts lead-acid battery as a power source. A 50 channel global positioning system (GPS) (eTrex 60C model, Garmin, USA) was used to record the sampling location.

The measurement of θv was done by a new designed FDA sensor, which consists of an electronic circuit generating a 100 MHz electromagnetic sine wave, propagated through the soil body by the central electrode in the form of a copper ring with a 10, 15 and 1.5 mm height, diameter and wall thickness, respectively. The copper ring is insulated from the probe body, which forms two shielding electrodes as they are connected to the electronic circuits' negative. Each shielding electrode has a cylinder shape with a 13 and 50 mm diameter and height, respectively (Fig. 2). The readout pin of the electronic circuit is connected to the HH2 meter (Delta-T devices, Cambridge, UK), which at the time of reading acts as a power supply and provides data storage. The probe body also provides protection for the optical fibres, as they run inside its cavity, as described above. As the combined probe inserted into the soil vertically, the surrounding soil in contact with probe electrodes will be affected by the fringe fields of the propagated signal, resulting from the two capacitors (Fig. 2).

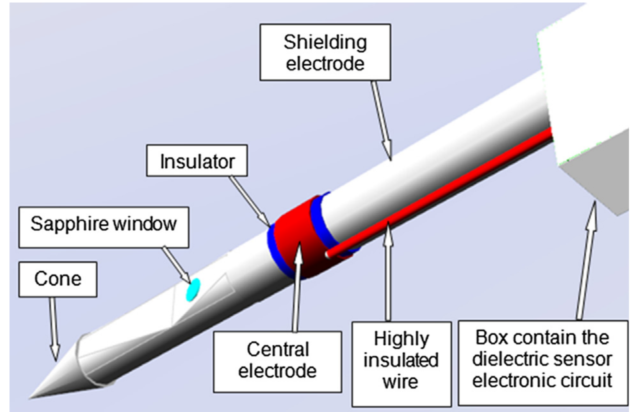

Fig. 1. The combined-penetrometer sensor prototype (CPSP) of a near infrared spectrophotometer (NIRS) and a frequency domain reflectometry (FDR) sensor, for the measurement of soil gravimetric moisture content (ω) and volumetric moisture content (θv), respectively, and assessment of bulk density (BD).

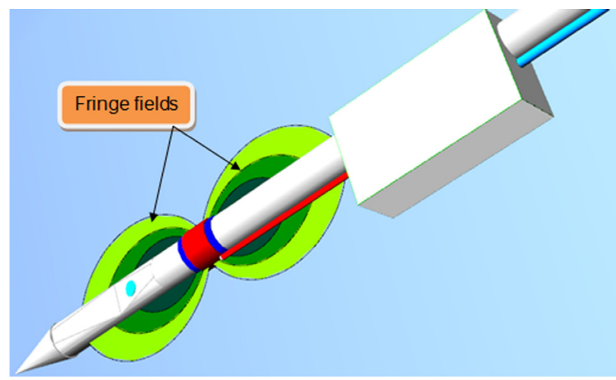

Fig. 2. Shows the electromagnetic fringe fields around the dielectric sensors' electrodes.

2.2. Experimental procedure

The CPSP portable measurement system was tested *in situ* in seven fields with various textures and growing crops (Table 1). The average field particle size distribution (PSD) was measured, using the sieving and sedimentation method (British Standards, 1998). The average soil

Table 1
Information of the seven fields used for testing the combined-penetrometer sensor prototype (CPSP).

Fields	Nr.	Soil texture	Clay%	Silt%	Sand%	OM%	Crop
Avenue 1	20	Sandy loam	17	20	63	3.6	Barley
Beechwood	20	Cay	66	11	23	5.8	Wheat
Clover hill	20	Clay loam	35	24	41	4.8	Barley
Orchard	20	Clay loam	33	26	41	4.15	Wheat
Showground	20	Sandy clay loam	24	17	59	3.34	Barley
Avenue 2	50	Sandy loam	29	20	51	2.98	Grass
Onley	50	Clay	60	30	10	5.4	

OM is organic matter