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In-situ soil water content estimation using new capacitive based sensors

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ABSTRACT: Water content and density measurements are important to many industries. At present, the most common ways of obtaining these parameters are time and labour intensive destructive methods or indirect invasive techniques, such as the nuclear densometer. Additionally, large scale remote sensing measurements are currently being implemented to acquire information such as water content in environmental studies. However, the integration between remote sensing and in-situ methods for soil investigation has not been examined thoroughly. Through an experimental study, this paper investigates the sensitivity of three new cost effective capacitance-based sensors to estimate in-situ soil water content and density non-invasively. Measurements with the sensors have been compared against oven dried water content and real dielectric constant measured with an Agilent 85070E dielectric probe. The capacitance sensors have been proven to detect changes in volumetric water content, with some limitations of contact area and soil composition, but show very low sensitivity to density variations.

1 INTRODUCTION

Quality control of soil compaction is an integral activity in civil engineering, agriculture, hydrology and forestry; with water content and dry density defining the level of compaction. The evaluation of these parameters in subgrades of civil construction projects bears significant influence on the overall performance of the project, with the strength and deformation attributes of geomaterials significantly correlated to the water content and density of the specific soil (Bryson, Jean-Louis, & Gabriel, 2012).

Current methods for the quality control of compaction include the nuclear densometer, sand-cone density apparatus and indirectly from dynamic cone penetrometer alongside the oven-drying method, with the nuclear densometer being the most commonly used method in civil engineering projects (Campbell, Soane, & Ouwerkerk, 1994). However, concerns about the use of hazardous radioactive materials, the cost of the required equipment, and the reliance on soil invasion for the transmission gauge insertion highlight the limitations and potential undesirability of this method (Campbell et al., 1994; Topp, Davis, & Annan, 1980; Yu & Drnevich, 2004). Despite these concerns, the use of nuclear densometers remains the preferred method. Alternative techniques for determining the water content and density rely on milder (non-radioactive) electromagnetic methods which involve the measurements of electrical properties of soils.

The dielectric constant κ of a material can be described as the degree that an electrical charge distributed in the material can be polarised by the application of an electric field (Xu et al., 2014). The dielectric constant is a complex number consisting of a real component κ', representing the electric field storage capacity of the material, and an imaginary component κ'', known as the dielectric loss term representing attenuation and dispersion (Martinez & Byrnes, 2001). Typically, soils are a three phase heterogeneous mixtures comprised of air, solid particles and water which each has values of $\kappa' = 1$, $\kappa' = (2 - 7)$ and $\kappa' = 80$, respectively. Given the significantly higher real dielectric constant of water compared to the other components, soils' dielectric properties are extremely sensitive to water content (Francisca & Rinaldi, 2003).

Furthermore, the capacitance of a material can be described by the following equation:

$$C = \kappa . g . \varepsilon_0 \qquad (1)$$

where C = capacitance (F); g = geometric constant; and ε_0 = permittivity of a vacuum (F/m). As can be seen from Equation 1, given a constant sensor geometry, the capacitance is directly proportional to the dielectric constant, thus, the potential exists to capture changes in soil water content using capacitive measurements as proxies for soil dielectric constant. Several methods and relationships therefore exist in relating soil dielectric properties to volumetric water content (θ) with the Topp correlation being the most common relationship (Topp et al., 1980):

$$\kappa' = 3.03 + 9.3\theta + 146.0\,\theta^2 - 76.7\,\theta^3 \tag{2}$$

Relationships such as this tend to be derived from indirect methods such as Time Domain Reflectometry (TDR) and invasive capacitive techniques, which involve sending waves into the ground using probes and measuring the reflected signals to acquire the material's real dielectric constant. These methods are usually invasive, requiring probe insertion.

This paper explores the effectiveness of three new non-invasive capacitance-based sensors to detect changes in soil water content through surface measurements, thus requiring no soil insertion.

2 MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 *Materials*

Disturbed soil samples were collected from three different sites within Victoria as detailed in Figure 1. The three soil samples used in this research are a Brighton Group sand from Caulfield (Sample 1, poorly graded sand), an extremely weathered Silurian mudstone from Doncaster (Sample 2, sandy silt), and a Basaltic clay from Mt. Ridley (Sample 3, silty clay). Thus, the samples come from different Melbourne geological formations.

Table 1 summarises each sample's grain size distributions, the optimum θ, and Unified Soil Classification System (USCS) classification.

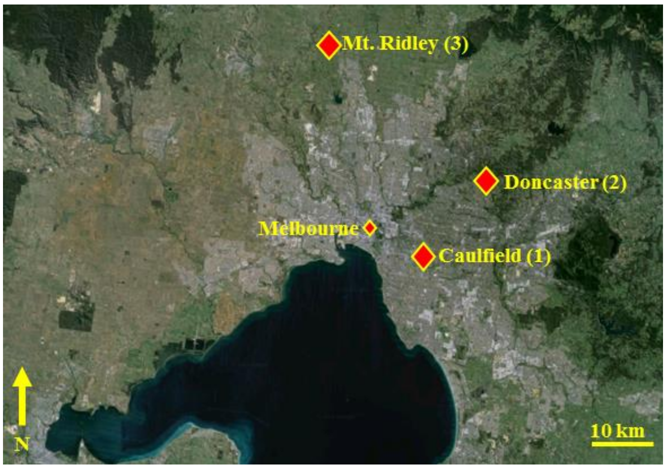

Figure 1. Location of Soil Samples

2.2 *Sensors*

The three new capacitance-based sensors utilised for this research are the AD7746 capacitive sensor board (denoted as "Circular Sensor" in this research), the MPR121 capacitive keypad sensor (denoted as "Rectangular Sensor" in this research) and a PCB capacitive sensor (denoted as "PCB Sensor" in this research). These sensors are Capacitance-to-Digital Converters (CDC) and are used to measure the capacitance of the sample, within the defined geometry of the particular sensor. The Circular Sensor and Rectangular Sensor are connected to an Arduino board, which utilises a C++ platform and transmit the measured capacitance through a USB cable. The capacitance readings have been stored and displayed on Arduino computer programs. Similarly, the PCB sensor transmits the capacitance reading through a USB cable to a CoolTerm computer program.

Table 1. Soil sample characteristics.

Sample	Optimum θ	Clay	Silt	Sand	USCS
	%	%	%	%	(-)
1	18	0	3	97	SP
2	21	20	51	29	ML
3	38	63	29	8	CH

Regarding sensor specifications, the Circular Sensor can measure up to 24 pF capacitance. Furthermore, its architecture features inherent high resolution, linearity (±0.01%) and accuracy (±4 fF factory calibrated), the positive supply voltage can vary between -0.3 V and +6.5 V, and it has an operational frequency of approximately 32 kHz (Analog Devices, 2005). The Rectangular Sensor has 12 capacitance sensing inputs that can measure in a range from 0.45 pF to over 2880 pF capacitance, and also has a positive supply voltage of 1.71 V to 3.6 V operated at 400 kHz (Freescale Semiconductor Inc, 2010). The PCB sensor is a capacitive sensor to measure changes in the capacitance of material. The sensors are shown in Figure 2.

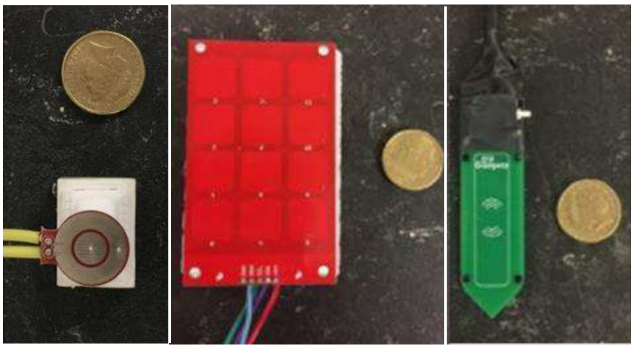

Figure 2. Three New Sensors: Circular Sensor (left), Rectangular Sensor (middle), PCB Sensor (right).

2.3 *Soil sample preparation*

A standard compaction curve was first defined for each soil (Standards Australia, 2003). Once defined, further samples were prepared in bulk at regular gravimetric water content intervals to achieve a range of samples on both the 'dry' and 'wet' side of the optimum water content.

For each of these samples, the soils were portioned into PVC compaction moulds of known dimensions, such that a variety of different compactive energies were inflicted on samples of specific gravimetric water contents. This was done using a standard compaction hammer and applying blows in the range of 2.5 to 40 blows per layer. This allowed specimens with different dry densities to be achieved whilst holding gravimetric water contents. The ‘exact’ gravimetric water content was measured using the oven dried method (Standards Australia, 2005), and dry densities were subsequently calculated. This allowed the gravimetric water contents to be converted to volumetric water content θ (water content hereafter) for the subsequent analyses.

2.4 *Experimental setup and tests*

The general setup of the experiments includes all three sensors connected to personal computers, a dielectric probe, a FieldFox Vector Network Analyser (VNA), a lab jack and a PVC compaction mould containing the soil specimen (to negate any effects the standard metal compaction mould would have on measurements). An example of a typical experimental setup is shown in Figure 3.

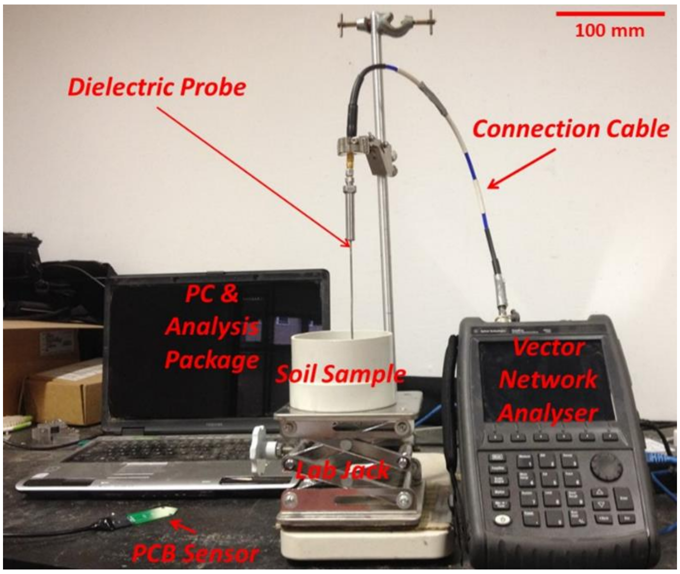

Figure 3. Typical experimental setup

2.4.1 *Circular Sensor test*

Upon trimming the surface of the soil specimen, electric measurements followed. The Circular Sensor test was typically performed first, where the sensor was held against the soil surface until a consistent reading with minimal noise is obtained. Following that, two extra surface measurements were taken with the sensor so that the measurements were representative of the entire surface. This also allowed means and standard deviations to be taken in the analyses to ensure the reliability of results.

2.4.2 *Rectangular Sensor test*

The Rectangular Sensor test was performed exactly the same way as the Circular Sensor, with the exception that a weight was placed on top of the sensor’s handle to ensure even and constant pressure against the soil surface when acquiring a reading. The amount of pressure was tested and proved to have no impacts on the sensor readings. Moreover, it is noted that the Rectangular Sensor actually retrieves twelve readings due to having twelve sensing electrodes. For the purpose of this research, the overall mean of these readings has been taken as the Rectangular Sensor reading.

2.4.3 *PCB Sensor test*

Three surface measurements were also conducted with the PCB Sensor. This sensor also operates slightly different to the other two, where a mean reading of the air (which was nearly constant all the time) was taken for calibration. Subsequently, the average of the three surface measurements was subtracted from the air reading, to compute the sensor reading.

2.4.4 *Dielectric probe test*

The dielectric properties of each soil were also measured through a Frequency Domain Reflectometry (FDR) technique, under controlled environmental conditions in a frequency range of 200 MHz – 6 GHz with an Agilent 85070E Slim Form Dielectric Probe. The probe was inserted a minimum depth of 10 mm into each specimen for 3 measurements in a triangular manner to minimise any errors. The probe insertion was facilitated with pre-drilling to compensate for specimens which may have been too hard or dense for the dielectric probe to otherwise penetrate. This probe measurement was always performed last to avoid any disturbance to the soil structure before performing the sensor measurements. The κ' obtained with the probe at 1 GHz through converting the reflection coefficient S_{11} to the real dielectric constant, has been used to compare to the sensors’ readings. It is important to note that the operational frequency of the probe is different form the operational frequencies of the sensors however, choosing 1 GHz, is solely for the purpose of investigating the trends between the measurements taken by the sensors and the dielectric probe.

3 RESULTS AND DISCUSSION

The results of experiments for each sensor for all three soil samples are detailed in the following sections. Each sensor reading is plotted using green triangles and a dotted line, whilst κ' obtained from the dielectric probe at a measurement frequency of 1 GHz is plotted with purple squares and an accompanying dashed trend line. All trend lines are fitted as 3rd order polynomials based on the Topp calibration. κ' has also been plotted based on the Topp calibration (Equation 2) with a solid red line.

3.1 *Circular Sensor*

Figure 4 shows the response of the Circular Sensor and the measured dielectric constants for each of the three soil types.

Firstly, for the sand sample, the sensor is able to detect changes in water content accurately for the entire range tested. Up to approximately the optimum water content of 18% the sensor reading pattern obtained follows the measured κ' closely. Above optimum volumetric water content however, the sensor reading pattern plateaus, likely due to it being close to the maximum capacitance that the sensor can measure. The relatively good readings correlation obtained from this soil sample are linked to the smooth surface and homogeneity of the material allowing good contact surface to be maintained. A similar response to the surface roughness has been also reported in Orangi and Narsilio (2015).

For the sandy silt sample, there is an initial decreasing trend from about 8% to 15% water contents for the Circular Sensor reading. The sensor reading values then stay relatively constant till approximately the optimum water content of 21%. Above this value, the sensor reading increases with water content, now reflecting the measured κ' trend line quite well. This may be explained by the variable surface mineralogy of this highly weather mudstone. It is likely that effect of the variable surface mineralogy on the 'dry' side (below optimum volumetric water content) is far more dominant causing the unexpected decreasing trend. However, as water starts to dominate, on the 'wet' side (above optimum volumetric water), the sensor is able to detect changes in water content as the variable surface mineralogy effect is less pronounced.

Lastly, for the silty clay, the Circular Sensor was able to achieve good contact between the soil surface and sensor, despite the 'rough' and uneven soil surface, due to the trimming of the soil specimen at the end of the compaction. Between water contents from 15% to 38% (optimum), the measured capacitance remains relatively unchanged. However, there is a transition point at roughly optimum water content, where the measured capacitance values significantly increase with moisture content, then to decrease, but still showing an increasing trend with moisture in the 'wet' side. Despite the Circular Sensor not being able to pick up changes in water content in the lower range of moisture in the 'dry' side, the sensor displays its ability to detect the optimum moisture content.

3.2 *Rectangular Sensor*

Figure 5 shows the responses of the Rectangular Sensor and real dielectric constant measured with the Agilent probe for each of the three soils as well as the predictions made with the Topp equation.

With the sand sample, it is apparent that there is little change in the measured capacitance from water contents between 4% and 18%. However, at approximately 18% (coinciding with the optimum water content of the soil) there is a noticeable transition point where the measured capacitance values increase continually up to the highest water content tested of approximately 24%. This highlights the ability of the Rectangular Sensor to capture the transition from the 'dry' to 'wet' side of the compaction curve in this particular soil where good contact surface area could be maintained and there were no observable variations in surface mineralogy which was observed with the Silurian mudstone sample (sandy silt). The sensor, however, is unable to accurately detect changes in water content on the 'dry' side.

With the sandy silt, the sensor reading decreases initially with increasing water content in the range of approximately 8% to 16%. Beyond this range, the sensor reading remains essentially constant with no

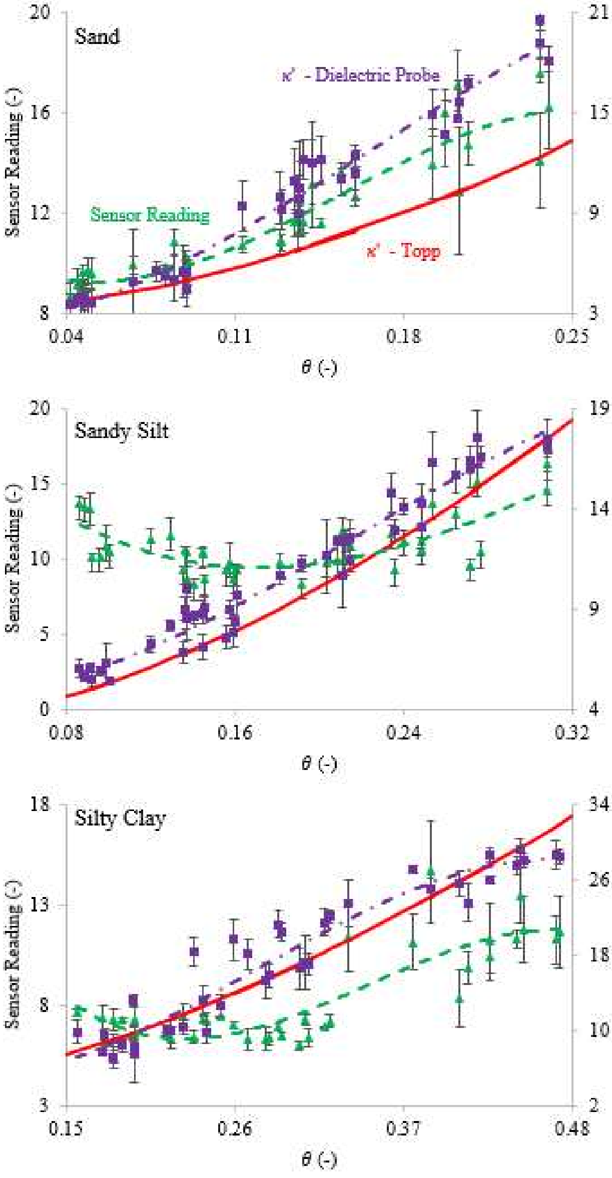

Figure 4. Circular Sensor readings compared against real dielectric constant at 1 GHz and Topp Equation.

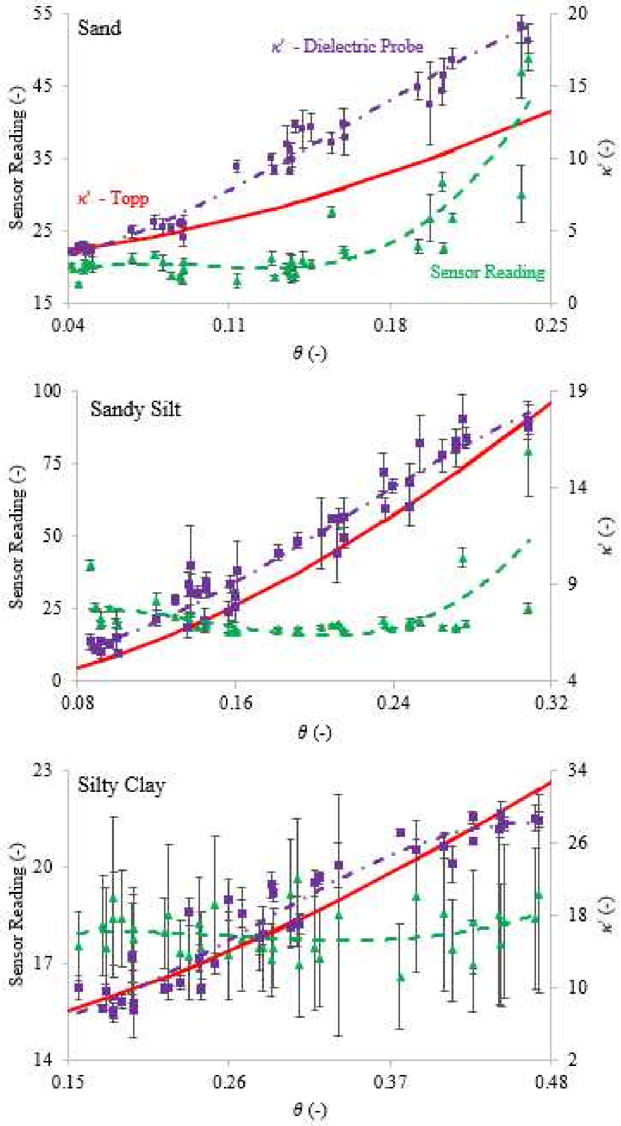

Figure 5. Rectangular Sensor readings compared against real dielectric constant at 1 GHz and Topp Equation.

increasing trend till the last three measurements beginning at approximately 27% which increases significantly. This may again be explained by the observation of the variable surface mineralogy of the Silurian mudstone which was also mentioned in the previous section. For water contents below optimum, this behavior may have more of an effect resulting in the more averaged response detected by the Rectangular Sensor, due to its larger footprint. As the effects of water start to truly dominate the soil behavior in the last three measurements, this variable mineralogy has less of an effect, resulting in a significant increase in sensor reading here. Overall the Rectangular Sensor is ineffective at detecting changes in soil water content and does not follow the same trend as the κ' values obtained with the dielectric probe for the sandy silt.

Turning to the silty clay sample, there is no apparent trend. It is suggested that this is due to the method of testing, where the specimen had to be trimmed after compaction resulting in a visibly 'rough' and uneven surface in the silty clay due to the higher fines content. This 'rough' and uneven surface in combination with the larger footprint of the rectangular sensor, meant it was difficult to maintain complete contact with the soil surface and thus, measurements were affected by more air voids being present between the soil specimen surface and the sensor, than in the actual specimen, hence, disturbing the measurements. This is reflected by the averaged response of the sensor readings, as well as the much higher standard error illustrated here relative to the range of sensor readings obtained.

3.3 *PCB Sensor*

Figure 6 details the response of the PCB Sensor, the measured real dielectric constant and the Topp correlation predictions for each soil sample tested.

With the sand sample, the PCB sensor performs exceptionally well for the range of water contents tested. The general trend of the sensor reading increasing with increasing water content is apparent for all water contents tested for this sample and the $R^2 = 0.97$ for the fitted cubic trend line.

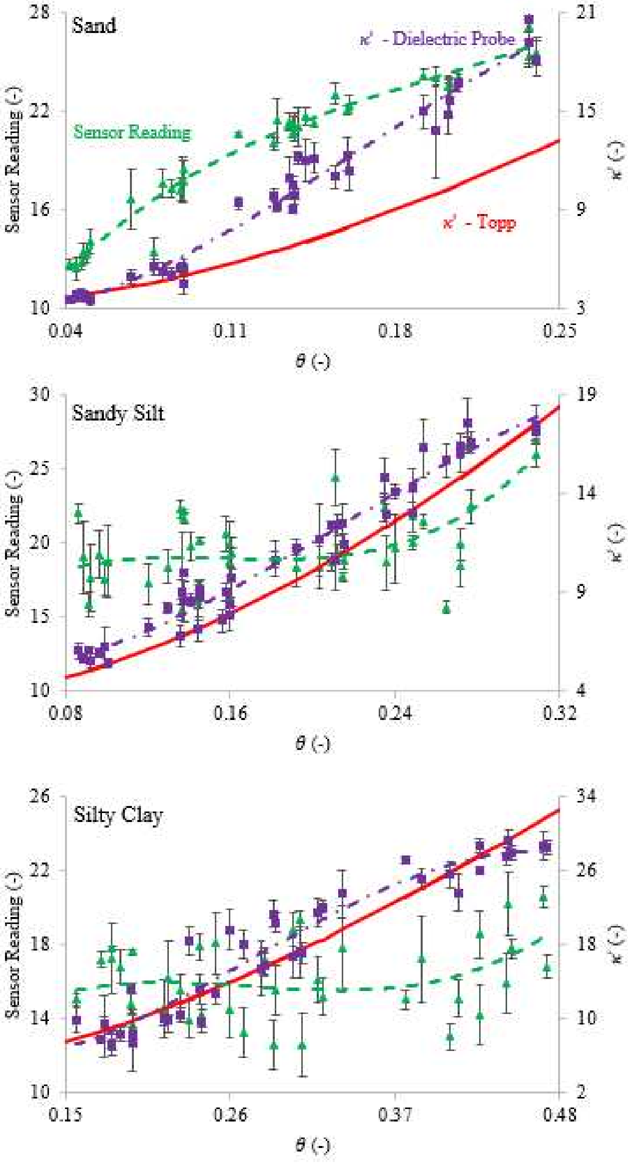

Figure 6. Rectangular Sensor readings compared against real dielectric constant at 1 GHz and Topp Equation.

The PCB sensor reflects the measured κ' here well, supporting the theory that they are directly proportional for a constant geometry. It is proposed that such a good fit is present here due to a good contact surface between the soil sample and the sensor.

For the sandy silt, there is no prominent increasing trend for the sensor readings on the 'dry' side for the range of water contents tested, where an averaged response similar to the Rectangular Sensor is present. However, beyond the optimum water content of 21%, there is a noticeable increase in the sensor reading as it starts to follow the shape of the κ' measurement obtained from the probe.

For the silty clay, there is no increasing trend apparent for the sensor. Similar to the previous scenarios, this can be attributed to the specimens' 'rough' and uneven surface after trimming where a good contact surface between the sensor and soil could not be achieved due to the sensors large footprint.

4 CONCLUSIONS

Based on the experimental work and analysis carried out in this research all three new sensors have shown the ability to detect changes in water content using a non-invasive surface measurement technique, with some limitations and to varying degrees of accuracy. This supports the initial theory that an increase in water content will increase the soil's dielectric constant and correspondingly increase capacitance. This preliminary assessment supports the potential for these fast and cost effective sensors to be developed as an alternative to current methods of estimating in-situ water content.

Comparing the results of the three sensors, the Circular Sensor performs the best across all three soils. It renders the highest R^2 for all trend lines, shows an overall increasing trend throughout (excluding the 'dry' side of the Silurian mudstone) and is most effective sensor due to its smaller geometry allowing good contact surface to be easily achieved. It is recommended that further testing of this sensor is performed for a larger range of water contents and soils.

The Rectangular Sensor appears to be able to detect changes in soil water content, especially on the 'wet' side but is largely limited by its larger footprint. In its current form, it is the least effective of the three sensors. It is recommended that this sensor is further tested with a method where a 'smooth' and even soil surface can be maintained or the sensor is cut into its smaller twelve electrodes to improve contact with the tested soil.

The PCB Sensor shows the best results for the Brighton Group Sand where a good contact surface area could be maintained, however, with an average response for the Silurian mudstone despite a smooth surface being achieved. Moreover, for the tested fine grained soil, the Basaltic Clay, a good contact surface area was unable to be maintained so results were not representative of its effectiveness in fine grained soils. Therefore, it is recommended that the PCB Sensor is further tested in clays where a method is adapted for a smoother contact surface.

Overall, the sensors show the potential to be a fast and cost effective replacement of current in-situ water content estimation techniques but need further research before they are ready to be utilised in field applications.

5 ACKNOWLEDGMENTS

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