New devices for water content measurement

Les appareils nouveaux pour la mesure de la teneur en eau

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ABSTRACT: Two new devices for water content measurement are described: (i) an automated multi-electrode resistivity system and resistivity probe and (ii) a coiled TDR probe that can be used in conjunction with a high suction tensiometer. A flexible resistivity data acquisition system has been developed to acquire resistivity data using different arrays and which automatically switches electrodes interchangeably. A wide range of high precision reference resistors and soils have been used to test the system and the output data have been compared with a commercial resistivity system. The system developed has been used to investigate wetting and drying of clay using a new resistivity probe with a square electrode configuration that can be used for localised water content determination. The novel coiled TDR device uses a two-pronged TDR wrapped around the body of the Durham University high capacity tensiometer. The calibration of the device takes account of the contact with the tensiometer body. The device can be used with a steel bodied tensiometer and provides accuracy in volumetric water content of ±0.075 over a range of volumetric water contents of 0 to 0.9. A ceramic bodied device has also been investigated that does provide improved accuracy of ±0.047.

RÉSUMÉ : Deux appareils nouveaux pour la mesure de la teneur en eau sont décrites: (i) un système automatique multi-électrode de résistivité et une sonde de résistivité et (ii) une sonde TDR qui peut être utilisée en parallèle avec un tensiomètre de forte capacité de succion. Un système d'acquisition de données de résistivité a été développé pour acquérir des données de résistivité en utilisant des tableaux différents et qui commute automatiquement par électrodes interchangeables. Une large gamme de résistances de référence de haute précision et les sols ont été utilisés pour tester le système et les données de sortie ont été comparées à partir d'un système commercial de mesure de résistivité. Le système mis au point a été utilisé pour étudier l'humidification et le séchage de l'argile à l'aide d'une nouvelle sonde de résistivité avec une configuration d'électrodes carrée qui peut être utilisée pour déterminer la teneur en eau localisée. Le dispositif de TDR utilise un TDR à deux volets enroulé autour du corps d'untensiomètre de grande capacité de l'Université de Durham. L'étalonnage du dispositif tient compte du contact avec le corps de tensiomètre. Le dispositif peut être utilisé avec un tensiomètre en acier et offre une précision de la teneur en eau volumétrique de ± 0,075 sur une plage de teneurs en eau volumétriques de 0 à 0,9. Un dispositif en céramique a également été étudié qui donne une meilleure précision de ± 0,047.

KEYWORDS: Resistivity, TDR, water content

1 INTRODUCTION

An accurate knowledge of soil water content is crucial to understanding the impact of climate change on engineered earth structures. However, quantifying water content in unsaturated soils is difficult due to the complexity of unsaturated soil systems and the difficulties associated with gathering representative measurements. A large spectrum of techniques has been developed to measure soil water content. These include; neutron scattering, dielectric methods such as Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR), capacitance probes and remote sensing techniques that provide measurements at regional scale. Robinson et al. (2008) and Vereecken et al. (2008) have presented detailed reviews of these techniques.

In geotechnical testing there is an increasing demand to develop efficient techniques to measure soil water content. Among the options available, TDR is becoming more widely used in geotechnical testing and electrical resistivity has also emerged as a cost effective and non-invasive tool to map the spatiotemporal variability of water content that cannot be provided by more traditional techniques (Zhou et al., 2001). In this paper, two new systems are described: (i) an automated multi-electrode resistivity system and resistivity probe (ii) a coiled TDR probe that can be used in conjunction with a high suction tensiometer to provide measurements of water content and suction at the same position. The devices have been developed to carry out experimental studies to monitor water content changes in unsaturated soil specimens submitted to drying and wetting cycles.

2 ELECTRICAL RESISTIVITY

2.1 *Theoretical Background*

An unsaturated soil is a multi-phase system consisting of air, water and soil grains. Electrical resistivity (the reciprocal of electrical conductivity) is an intrinsic physical property of a material that describes its ability to resist the ionic mobility in pore water. Since electrical conduction is mainly electrolytic and takes place through the pore water (Bryson, 2005), electrical properties of soils are mainly controlled by water content. A traditional four-electrode resistivity system therefore is based on the principle that the potential drop across a pair of electrodes due to a direct (DC) or low frequency current injected via another pair of electrodes is proportional to the electrical resistivity, that is:

$$\rho = K * \Delta V / I \quad (1)$$

Where, ρ is resistivity (Ohm.m), the ratio of ΔV, the potential drop (Volts), and I, the current (Amps), is the material resistance (Ohm). K is a geometric factor (m) representing the electrode arrangement. For 2D and 3D resistivity studies, traditional four-electrode systems are time consuming and impractical. Therefore, the development of automated multi-

electrode resistivity systems (e.g. Damasceno et al., 2009) has triggered rapid and efficient data acquisition of resistivity measurements to address a wide range of applications such as water content estimations.

A number of authors have demonstrated an explicit relationship between resistivity and water content. Shah and Singh (2005) proposed 'a generalized Archie's Law' as:

$$\rho = \rho_w \theta^{-m} \quad (2)$$

Where θ is the soil water content (volumetric), ρ_w is a fitting parameter related to pore water resistivity, and m is a dimensionless constant.

2.2 *The multi-electrode resistivity system*

A multi-electrode resistivity system is based on the traditional four-electrode principle combined with automatic multiplexing for a larger number of electrodes (Damasceno et al., 2009). The system described here consists of: a constant current power source, a switching system and acquisition software. A 30V/2A programmable DC power supply type EL302P and MSL Datascan logger type 7220, both connected to a PC via RS 232 interface, were used to measure the voltage and log the current by measuring the voltage drop across a 1 Ω high precision shunt resistor. A similar approach has been adopted in commercial equipment e.g. MPT/ERT 2004 system from Multi-Phase Technologies, LLC (MPT) (LaBrecque and Daily, 2008).

Windows based data acquisition and control software named Resist has been developed to integrate the hardware and to control the data collection process. The user can set the current injected into the soil specimen and read the current, the voltage drop, and hence the resistance in a fully automatic procedure. To prevent electrode polarization (LaBrecque and Daily, 2008) short current pulses are used and an average reading (i.e. stacking) of a number of normal and reverse polarity readings are automatically acquired.

The aim of the laboratory testing described here was to check the data quality of the developed system. A wide range of high precision reference resistors (ASTM G57, 2006) was used to calibrate the system, and the measurements were compared with those acquired with a Terrameter SAS 300C (ABEM) system. The results are reported in Table 1. It can be seen that Resist gives better results than the commercial Terrameter with a maximum error of 0.8%.

Table 1. A comparison between Terrameter SAS 300C system and Resist reading for a range of reference resistors

Reference Resistor (Ohm)	SAS 300 Terrameter		Resist	
	Average Reading (Ohm)	Percentage Error (%)	Average reading (Ohm)	Percentage Error (%)
10	9.9	1.00	10.0	0.00
56	56.1	0.18	56.3	0.54
100	98.0	2.00	99.2	0.80
120	119.3	0.58	120.2	0.17
150	149.0	0.67	150.1	0.07
220	217.0	1.36	218.9	0.50
270	268.0	0.74	270.5	0.19
370	368.0	0.54	368.9	0.30
490	486.0	0.82	489.0	0.20
590	585.0	0.85	589.1	0.15
1000	996.0	0.40	998.4	0.16
1120	1118.0	0.18	1118.4	0.14
1220	1217.0	0.24	1215.9	0.33

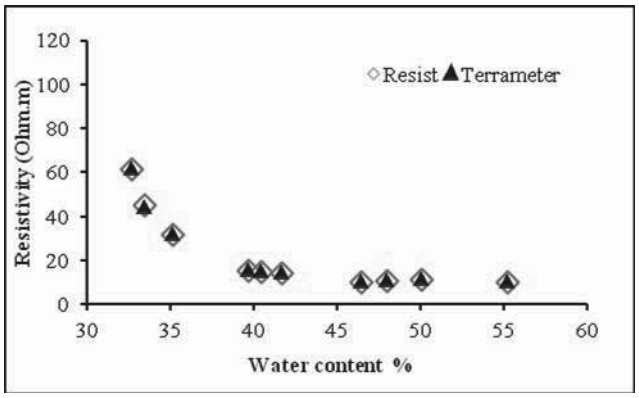

Figure 1. Resistivity-gravimetric water content relationship of a kaolin specimen

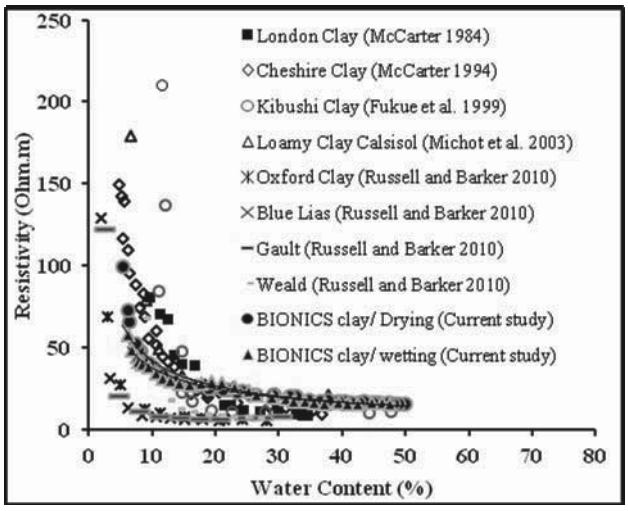

Figure 2. Resistivity-water content relationships of BIONICS clay and different clays reported in the literature

A resistivity box (ASTM G57, 2006) was constructed to measure resistivity of a Kaolin specimen during drying. A good comparison between Terrameter SAS 300C and Resist readings is shown in Figure 1 with a percentage difference less than 1.59%.

The developed system has been used to investigate drying and wetting of sandy clay sampled from the BIONICS project (Mendes, 2011). The soil is classified as being intermediate plasticity with Liquid Limit (43.3%), Plastic Limit (23.7%), Plasticity Index of 19.6, and a Liquidity Index of -0.05. A resistivity probe based on a square arrangement (Habberjam and Watkins, 1967) with inter-electrode spacing of 15mm was constructed to monitor water content changes of a specimen subjected to controlled drying and wetting procedures. Figure 2 shows the drying and wetting curve compared to different clays reported in the literature.

The experimental data followed the power law function reported in the literature (Calamita et al. 2012), within the typical range of clay resistivity (1-100) Ohm.m (e.g. Loke 2011). As resistivity is mainly controlled by water content, in both drying or wetting the resistivity is relatively low at high water content (the capillary and gravitational water ranges) and high at low water content (the range of adsorbed, film, and film-capillary water) (Pozdnyakov et al., 2006). However, the rate of the resistivity changes is higher at low water content due to air replacement of water in the pores. The well defined resistivity-water content relationship obtained in this study with high correlation coefficient 0.945 and 0.966 for drying and wetting respectively, suggest that it can be used to calibrate resistivity against water content (Muñoz-Castelblanc et al., 2011) and to estimate in situ water content changes (Calamita et al., 2012).

Although resistivity provides an excellent technique for non-intrusive measurement of the spatiotemporal variation in water content on a large scale in the field, it can also be used to provide localised measurements in the laboratory (e.g. Muñoz-Castelblanc et al., 2011). The system described here has also been adopted for use in large-scale laboratory lysimeters (Asquith et al., 2012).

3 TIME DOMAIN REFLECTOMETRY

The TDR technique (Topp et al., 1980) is a method to measure soil water in hydrological and geotechnical testing, by measuring the soil bulk permittivity or dielectric constant that determines the velocity of an electromagnetic wave transmitted through the soil via a TDR probe (Tarantino et al., 2008). Since the dielectric constant of water (K=80) is larger than air (K=1) and soil constituents (K= 2-5), the bulk permittivity is mainly governed by soil water content. To estimate water content from the dielectric constant, K, the empirical equation of Topp et al. (1980) is commonly used.

3.1 *Coiled TDR*

In geotechnical testing it would be hugely beneficial to have a device that is capable of simultaneous measurements of soil water content and pore water pressure at the same position. To achieve this, a coiled TDR device was developed that could be wound around a high suction tensiometer. The tensiometer was developed at Durham University (Lourenço et al., 2006) and is capable of measuring negative pore water pressures down to -2 MPa.

A double pronged TDR device was constructed by coiling copper wire around the insulated stainless steel housing of the tensiometer (Figure 3). A second device was also constructed using an impermeable ceramic tensiometer housing (Figure 4). The ceramic chosen was an impermeable Macor machinable glass ceramic, with a Young's Modulus of 66.9 GPa and a compressive strength of 345 MPa.

Each housing had two helixes (0.8 mm wide, 0.4 mm deep) cut into them at a pitch of 6 mm. This was so that the TDR prongs sat 3 mm apart as shown in Figure 3. This ensured that the probe diameter to spacing ratio was within the recommended region given by Noborio (2001) and Knight (1992), thus promoting an even distribution of electric field between the TDR prongs. The stainless steel body was insulated using five coatings of an insulating varnish.

The devices were tested alongside a conventional three-pronged TDR probe in three different soils (Leighton Buzzard sand, Birtley Clay and a very loose organic soil) over a range of known water contents.

The device could be simply calibrated based on the measured dielectric constant K_a for known soil water contents. However, to better understand the effect of coiling the probe around a steel or ceramic body and to take account of the fact that the coiled TDR is measuring the effect of the steel or ceramic housing that it is wound around, as well as the properties of the soil surrounding it, a mixing model approach (Roth et al., 1990) was investigated for interpreting the data. The aim was to split the apparent dielectric constant K_a into two parts, the dielectric constant of the tensiometer housing K_{house} and the dielectric constant of the soil K_{soil}.

Ferré et al. (1998) showed that for the special case where the rod surface was divided equally between two materials, the apparent dielectric constant could be described as:

$$K_a = 0.5K_1 + 0.5K_2 \quad (3)$$

where K_1 and K_2 are the dielectric constants of the two surrounding materials.

The helix which seats the TDR probe was designed so that half of each prong was exposed to the soil. Therefore K_1 can be replaced by K_{house} and K_2 by K_{soil}. By measuring K_a, K_{soil} was then interpreted by rearranging eq. (3) and finding a suitable value of K_{house}.

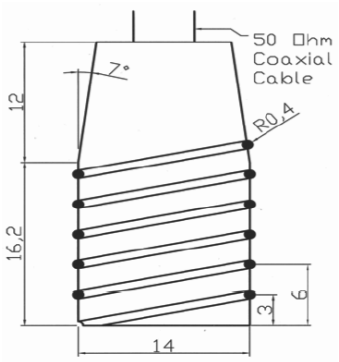

Figure 3. Schematic of tensiometer housing and coiled TDR (dimensions in mm)

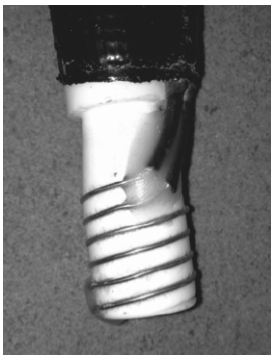

Figure 4. Coiled TDR constructed around a ceramic tensiometer body

The manufacturer's specifications give the dielectric constant of the ceramic to be 6.03 at 1 kHz and 5.67 at 8.5 GHz. Since the TDR bandwidth extends to around 1.5 GHz, a value of 6.0 was taken as the first approximation of K_{house}. This value, however, still caused large underestimations of volumetric water content, θ. By using trial and error and measuring the standard deviation of the difference between the actual dielectric constant calculated from θ, and K_{soil} obtained from the mixing model, the best value of K_{house} was found to be 3.5.

This value of K_{house} for the ceramic was significantly lower than the dielectric constant given by the manufacturer. Adopting a K_{house} value of 6.0 would be assuming that there was a perfect contact between the copper wire and the ceramic within the helix. However, as the grooves cut into the ceramic were not perfectly smooth and some tension in the prongs was lost when gluing them in place, this could introduce a small air gap between the copper wire and the ceramic body, changing the effect that the housing would have on the measured result.

For the stainless steel probe, using the same approach gave the optimal value of K_{house} to be 2.65. In the case of the stainless steel body, the dielectric constant of the insulation was unknown so comparisons could not be made.

The results of applying the simplified mixing model to the data (using K_{house} as 2.65) are shown in Figure 5. It can be seen that the results are slightly underestimated for clay and overestimated for sand, compared to the readings obtained from the conventional 3-prong TDR device.

It is likely that the higher values for sand are due to poor contact with the probe. If these higher values for sand were

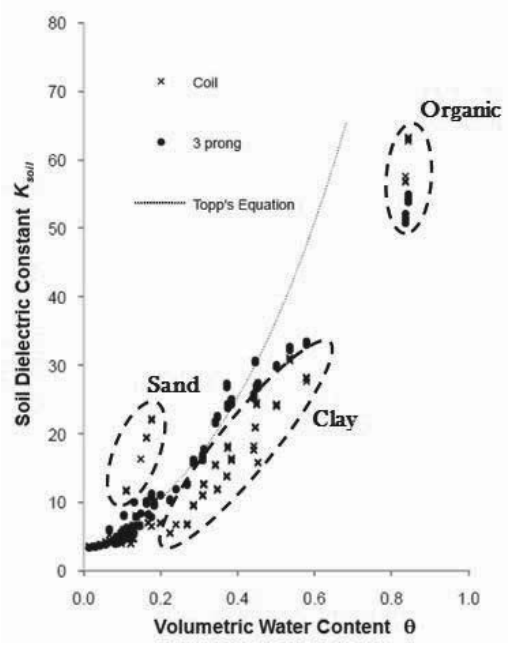

Figure 5. Comparison between the Coiled TDR (with a steel tensiometer housing) and a conventional 3 prong TDR device for Leighton Buzzard sand, Birtley Clay and a very loose organic soil.

neglected, a different optimal value of K_{house} would be achieved that would provide a closer fit to the observed values.

Ignoring the anomalous results for sand and comparing calculated and measured water contents it was found that the ceramic probe gave an accuracy for water content determination of ±0.047. This resulted in an R^2 value of 0.966 for K_{soil} when compared to the actual K_a found from known θ. Likewise for the stainless steel probe, accuracy was found to be ±0.075 with an R^2 value of 0.937. Improved accuracies can be obtained from direct calibration, rather than applying a mixing model.

It can be seen that Topp's equation does not provide a good fit to the results (from either device) for the very loose organic soil. It is known that Topp's equation is not appropriate for high volumetric water contents (>0.5).

4 CONCLUSIONS

The design and laboratory testing of new devices for water content measurement are described. A flexible multi-electrode resistivity system has been developed to acquire resistivity data using different arrays, including a resistivity probe. The novel coiled TDR device uses a two-pronged TDR wrapped around the body of the Durham University high capacity tensiometer. The devices have been developed to carry out experimental studies to monitor water content changes in unsaturated soil specimens submitted to drying and wetting cycles.

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