Evaluation of Soil Parameters
Using Dielectric Permittivity

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Abstract

Site characterisation plays an important role in a diverse range of engineering and non-engineering projects. Engineering projects may include geotechnical and geoenvironmental investigations while non-engineering applications can be found in agricultural and archaeological surveys. Regardless of the nature of the project, a significant part of the site characterisation process is devoted to the characterisation of the soil upon which projects will take place. Within soil characterisation, soil fundamental parameters such as water content and density are usually required to be measured and monitored frequently to ensure successful delivery and operation of a project. These parameters are often measured using conventional techniques presenting major drawbacks, for example, being destructive, invasive and/or radioactive-based. One relatively recent innovation in soil investigations is utilising electromagnetic geophysical methods to characterise the soil and subsurface. The key to the successful application of these methods, however, is a robust understanding of the interactions and physical processes which underpin the relationships between soil electrical parameters and geoenvironmental properties. Further, to enhance the quality and speed of data acquisition as well as increasing the spatiotemporal availability of the data without compromising costs, the development of new alternative ways to measure soil parameters is crucial. Thus, through an experimental investigation, this thesis studies the relationship between geotechnical and other soils physical parameters and their dielectric properties. Moreover, an essential counterpart of this thesis is the development of an alternative way of measuring soil water content and density non-invasively. Therefore, within the context of this thesis, the following studies have been undertaken and novel findings and conclusions have been drawn, these are of paramount significance to the geotechnical, environmental, agricultural and archaeological disciplines:

- As part of a unique tri-nation study to commemorate the centenary of the iconic First World War ANZAC landing, physical characterisation of the soils recovered from the battlefield in this region was carried out in a frequency range of 200 MHz to 6 GHz. Subsequently, empirical models for geophysical site investigations were developed encapsulating soils water content, dielectric properties as well as the frequency pertinent to certain in-situ geophysical applications and satellite surveys. Moreover, attenuation coefficients related to Ground Penetrating Radar applications were also estimated for a range of water contents at 200 MHz. Given the historical and archaeological significance of the ANZAC battlefield, these results can be used as a database for future feasibility studies, planning, result analysis and modelling of geophysical investigations, including choosing the most appropriate time of the year and geophysical prospection tool in this restricted-access study area.

- Dielectric characteristics of soils from the ANZAC battlefield and Melbourne geological formations were evaluated against different water content and dry density levels. The data were utilised in the development of a new physically-based mixture model encompassing 500 MHz, 1 GHz and 6 GHz frequencies, pertinent to insertion probes such as Time Domain Reflectometry, Ground Penetrating Radar and remote sensing applications. This model uses soil specific surface area as a more fundamental physical input variable which has shown to be a better representation than particle
size distribution in defining the response of soils to electromagnetic waves. Moreover, based on the performance of the newly developed mixture model and in order to provide simple but robust site–specific calibrations for these Australian soils, new empirical relationships have been developed by taking into account the specific surface area of the samples. The new models can be specifically used for soils from these regions as well as for soils with similar characteristics when planning and conducting geophysical prospections utilising electromagnetic waves.

- The effects of dry density or degree of compaction on the dielectric constant of different soil types ranging from sand to bentonitic clay were experimentally investigated and evaluated based on the use of two simple mixture models (De Loor and Birchak) at 1 GHz frequency. It was found that the effects of dry density on the soil dielectric constant depends on the soil type. Through a parametric study on the experimental data, this soil type dependent behaviour was shown to be defined by the changes in the free water, bound water, and solid particle volume fractions, ultimately controlled by the soil specific surface area. Subsequently, a threshold for specific surface area was estimated theoretically and corroborated experimentally. In addition, supported by the experimental observations, ranges for the dielectric constant of bound water and geometrical parameter in the Birchak model were identified.

- The effectiveness of a low–cost non–invasive method to estimate water content of different soil types ranging from sand to clay was investigated. Firstly, three sensors were developed and tested against water content variation. Subsequently, the best geometrical and electronic features of these sensors were incorporated into the design of a new sensor. This sensor demonstrated superior performance in estimating near surface soil water content non–invasively. The sensor can be potentially utilised in agricultural applications, satellite imaging and remote sensing applications of soil water content data; quantifying the risk of bushfire and generating warnings to the pertinent authorities as well as a fast way of estimating the water content of sub–base and stockpile materials in the road construction industry.
Declaration

This is to certify that

i. the thesis comprises only my original work towards the degree of Doctor of Philosophy,

ii. due acknowledgement has been made in the text to all other material used,

iii. the thesis is fewer than 100,000 words in length, exclusive of tables, figures and references.

_____________________

Amir Orangi
Publications relating to this work

Several independent research works were produced as part of the research undertaken towards this doctoral thesis. Three works have been published and one work is under review. The three published works are:


The work that is currently under review is:


Publications 1, 2 and 3 are the bases for Chapter 3, 5 and 6 of this doctoral thesis and are inserted in the body of the text as the original published work. Publication 4 is the bases for Chapter 4 and is currently under review and since it has not yet been published, the text and format have been modified to be consistent with this doctoral thesis.

In each case, I contributed more than 50% of the work and the co–authors contributions have been described in detail at the beginning of each chapter.

For each published work in the body of this work, the required co–author authorisation forms have been provided with this submission.
Acknowledgement

What follows next is a summary of a four-year endeavour which has not only helped me grow intellectually but also allowed me to believe in myself, become more resilient, challenge my thoughts and ideas, and more importantly meeting beautiful people along the way. What I have gained intellectually and how I have grown throughout this journey could not be possible without the help and support of significant people who have been beside me; first and foremost, A/Prof Guillermo Narsilio, whom his mentorship and supervision were inevitable in successfully finishing this journey. I am proud to say I had a magnificent mentor who not only cared about my research and allowed me to develop and pursue my research interest but also was interested in my personal and professional development and my life outside the university. I am delighted to have a mentor who is in my eyes, a family member rather than a supervisor. I am sincerely grateful for his consistent support, constructive criticism and the opportunity for growth. It is quite an invaluable asset to find a mentor who you can trust and go beyond just research and academic life; we co-founded AquaTerra, undertaken several industry projects and led many research projects together with ups and downs – I enjoyed every moment, regardless! Secondly, I would like to thank my co-supervisor A/Prof Dongryeol Ryu who was always there for me when I needed him, challenged me, and openly supported me throughout this journey with his insightful feedback. Prof Yu–Hsing Wang from the Hong Kong University of Science and Technology is appreciated for providing me with the opportunity to take my Endeavour Fellowship under his supervision and guidance which enhanced my research and laboratory experimental skills and capabilities. I would like to extend my thanks and gratitude to Prof Andrew Western as the chair of my advisory committee who provided me with guidance and direction over the course of my candidature.

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1 Introduction
The hand of Mother nature has established a unique ground underneath every civil engineering related projects. Site characterisation is, therefore, an inevitable stage in the lifetime of projects in which data with respect to the conditions of the subsurface is collected. While there are many conventional established practices adopted in site characterisation, there exist some newer technologies that can provide additional detailed information. Geophysical techniques represent one such technology where mechanical and electromagnetic waves are utilised to characterise the subsurface. The use of geophysical methods in soil and site characterisation has become increasingly popular due to their non-destructive nature which, in turn, enables gathering richer spatiotemporal soil information data than by conventional methods in a given timeframe. In particular, electromagnetic EM wave based techniques have been used in engineering (e.g., geotechnical site investigations and agricultural soil moisture mapping) and non-engineering applications (e.g., archaeological studies) to characterise the subsurface, mapping soil and rock conditions, studying near-surface soil water content, and to gather information about underground features (Davis & Annan, 1989; Khakiev, Shapovalov, Kruglikov, & Yavna, 2014; Loewer, Wagner, & Igel, 2013; Sternberg & McGill, 1995).

In the aforementioned applications, the key to an efficient use and result interpretation of EM geophysical methods is a clear understanding on the relationship between soil or geotechnical parameters such as water content, density and salinity and its electrical properties, such as dielectric permittivity. In addition, this kind of information are crucial in electromagnetic wave based geophysical investigations techniques, such as Time Domain Reflectometry (TDR), Ground Penetrating Radar (GPR), Electromagnetic (EM) prospections, remote sensing and Light Detection and Ranging (LIDAR) (Drnevich, Lin, Yi, & Lovell, 2001; Lauer, Albrecht, Salat, & Felix-Henningsen, 2010; Liu & Mitchell, 2009; Roth, Schulin, Flühler, & Attinger, 1990; Schön, 2015; Topp, Davis, & Annan, 1980; Wagner, Emmerich, Bonitz, & Kupfer, 2011).

Despite the importance of the correlations between the soil geotechnical and electricals parameters in geophysical site characterisation, there are no regional studies conducted on Australian soils to serve as a database that may aid in future investigations and modelling. One way to infer geotechnical parameters from geophysical data is through the use of mixture models that link soil dielectric properties to geotechnical parameters of interest such as water content amongst others. Thus, establishing such database can enable conducting more accurate feasibility studies and defining a framework for geophysical prospections (e.g., Ground Penetrating Radar; remote sensing applications) as well as in the corresponding data interpretation. Having access to a database which captures the all this information for a given site is, therefore, extremely beneficial for feasibility studies, planning and result interpretation of forthcoming geophysical site characterisations.

Soil dry density or the degree of compaction is one of the parameters that is partially responsible for the overall dielectric response to an incident electromagnetic wave. Despite this known fact, most of the research to date has been primarily focused on the relationship between soil properties such as water content and salinity and dielectric properties. There have been
very limited studies investigating the role of soil dry density on the dielectric properties and they report equivocal results.

Using geophysical methods to measure water content and density, could alleviate the drawbacks of the conventional methods like oven drying and nuclear probes, which are labour intensive and require special permits to handle radioactive materials. Nonetheless, from a practical point of view, there are some aspects of the geophysical methods that hinder their extensive utilisation. As such, the need for probe insertions (e.g., TDR), relatively high cost of equipment (e.g., Ground Penetrating Radar and EM antennas) and comparatively low resolution of remote sensing data, are some practical limitations which can be highlighted.

To readdress these issues, this research gathers experimental data from different soil types collected from two regions in the world, of particular interest to Australia. We have retrieved limited number of soil samples from the ANZAC battlefield in Turkey due to some governmental restrictions, and as well as targeting different geological formations in metropolitan Melbourne, Victoria in Australia. The general experimental program consists of the dielectric characterisation of these soil samples against water content and the degree of compaction or dry density for a range of frequencies as well as focusing on frequencies which are of interest to specific geophysical methods. The data has been used to start populating a database of the geophysical characterisation of selected Australian soils. Coinciding with the centenary of the ANZAC battlefield, a study was undertaken by the University of Melbourne to identify and record sites of significance by using advanced archaeological prospection techniques, including GPR. No prior information about site specific soil characterisation was available to the team of three nations (Australia, New Zealand and Turkey). It was clear that such information would have been useful to decide on the type of prospections, frequency, and even time of the year to plan and later interpret the geophysical surveys. Consequently, the experimental data collected from the ANZAC soil samples were used in proposing empirical correlations encompassing water content and frequency for this battlefield to help in interpreting GPR results and in future prospections. Furthermore, the data was utilised in proposing a new physically based model inspired on the Dobson Soil Mixing Dielectric Model. This new model was used to investigate the effect of dry density on the dielectric properties of soil and water mixtures with different specific surface areas.

The improved understanding of dielectric properties of soils has been also used to develop a new mean for soil water content estimation which is inexpensive, portable and most importantly non-invasive, thus alleviating the drawbacks of the current methods used for such purpose. This development is also part of this thesis.

1.1 Research Objectives

Based on the preceding discussion and the current state of the knowledge (in chapter 2), the objectives of this research are summarised as follow:

- To collect information and initiate a database of the dielectric properties of the Australian Soils.
• To understand the efficacy of Soil Mixing Dielectric Models in predicting soil dielectric properties, and to identify the fundamental soil parameters that control the model performance and suggest improvements.
• To investigate the effects of density on the dielectric properties of soils.
• To develop a more cost effective and non-invasive geophysical testing method to estimate soil water content and density.

1.2 Thesis Organisation

The thesis spans over seven chapters (including this introduction) to address the above objectives. This thesis is structured as a series of standalone but interdependent units, some of which have been already published or in the process of being published. Chapter 1 (this chapter) provides a brief overview on the motivation and aims of this research.

Chapter 2 provides a background into the importance of soil water content and its implication in engineering and non-engineering fields. Current methods of soil water content measurement will be discussed and a background to soil dielectric properties will be provided using the current literature. Within this context, the relationship between soil parameters and dielectric properties will be discussed with a focus on the role of water content and dry density.

In chapter 3, a physical characterisation of the soils recovered from the ANZAC battlefield in Turkey will be presented which leads to establishing empirical models for geophysical site investigations. This correlation encapsulates soils water content, dielectric properties as well as the frequency of the geophysical techniques.

Chapter 4 utilises the data form the ANZAC soils and the soils from Melbourne geological formations to develop a new physically based mixture model inspired on the Soil Mixing Dielectric Model by Dobson et al. (1985), introducing soil specific surface area as a more fundamental input variable. Furthermore, semi-empirical relationships the use less parameters than mixture models have been derived for frequencies pertinent to geophysical prospections using soil specific surface area as main input. Soil specific surface area will be shown to be a better representation than particle size distribution in defining the response of soil to electromagnetic wave.

Chapter 5 aims to investigate the effects of dry density on the dielectric properties of soils. This chapter provides an explanation to the conflicting results reported in the limited studies on this topic, based on comprehensive experimental evidence collected during this research. The experimental data is utilised to examine Birchak and De-Loor mixture models in capturing the effect of dry density on the dielectric properties. Furthermore, a parametric study on the experiment data is utilized to introduce specific surface area (SSA) as the parameter that controls the variation of the soil dielectric constant against dry density, and a threshold SSA is found theoretically and corroborated experimental at which trends in data change, this is the root of the conflicting results reported in the literature, we offer here a way to reinterpret these results.

Motivated by the importance of soil water content and the drawbacks of its current measurement techniques, Chapter 6 introduces a new sensor for soil water content estimation.
Based on a laboratory experimental investigation, we initially compare three new non-invasive capacitive sensors developed to estimate soil volumetric water content and examine their performance for four different soil types. Subsequently, based on the comparative performance of these three new sensors, a fourth sensor was designed and manufactured to substantially reduce the limitations of the previous versions.

Chapter 7 concludes the research and provides recommendations and insights for future work.
2 Soils characterisation from an electromagnetic perspective: Theory and Background

As fundamental parameters of soil, moisture content and density play important roles in various applications. Their values and variations have implications in civil engineering, agriculture, water resource management, climate science and hydrology (Albergel et al., 2012; Brocca, Melone, Moramarco, & Morbidelli, 2010; Bryson, Jean Louis, & Gabriel, 2012; Crow et al., 2012; Famiglietti, Ryu, Berg, Rodell, & Jackson, 2008; Han et al., 2018; Ryu & Famiglietti, 2005; Vereecken et al., 2008; Yu & Drnevich, 2004). The conventional direct (e.g., oven drying, sand cone) and indirect (nuclear probes) methods of measuring the properties have some limitations, such as being time consuming and labour intensive, being unable to be used as a monitoring measure, using hazardous radioactive material, requiring probe insertion, and having high cost (Robinson & Dean, 1993; Soane & van Ouwerkerk, 2013; Wu, Zhou, Wang, Yang, & Ling, 2011; Yu & Drnevich, 2004).

It is, therefore, of great advantage to the areas of sustainable infrastructure and water management to be able to measure soil moisture and density using non-destructive, non-invasive and non-nuclear methods. These advantages can be attributed to geophysical electromagnetic methods which are based on measuring soil electrical properties such as dielectric constant and capacitance to reveal important information related to the soil mass, including their spatial distribution (Robinson & Dean, 1993; Santamarina & Fam, 1995).

In this context, some electromagnetic properties of soil have been shown to be good indicators of other soil parameters such as moisture content and salinity (Campbell, 1990; Cerato, 2012; Chen, Chen, Xu, & Yu, 2010; Dalton, Herkelrath, Rawlins, & Rhoades, 1984; Grote, Hubbard, & Rubin, 2003; Huisman, Hubbard, Redman, & Annan, 2003; Jones, Estevez, & Robinson, 2008; Steelman, Endres, & Jones, 2012; Wensink, 1993; Wu et al., 2011). A few studies (see e.g., Lauer, Albrecht, Salat, & Felix-Henningsen, 2010; Salat & Junge, 2010; Siddiqui, Drnevich, & Deschamps, 2000; Yu & Drnevich, 2004) show correlations between the density of the soil and its dielectric properties. These signify the validity of using electromagnetic measurements as indicators of geotechnical properties.

2.1 Phase relationships for soils

Soil is considered as a porous medium consisting of three phases: a solid phase which is typically clay, silt, and sand minerals; a liquid phase which is typically water and, depending on the site condition, could be replaced by salty water or contamination; and a gas phase which is normally air. The soil properties are essentially governed by these three phases, their composition, and their arrangement (Powrie, 2013). Figure 1 illustrates a soil phase diagram showing the relationship between these three phases in terms of mass and volume. This figure will be further utilised in Section 2.3 to illustrate the dielectric properties of individual soil phases.
In Figure 1, m and V correspond to mass and volume, respectively, and s, w, and a refer to solid, water, and air. Thus, m_s refers to the mass of solid phase, m_w represents the mass of liquid phase (water), and m_a is the mass of air, which is approximately zero. Similarly, V_s is the volume of the solid phase, V_w is the volume of the liquid phase (water), and V_a is the volume of the gas phase (air). The volume of the void is comprised of a volume of air and water. Based on the soil phase diagram given in Figure 1, a number of fundamental definitions which are known as phase relationships can be defined. These relationships provide information about the relative volumes of the soil phases (i.e., soil, liquid, and gas), which are important in soil characterisation. Table 1 provides a summary of these relationships:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric water content</td>
<td>( w = \frac{\text{Mass of water (m_w)}}{\text{Mass of solid (m_s)}} ) (1)</td>
</tr>
<tr>
<td>Volumetric water content</td>
<td>( \theta = \frac{\text{Volume of water (V_w)}}{\text{Volume of soil (V_T)}} ) (2)</td>
</tr>
<tr>
<td>Void ratio</td>
<td>( e = \frac{\text{Volume of void (V_v)}}{\text{Volume of solid (V_s)}} ) (3)</td>
</tr>
<tr>
<td>Porosity</td>
<td>( n = \frac{\text{Volume of void (V_v)}}{\text{Volume of soil (V_T)}} ) (4)</td>
</tr>
<tr>
<td>Saturation degree</td>
<td>( S = \frac{\text{Volume of water (V_w)}}{\text{Volume of void (V_v)}} ) (5)</td>
</tr>
<tr>
<td>Dry density</td>
<td>( \rho_d = \frac{\text{Mass of solid (m_s)}}{\text{Volume of soil (V_T)}} ) (6)</td>
</tr>
</tbody>
</table>

A successful application of geophysical methods strongly depends on a thorough understanding of electromagnetic theory, the electromagnetic properties of soil and individual phases, and the effects of geotechnical parameters on the electromagnetic properties. This
understanding enables the derivation of robust and precise relationships and calibrations between the electromagnetic properties and geotechnical parameters of soils. What follows in this chapter is a review of the literature on electromagnetic theory, wave propagation, and the constitutive equations explaining the material response under an electromagnetic field. Furthermore, the frequency-dependent behaviour of materials under an electromagnetic field will be discussed. This will be followed by a description of the electromagnetic properties of soil phases. Next, we will describe the parameters that affect these electromagnetic properties as well as models linking these properties to soil geotechnical parameters. Finally, a summary of the current techniques for measuring soil water content and density will be provided.

2.2 Electromagnetic Theory

2.2.1 EM wave propagation

The fundamental laws and equations that govern static charges, moving charges, and time-varying electrical and magnetic fields are known as Maxwell equations. These equations form a set of four equations, namely Gauss’s law of electricity, Gauss’s law of magnetism, Faraday’s law of induction, and Ampere-Maxwell’s law (Santamarina, Klein, & Fam, 2001). These are summarised in Table 2.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nabla \cdot \mathbf{E} = \frac{1}{\varepsilon^*} \rho_v &lt;\text{free}&gt; )</td>
<td>Gauss’s law of electricity</td>
</tr>
<tr>
<td>( \nabla \cdot \mathbf{B} = 0 )</td>
<td>Gauss’s law of magnetism</td>
</tr>
<tr>
<td>( \nabla \times \mathbf{E} = -\mu \frac{d\mathbf{H}}{dt} )</td>
<td>Faraday’s law of induction</td>
</tr>
<tr>
<td>( \nabla \times \mathbf{H} = \sigma^* \mathbf{E} + \varepsilon \frac{d\mathbf{E}}{dt} )</td>
<td>Ampere-Maxwell’s law</td>
</tr>
</tbody>
</table>

In Equations (7) to (10), \( \mathbf{E} \) is the electric field intensity, \( \mathbf{B} \) is the magnetic induction, \( \mathbf{H} \) is the magnetic field intensity, \( \varepsilon^* \) is the permittivity, \( \rho_v \) is the volumetric free-charge density, \( \mu \) is the magnetic permeability, \( \sigma^* \) is the conductivity, \( \nabla \cdot \) is the divergence operator, and \( \nabla \times \) is the curl operator. In Gauss’s law, only the free charges are considered, and the effect of bound charges is taken into account in the polarisation vector through \( \varepsilon \). If there are no free charges in the body, then it is an electrically neutral body and the volumetric charge density (\( \rho_v \)) is zero, as in an ordinary dielectric. Gauss’s law of magnetism states that the divergence of a magnetic field is equal to zero. Furthermore, Faraday’s law of induction explains that the rotation of an electric field is equivalent to a negative temporal change of a magnetic field whereas a temporal change of a magnetic field will in turn create an electric field. Similarly, Ampere-Maxwell’s law states that the rotation of a magnetic field is equal to the summation of the electric current density \( \sigma^* \mathbf{E} \) and changes to the electric field \( \varepsilon \frac{d\mathbf{E}}{dt} \).
2.2.2 Constitutive equations

The Maxwell equations (see Table 2) describe the relationships between electricity and magnetism in mathematical terms. The following equations describe the behaviours of a material when it is subjected to an EM field:

\[ J_c(\omega) = \sigma^* E(\omega) \]  \hspace{1cm} (11)

\[ D(\omega) = \varepsilon^* E(\omega) \]  \hspace{1cm} (12)

\[ B(\omega) = \mu^* H(\omega) \]  \hspace{1cm} (13)

where \( J_c(\omega) \) is the electrical current density; \( \omega \) is the angular frequency, equal to \( 2\pi f \), where \( f \) is frequency; \( \sigma^* \) is the electrical conductivity; \( D(\omega) \) is the electrical flux density; \( \varepsilon^* = \varepsilon_0 \varepsilon_{\ast} \) is the complex permittivity, where \( \varepsilon_0 \) is the permittivity of the free space or vacuum equal to \( 8.85 \times 10^{-12} \text{ F/m} \) and \( \varepsilon_{\ast} \) is the relative complex permittivity; and \( \mu^* = \mu_0 \mu_{\ast} \) is the complex magnetic permeability, where \( \mu_0 \) is the magnetic free space or vacuum equal to \( 1.257 \times 10^{-12} \text{ H/m} \) and \( \mu_{\ast} \) is the relative complex magnetic permeability (Santamarina et al., 2001). In the case of soils, \( \sigma^*, \varepsilon^* \), and \( \mu^* \) are material-specific properties with scalar quantities, which is a valid assumption where all of these are dependent on the frequency \( f \), temperature \( T \), and pressure \( P \) (Börner, 2006; Hoekstra & Doyle, 1971; Jonscher, 1977; Schön, 2015; Stillman & Olhoeft, 2008). The importance of each of these parameters is prioritised based on the purpose of the investigation. Within this research, the dielectric permittivity \( \varepsilon^* \) and electrical conductivity \( \sigma^* \) are the parameters which will be examined against soil geotechnical parameters such as water content and dry density.

2.2.3 Dielectric permittivity

A material is classified as “dielectric” if it has the ability to store energy when it is exposed to an external electromagnetic field. This is essentially the ability of the material to polarise by an external electromagnetic field (Santamarina et al., 2001; Xu et al., 2014). Dielectric permittivity is a complex number which describes the behaviour of a material when it is exposed to an electric field and is the fundamental parameter that controls the propagation of electromagnetic waves in any material (Huisman et al., 2003).

Dielectric permittivity constituents are represented in Equation 14, as described by (Huisman et al., 2003):

\[ \varepsilon^* = \varepsilon' - j\varepsilon'' \]  \hspace{1cm} (14)

where \( \varepsilon^* \) is the complex dielectric permittivity (F/m), \( \varepsilon' \) is the real component of dielectric permittivity (F/m), \( j = \sqrt{-1} \) is the imaginary number, and \( \varepsilon'' \) is the imaginary component of dielectric permittivity (F/m) (Arcone, Grant, Goitnott, & Bostick, 2008; Wagner et al., 2013).

The relative dielectric permittivity of a material \( \varepsilon_{\ast} \) or \( \kappa \) is the ratio of its permittivity \( \varepsilon^* \) to the permittivity of vacuum or air \( \varepsilon_0 \); hence \( \kappa^* = (\varepsilon^*/\varepsilon_0) \). Since the dielectric constant is just a ratio of two similar quantities, it is dimensionless. Having mentioned the relationship between the dielectric permittivity and the dielectric constant, the dielectric constant \( \kappa \) of a material can also be written as (Santamarina et al., 2001):

\[ \kappa^* = \frac{\varepsilon^*}{\varepsilon_0} = \kappa' - j\kappa'' \]  \hspace{1cm} (15)
where the real component and the imaginary component are known as the dielectric constant and the loss factor and are denoted by \( \kappa' \) and \( \kappa'' \), respectively. Each of the components of the relative dielectric permittivity is the representative of energy that is either stored in or dissipated from the material through heat. The term \( \kappa' \) expresses the storage of energy in the material and its ability to be polarized by an electrical field. Therefore, the larger the number of dipoles, the larger the value of the real part, according to (Francisca & Rinaldi, 2003; Klein & Santamarina, 2005). The imaginary component, however, is related to polarization and conduction losses and thus represents the energy that dissipates through heat from the material once it is exposed to an electric field (Hilhorst, Dirksen, Kampers, & Feddes, 2000; Martinez & Byrnes, 2001; Robinson et al., 2008). As a result, the higher the conduction currents and the displacement losses, the higher the value of \( \kappa'' \) at a given frequency (Rinaldi & Francisca, 2006). The imaginary component of permittivity, \( \kappa'' \), is in phase with the direct electrical conductivity (\( \sigma_D \)). Therefore, losses due to the polarization and conduction are measured together and imaginary permittivity can be expressed in greater detail, as shown in Equation 16, known as the effective imaginary permittivity \( \kappa''_{\text{eff}} \) (Santamarina et al., 2001).

\[
\kappa''_{\text{eff}} = \kappa'' + \frac{\sigma_D}{\omega \varepsilon_o}
\]

(16)

where \( \sigma_D \) is the direct conductivity of the sample at very low frequency.

The first term on the right-hand side of Equation 16 represents the polarization losses and the second term represents the losses due to conduction. It is evident that the higher the frequency, the lower the effect of conduction losses. Furthermore, the loss tangent, denoted by \( \tan \delta \), is known as the magnitude of the imaginary part divided by the real part and is calculated by (Campbell, 1990; Chelidze & Gueguen, 1999):

\[
\tan \delta = \frac{\kappa''_{\text{eff}}}{\kappa'}
\]

(17)

Furthermore, the capacitance is the ability of any material to store an electrical charge. The capacitance of a capacitor depends on the geometry and the dielectric permittivity of the material which is used as the insulator. For instance, for a parallel plate capacitor constructed of two parallel plates with a total area (A) separated by a distance (d), as shown in Figure 2, the capacitance (C) is approximately equal to (Rinaldi & Francisca, 1999; Robinson et al., 1998):

\[
C = \kappa' \varepsilon_o \frac{A}{d}
\]

(18)

![Figure 2- Plate capacitor](image)
2.2.4 Polarisation and relaxation mechanism

Electrical charges within a dielectric material are randomly oriented in the absence of an electromagnetic field. These electric charges start to become displaced and reoriented once an electromagnetic field is applied in order to compensate for the applied electric field (Santamarina et al., 2001). This process in which the charges are aligned with the incident electromagnetic field is called polarisation. As explained previously, the real part of the dielectric permittivity is a measure of the degree of polarisability of the material, which is often related to its ability to store electrical charges. In addition, the imaginary component represents the losses that occur due to polarisation and conduction due to an incident electrical field. Under an electromagnetic field with a reversing polarity, charges which are moved with finite velocity will not be able to move fast enough to adapt their polarity to the external electromagnetic field, therefore, the dielectric permittivity may be a function of the frequency (Stillman & Olhoeft, 2008). This dependency on frequency is attributed to the charge separation and reorientation that do not take place instantaneously. Such materials whose dielectric behaviour alters with frequency are called dispersive dielectric media (Kraus, 1984; Von Hippel & Arthur, 1954).

Looking into the geophysical investigation techniques, the operational frequency can typically vary between 10 MHz and 1 GHz for point sensors such as Time Domain Reflectometry (TDR) probes, 50 MHz and 1 GHz for Ground Penetrating Radar (GPR), and 400 MHz and 10 GHz for remote sensing applications. Moreover, the purpose of the investigation governs the most suitable frequency range for a given application. Based on the utilised frequency of investigation and the dependency of dielectric behaviour of the material (i.e., soil as shown in Figure 3a), several polarisation mechanisms may be active within a given frequency range. An understanding of the different polarisation mechanisms which occur in soils is, therefore, crucial within this context.

In the frequency range above $10^{10}$ Hz, electron polarisation occurs due to the movement of the electron cluster displacement with respect to the atomic nuclei. This displacement creates a dipole moment which leads to electronic polarisation. Furthermore, under an incident electromagnetic field, the equilibrium between the atoms gets disturbed, resulting in atomic displacement. This relative movement of atoms with each other creates an additional dipole moment known as atomic polarisation (Santamarina et al., 2001; Von Hippel & Arthur, 1954).

As the frequency decreases below 10 GHz, dipolar polarisation can occur in materials with dipolar molecules. One popular dipolar substance is water, where the oxygen and two hydrogen molecules form a 104.45° angle when creating one water molecule. In addition, due to the higher electronegativity of the oxygen compared with hydrogen molecules, the oxygen side of the molecule has a higher negative charge. This is the reason why the water molecules are known as dipoles. Under an electromagnetic field, randomly oriented water molecules in soils which are not bound to the solid particles become polarised and subsequently aligned with the direction of the EM field as shown in Figure 3b (Santamarina et al., 2001).

In the frequency range below 1 GHz, interfacial polarisation can occur in the megahertz and kilohertz ranges. Interfacial polarisation comprised of Maxwell-Wager effect and double layer polarisation primarily; it occurs at the interface between two phases due to their dissimilar electromagnetic properties (Chelidze & Gueguen, 1999; Chen & Or, 2006; Fam & Santamarina,
Maxwell-Wagner polarisation occurs below 100 MHz in heterogeneous material in which spatially separated phases are connected by common interfaces, which leads to an accumulation of charges at the interface under an electromagnetic field to essentially increased polarisation in the material (Alvarez, 1973; Chen & Or, 2006). In addition, double layer polarisation is initiated due to charge displacement where a positively charged ionic cloud is displaced with respect to a negative particle (e.g., clay particles in the case of soils) under the application of an electric field which occurs in the kilohertz or megahertz range as shown in Figure 3b (Drnevich et al., 2001; Fam & Santamarina, 1997).

Considering soils, the water phase can consist of free and bound water. Free water is the molecules that can freely move within the soil under an electromagnetic field and that are not experiencing large attraction forces from the solid particles. These molecules can experience dipolar polarisation. On the other hand, the definition of bound water essentially refers to the water molecules whose mobility is hindered by the binding forces exerted by the solid particles when subjected to an electromagnetic field; hence it exhibits dielectric properties different to those of free water and its polarisation occurs at lower frequencies – below 1 GHz which is shown in Figure 3c (Boyarskii, Tikhonov, & Komarova, 2002; Friedman, 1998; Jones & Or, 2002; Kaatze, 2011; Mulla, Cushman, & Low, 1984; Or & Wraith, 1999; Regalado, 2006; Saarenketo, 1998; Tikhonov, 1997).

As the frequency approaches the kilohertz range, counterion polarisation emerges; in the case of soils, this is caused by tangential movement and normal diffusion of ions along the solid particles and through the water field pores, which results in the induced dipolar moment which is shown in Figure 3d (Tomoyuki Ishida & Makino, 1999). Figure 3 illustrates a schematic of soil phases, polarisation mechanisms, and the corresponding spectrum.

Figure 3 – Polarisation mechanisms and corresponding frequency ranges for soils: a) soil phases, b) dipolar polarisation ($f < 1010$ Hz), c) bound water and interfacial polarisation ($f < 109$ Hz), d) counterion polarisation ($f < 106$ Hz), e) dielectric polarisation spectrum Modified from (Chen & Or, 2006; Santamarina et al., 2001; Schwing, 2015; Wagner & Scheuermann, 2009)
The frequency at which a given mechanism is no longer effective is called the characteristic or cut-off frequency. On the other hand, the contribution of a given mechanism remains at frequencies lower than its characteristic frequency and therefore the polarisations from different mechanisms will accumulate towards lower frequencies. Thus, a lower frequency of measurement yields a higher value of the real dielectric (Campbell, 1990; Santamarina et al., 2001).

From the preceding discussion, it can be concluded that the complex permittivity which is determined by polarisability and the dielectric loss is a function of frequency. Once the applied electromagnetic field is removed, however, the stored energy in the material (e.g., soil) starts to dissipate with time and returns to equilibrium, which is known as relaxation (Arcone & Boitnott, 2012). One common way to describe this behaviour (for a single-type relaxation) is by the Debye equation (Debye, 1934; Mironov, Kosolapova, & Fomin, 2009):

\[ \kappa^*(\omega, T) = \kappa_\infty(T) + \frac{\kappa_0(T) - \kappa_\infty(T)}{1 + j\omega\tau(T)} \]  \hspace{1cm} (19)

where \( \kappa_\infty \) is the high frequency limit of permittivity when the frequency approaches infinity, \( \kappa_0 \) is the low frequency of the permittivity when the frequency approaches zero, \( \kappa_0(T) - \kappa_\infty(T) \) is known as the relaxation magnitude, and \( \tau \) is the relaxation time.

Figure 4 illustrates this behaviour according to the Debye equation, which is typically observed for a single-phase material such as pure water (Agmon, 1996).

Expanding Equation 19, the real and imaginary components can be written as:

\[ \kappa'(\omega, T) = \kappa_\infty(T) + \frac{\kappa_0(T) - \kappa_\infty(T)}{1 + (\omega\tau)^2} \]  \hspace{1cm} (20)

\[ \kappa''(\omega, T) = \frac{\omega\tau(\kappa_0(T) - \kappa_\infty(T))}{1 + (\omega\tau)^2} + \frac{\sigma_{\text{eff}}}{2\pi\varepsilon_0 f} \]  \hspace{1cm} (21)
Based on Equation 21, the imaginary part of the complex permittivity shows a peak value which is located at the inflection point of the relaxation magnitude with \( \tan \delta = 1 \), which indicates a single relaxation time (see Figure 4). As shown previously by Equation 16, the imaginary component of the complex dielectric permittivity is affected by the electrical conductivity; hence the Debye equation can be modified to take the conductivity contribution into account:
\[
\kappa^*_{\text{eff}}(\omega, T) = \kappa_\infty(T) + \frac{\kappa_0(T) - \kappa_\infty(T)}{1 + j \omega \tau(T)} + j \frac{\sigma}{\omega \varepsilon_0}
\] (22)

Furthermore, since there exist multiple phases with different electromagnetic properties in heterogeneous materials such as soil, they might exhibit several relaxation mechanisms with a distribution of relaxation times. In soils, this arises from the complexity of the soil structure, texture, and mineralogy (Arcone & Boitnott, 2012; Cerato, 2012; Knight & Nur, 1987; Liu & Mitchell, 2009; Santamarina et al., 2001; Wensink, 1993). This behaviour can be described by the Cole-Cole model, which is very similar to the modified Debye equation, with a parameter to account for this distribution of the relaxation times (Ishida, Makino, & Wang., 2000; Kaatze, 2007; Kaatze & Feldman, 2006; Wagner & Schueermann, 2009):
\[
\kappa^*_{\text{eff}}(\omega, T) = \kappa_\infty(T) + \frac{\kappa_0(T) - \kappa_\infty(T)}{1 + (j \omega \tau(T))^{\beta_{CC}}} + j \frac{\sigma}{\omega \varepsilon_0}
\] (23)

where \( \beta_{CC} \) is known as the Cole-Cole parameter and varies between 0 and 1. \( \beta_{CC} \) is also known as the relaxation time distribution which can be used to derive the relaxation spectrum for materials. In the case of single-phase material such as pure water, \( \beta_{CC} = 1 \), where the Debye equation and the Cole-Cole model become equal.

2.3 Electromagnetic properties of individual soil phases

In general, soil forms a heterogeneous material made of a mineral–air–water mixture. Each phase shown in Figure 1 possesses individual electromagnetic properties. Therefore, the average dielectric constant of a heterogeneous material consisting of two or more substances is related to the dielectric constant of the individual substances, their volume fractions, their spatial distributions, and their orientations relative to the direction of the incident electrical field. Usually, the substance with the highest volume fraction is regarded as the host material and the other substances are regarded as inclusions (Endres & Knight, 1991; Robinson & Friedman, 2002; Ulaby, Moore, & Fung, 1981; Wobschall, 1977). In this section, the electromagnetic properties of individual soil phases will be described and the water phase will be considered as two phases: free water and bound water.

2.3.1 Solid Particles
As discussed in Section 2.2.4, despite being termed a “constant”, the soil dielectric constant is a frequency-dependent parameter (Schön, 2015). The dependency of soil dielectric properties on frequency has been extensively studied in the literature. Below the microwave frequency region (i.e., 300 GHz), however, the real dielectric properties of soil solid grains are almost independent of frequency. Furthermore, the effects of temperature on the dielectric constant of soil grains and air are negligible within the range considered in this study which were between 19 and 21 °C (Davis & Annan, 1989; Wagner et al., 2013; Pepin, Livingston, & Hook, 1995;
Stogryn, 1971; Weast, Astle, & Beyer, 1989). It is therefore considered to be a constant real number and suggested to be within the range of 2–15 based on the mineralogical composition (Daniels, 1996; Davis J. L. & Annan A. P., 1989; Wagner et al., 2013; Fawwaz T. Ulaby et al., 1981; Wagner & Scheuermann, 2009). An example of an empirical correlation to estimate the dielectric constant of soil particles is given in Dobson, Ulaby, Hallikainen, and El-rayes (1985):

\[
\kappa_s' = (1.01 + 0.44\rho_s)^2 - 0.062
\]  

(24)

where \(\rho_s\) is the particle density or specific gravity. There have been other attempts to empirically calculate the dielectric permittivity of solid grains (Olhoeft, 1981; Robinson, 2004; Robinson & Friedman, 2003); however, Equation 24 has been widely used in this context as well as this study.

2.3.2 Free Water

Unlike the dielectric properties of solid particles, the dielectric properties of water are highly dependent on frequency, temperature and salinity. Generally speaking, in the megahertz range, the dielectric constant of free water reaches a constant value of approximately 80.1 at 20 °C with a dielectric loss of around zero, whereas in the case of ice at −20 °C, it is around 3.18 (Daniels, 1996; Davis & Annan, 1989; Dirksen & Dasberg, 1993; Kaatze, 2007; Schön, 2015). As the frequency increases towards the gigahertz range there will be less polarisation and more losses will occur. The losses (imaginary component) show a parabolic shape with a peak at the inflection point of the real part curve as shown in Figure 4 and described by the Debye equation (Equation 19). There have been several studies on the effect of temperature on the dielectric properties of pure water (Kaatze, 1997; Kaatze, 2007; Kaye & Laby, 1921), which have all reported an inversely proportional relation between the dielectric constant and temperature for free water. Similarly to the temperature, with an increase in salinity, the dielectric constant of free water decreases. This effect, however, is proportional on the loss factor (Stogryn, 1971). The effects of frequency, temperature and salinity will be described further in Section 2.4.

2.3.3 Bound Water

Bound water is the water molecules which are tightly absorbed by the soil solid particles and hence experience higher binding forces and are rotationally hindered. The dielectric constant of water molecules near soil solid particles is low due to the van der Waals forces experienced by the water molecules near these particles. These forces prevent the water molecules from being rotationally free under an electromagnetic field, hence leading to a lower dielectric constant above the megahertz range (Boyarskii et al., 2002; Friedman, 1998; Fripiat, Cases, Francois, & Letellier, 1982; Hoekstra & Doyle, 1971; Ishida & Makino, 1999; Jones & Or, 2002; Regalado, 2006; Robinson, Cooper, & Gardner, 2002). It is generally accepted that the dielectric constant of water is proportional to the distance from a charged surface and that it varies exponentially from a low value to its bulk value over a distance equivalent to one to several water molecule diameters, where the dielectric properties of the bound water are essentially similar to those of free water with no further increase with the wetness of the soil (Boyarskii et al., 2002; Ishida & Makino, 1999; Mohajeri, Narsilio, Pivonka, & Smith, 2010; Pivonka, Narsilio, Li, Smith, & Gardiner, 2009). Past experimental research shows that the dielectric constant of rotationally hindered water (i.e., bound water) near the solid surface is somewhere between that of ice and water – between 3.2 and 80.1 – in the kilo to gigahertz.
frequency range (Boyarskii et al., 2002; Hoekstra & Doyle, 1971). This was further refined by Pennock and Schwan (1969) to 10–50 for TDR frequencies near to 1 GHz for haemoglobin-bound water. Moreover, Dobson et al. (1985a) reported a narrower range of 20–40 between 1.4 and 18 GHz for soils ranging from sandy loam to silty clay. Additionally, Or and Wraith (1999), based on the harmonic averaging method proposed by Bockris, Devanathan, and Muller (1963), computed the effective dielectric constant of bound water as a function of distance from the solid surface to be 6, 10, and 14 for the first, second, and third molecular thicknesses of bound water. However, other works such as Friedman (1998) and Robinson et al. (2002) suggested an average value for the dielectric constant of these phases based on the thickness of the water covering the solid particles.

2.3.4 Air

The dielectric permittivity of air is independent of frequency and temperature in microwave frequency range, where the real component is equal to one and the imaginary component is very small and is less than 0.05, which is often considered as zero (Campbell & Ulrichs, 1969; Cummings, 1952).

Considering the above review of the dielectric properties of individual soil phases, the soil phase diagram shown in Figure 1 can be further modified by adding the real dielectric properties of each phase at 1 GHz.

\[
\begin{align*}
\kappa'_{a} & = 1 \\
\kappa'_{fw} & = 80 \\
\kappa'_{bw} & = 10–50 \\
\kappa'_{s} & = 2–7
\end{align*}
\]

Figure 5. Dielectric properties of individual phases of soil at 1 GHz

2.4 Effect of different parameters on dielectric properties of soils

It is stated that the average dielectric constant of a heterogeneous material consisting of two or more substances is related to the dielectric constant of the individual substances, their volume fractions, their spatial distributions, and their orientations relative to the direction of the incident electrical field (Endres & Knight, 1991; Robinson & Friedman, 2002; Ulaby et al., 1981; Wobschall, 1977). To establish robust calibration and models to link dielectric properties with other soil parameters, studies have been conducted to evaluate the effects of these elements on the dielectric properties of soils. These elements range from the physical and chemical properties of the soil and its components to non-soil parameters such as the frequency of measurement and temperature. The following sections provide an overview summary of these important features.
2.4.1 Soil water content

Almost every individual study in this context has reported a proportional trend with a strong correlation between the soil water content and the dielectric permittivity of soils. It is found that as the soil water content increases, the number of dipoles that can be polarised under an electric field increases accordingly. This increased polarisation leads to an increase in the dielectric permittivity of the medium. The distinct difference between the dielectric properties of water and those of solid and air (refer to Figure 5) signifies that the dielectric properties of soil are greatly affected by water and its interaction with other phases, with a direct proportionality (see e.g., Dirksen & Dasberg, 1993; Herkelrath, Hamburg, & Murphy, 1991; Roth, Malicki, & Plagge, 1992; Roth, Schulin, Flühler, & Attinger, 1990; Schmalholz, Stoffregen, Kemna, & Yaramanci, 2004; Siddiqui et al., 2000; Topp, Davis, & Annan, 1980; Van Dam, 2014; Wang & Schmugge, 1980). Differences observed in these increasing trends were found to be related to variables such as the density, soil mineralogy, and frequency of at which the measurement took place.

2.4.2 Dry density or degree of compaction

Unlike the effects of water content on the dielectric properties of soil, there are limited studies which describe the relationship between the soil’s dry density and its dielectric properties. To date, the limited studies which have attempted to evaluate the effects of dry density on the soil dielectric properties have produced equivocal results that can mislead interpretation of the soil water content estimation using dielectric properties. For example, some studies have pointed to a directly proportional relation between the dielectric constant and density for dry samples (Dirksen & Dasberg, 1993; Lauer et al., 2010; Salat & Junge, 2010). This proportionality assumes the dominance of the solid phase in determining the overall dielectric properties of the soil matrix from the compaction point of view. Moreover, a small number of studies have reported that an inversely proportional trend could be manifested when the interaction between the solid particles and water molecules impacts considerably on the electrical properties in the presence of clay, but without adequate experimental evidence (Jacobsen & Schjønning, 1993). It is envisaged that this inversely proportional relationship is due to the dominance of the water phase over the solid phase due to the volume fraction of the bound water in the soil matrix. The bound water volume is proportional to the dry bulk density $\rho_{\text{dry}}$ (g/cm$^3$), the soil specific surface area, SSA (cm$^2$/g) (i.e., the mineralogical composition), and the thickness of bound water surrounding the soil solid particles ($\delta$) (cm):

$$\theta_{\text{bw}} = \rho_{\text{dry}} \cdot \text{SSA} \cdot \delta$$  \hspace{1cm} (25)

The bound water volume at a given temperature is therefore influenced by the soil dry bulk density and the soil specific surface area.

Essentially, at a constant volumetric water content, an increase in the dry density will increase the solid content as a result of removing the air voids which make a positive contribution to the overall dielectric constant of the soil matrix. On the other hand, the same increase in the dry density will increase the volume of bound water based on Equation (25) and thus reduce the free water volume fraction. This will cause the overall dielectric constant of the liquid phase to decrease, owing to the fact that $\kappa'_{\text{bw}}$ is significantly smaller than $\kappa'_{\text{fw}}$. The dielectric constant response of the soil at a constant volumetric water content to the variation in dry density is,
therefore, a consequence of an interplay between these two aforementioned scenarios. Firstly, the increase in the solid content volume fraction replaces the air voids, and secondly, the reduction in the free water volume fraction owing to a change in the soil dry density which increases of the bound water volume fraction (refer to Equation 25). These two scenarios are instigated by an increase in dry density or degree of compaction concurrently. The effect of dry density on the dielectric properties of soil could, therefore, vary for different soils in contrast to the consistent proportional effects of the water content; however, existing studies with adequate experimental data to reconcile this issue are limited. This, in turn, may affect the results of the interpretation of the geophysical investigations of different sites which contain soils with distinct characteristics, such as expansive soils, which normally have a higher specific surface area. Furthermore, utilising empirical calibrations for TDR probes to estimate the soil volumetric water content, which is normally obtained without accounting for the effect of soil dry density, could lead to inaccurate estimations when the density of the sample in the laboratory is different to the in-situ condition.

2.4.3 Mineralogy and clay content

Soil solid particles vary in mineralogy and chemical composition, which results in different soil types (e.g., sand, silt, or clay). This will ultimately result in different interactions between individual soil phases under an electromagnetic field, leading to different polarisation mechanisms (Ishida & Makino, 1999; Mironov et al., 2009; Rinaldi & Francisca, 1999; Santamarina et al., 2001; Arcone et al., 2008). A study by Li and Mitchell (2009) suggested that the relaxation magnitude from 50 MHz to 1 GHz is controlled mainly by the clay mineralogy and clay percentage. These two parameters essentially control the specific surface area of a given soil. It was illustrated that, at the same volumetric water content, the higher the specific surface area, the larger the dielectric dispersion magnitude in this frequency band due to the larger amount of bound water (see Equation 25), which can influence the dielectric properties of soil due to different polarisation mechanisms. Moreover, at the same volumetric water content, soil with a higher specific surface area will exhibit less polarisation at frequency of 1 GHz, due to the smaller amount of free water, leading to a lower dielectric constant (Hallikainen, Ulaby, Dobson, El-rayes, & Wu, 1985).

2.4.4 Salinity

The term “salinity” refers to the presence of the major dissolved inorganic solutes (essentially Na⁺, Mg²⁺, Ca²⁺, K⁺, Cl⁻, SO₄²⁻, HCO₃⁻, NO₃⁻, and CO₃²⁻) in aqueous samples. As applied to soils, it refers to the soluble plus readily dissolvable salts in the soil or, operationally, in an aqueous extract of a soil sample. Simply, it refers to the presence of soluble salts in the soil structure. Salinity is quantified in terms of the total concentration of such soluble salts, or more practically, in terms of the electrical conductivity of the solution (Rhoades, Chanduvi, Lesch, 1999).

At a given temperature, an increase in salinity generally reduces 𝜅’ but increases 𝜅”, since there will be less polarisation occurring within the medium (Lasne et al., 2008; Schwank & Green, 2007). On the other hand, with an increased salinity, conductivity losses increase due to the higher number of ions within the solution, leading to a larger imaginary component. At a given frequency, the conductivity (σ) has a maximum as a function of water content. This is
tentatively explained by assuming that $\sigma$ is the sum of the pore water conductivity which increases with water content until all the salts in the soil are dissolved into the water and then decreases because the concentration of the dissolved salts decreases (Wensink, 1993).

The effect of salinity on the soil dielectric constant has been proven to mainly affect the imaginary part (and thus the soil conductivity) with only a minor influence on the real part of the dielectric constant, except for soils with high moisture content, where the real component decreases with salinity due the reduction in the permittivity of saline water. Soil salinity thus has a stronger influence on the imaginary part of the dielectric constant, whereas water content primarily affects the real part (Lasne et al., 2008; Schwank & Green, 2007; Sreenivas, Venkataratnam, & Rao, 1995).

2.4.5 Frequency of measurement

As explained in Sections 2.3.1 and 2.3.4, the dielectric properties of soil solid grains and air are independent of frequency (under 300 GHz), whereas the dielectric properties of water molecules are frequency dependent. Hence, considering as a matrix, the overall dielectric behaviour of soil may become frequency dependent due to the fact that the interactions between the solid and liquid cause different polarisation mechanisms. Within this frequency range (i.e., < 300 GHz), particularly for wet soils, permittivity is primarily due to the presence of water molecules and manifests via three major effects: double layer polarisation, the Maxwell-Wagner or spatial polarisation effect, and bound water polarisation (Drnevich et al., 2001) as explained in Section 2.2.4 and in Figure 3.

It was explained in Section 2.2.4 and shown in Figure 3 that the double layer polarisation is effective up to 100 kHz according to Chew & Sen (1982), and the effect of Maxwell-Wagner polarisation accumulates up to the megahertz range. The double layer polarisation occurs in response to an electric field because of the relative displacement of the double layer counterions cloud with respect to the charged particles. Furthermore, the difference between the polarisability and conductivity of the component within the soil matrix will cause charge accumulation at interfaces, which results in the spatial or Maxwell-Wagner polarisation upon applying the electromagnetic field. Moreover, higher frequencies are controlled by bound water polarisation and free water polarisation, where the bound water polarisation results from the polarisation of water molecules adsorbed onto the surface of soil particles when subjected to an electrical field (Hilhorst & Dirksen, 1994). At lower frequencies of measurement, the real dielectric permittivity yields a higher value of the real dielectric constant (Campbell, 1990; Santamarina et al., 2001) due to the accumulation of polarisation mechanisms towards lower frequencies (refer to Section 2.2.4). The effects of the frequency on the dielectric properties of different soil types have been studied over diverse frequency ranges in the literature and are summarised in Figure 6. The investigation range of this present study is also shown.
Figure 6. Ranges of measurements frequency in past research compared to this work.
2.4.6 Temperature

The effects of temperature on the dielectric properties of individual soil phases were briefly summarised in Section 2.3. It was stated that, similarly to the effects of frequency, the dielectric properties of solid particles and air are minimally affected by temperature, whereas the dielectric properties of the water phase are inversely proportional to temperature (Mohamed, 2006). However, once considered as a matrix, the effect of temperature on the dielectric properties of soil demonstrated different behaviour. As such, some researches have shown an inversely proportional relation with temperature (Halbertsma, Elsen, Bohl, & Skierucha, 1995; Pepin et al., 1995), whereas others show a direct proportionality (Alvenaes & Stenberg, 1995; Verstricht, 1994). It is important to note that the soil types tested in these researches were different, where the former evaluated this behaviour for sandy soils and the latter were conducted on clayey soils. It has been explained that in the gigahertz frequency range, when the temperature increases, the dielectric constant of the free water phase decreases, resulting in an overall decrease in the dielectric constant of the matrix (Pepin et al., 1995; Skierucha, 2009; Wraith & Or, 1999). In contrast, according to the same studies, the thickness of the rotationally hindered water (i.e., bound water) is inversely proportional to temperature. Subsequently, as the temperature increases, the thickness of the bound water attached to the solid particles decreases due to the release of water molecules from the mineral surfaces, causing an increase in the free water volume in the matrix. This increase in the volumetric free water content leads to an increase in the overall dielectric constant of the matrix owing to an increase in the number of free water dipoles.

The effects of temperature on the dielectric constant of soil will therefore be the result of an interplay between the reduction of the dielectric constant of the free water phase with temperature and the reduction of the bound water thickness (this increases the amount of free water in the matrix). This behaviour was envisaged to be controlled by the specific surface area of the soils in the study by Or and Wraith (1999), without a threshold being identified. Although the effect of temperature has been an important element in studying the dielectric behaviour of soils, the temperature range of the current study was kept constant between 19 and 21 °C, and thus the effect of temperature variation on the experiments was minimised.

2.5 Empirical calibrations and mixing rules

It is evident from the literature that there are several parameters that affect the dielectric behaviour of soils. Several empirical material-specific calibrations, as well as theoretical mixture models, have been developed to capture these interactions, particularly for 1 GHz frequency (Dobson et al., 1985; Hallikainen et al., 1985; Jacobsen & Schjønning, 1993; Mironov et al., 2009; Roth et al., 1992; Topp et al., 1980; Wagner, Emmerich, Bonitz, & Kupfer, 2011; Wang & Schmugge, 1980; Wensink, 1993). In this section, we will provide a summary of these types of models.

2.5.1 Empirical calibrations

Empirical calibrations in this context describe the relationships between the dielectric properties and other soil characteristics such as moisture content using polynomial equations. There is no apparent physical basis for these kinds of functions, and therefore they may be valid for the soil types that were used to develop the relationship (Van Dam, 2014). These types of
empirical calibrations are obtained by the measurement of dielectric properties of several soil samples over a range of water contents (e.g., from dry to saturation point). To date, only the real part has been used to derive such calibrations and the imaginary component is usually neglected as stated in Hailemariam, Shrestha, Wuttke, and Wagner (2016) except for limited studies (Hallikainen et al., 1985). The general format of these empirical calibrations is as follows:

\[ \kappa' = A + B \cdot \theta + C \cdot \theta^2 + D \cdot \theta^3 \]  

(26)

Several polynomial calibrations have been derived for different soil types based on this format (e.g., Dasberg & Hopmans, 1992; Jacobsen & Schjønning, 1993; Roth et al., 1992; Topp et al., 1980).

Table 3 shows selected empirical calibrations that are used in this context.

<table>
<thead>
<tr>
<th>Calibration</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Number of soil samples and soil types used for calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topp et al. (1980)</td>
<td>3.03</td>
<td>9.3</td>
<td>146</td>
<td>-76.7</td>
<td>4 samples, inorganic minerals ranging from clay to sandy loam</td>
</tr>
<tr>
<td>Roth et al. (1992)</td>
<td>2.87</td>
<td>-11.10</td>
<td>276</td>
<td>-272</td>
<td>9 samples, clayey sand, clayey silt, silty sand, sandy clay, silty clay, clayey silt</td>
</tr>
<tr>
<td>Jacobsen and Schjønning (1993)</td>
<td>2.9</td>
<td>39.6</td>
<td>81</td>
<td>-76</td>
<td>5 samples clayey sand, silty sand with minimal organic content</td>
</tr>
<tr>
<td>Dasberg and Hopmans (1992)</td>
<td>2.7</td>
<td>38.4</td>
<td>44</td>
<td>-48</td>
<td>2 samples, sandy and clayey loam</td>
</tr>
</tbody>
</table>

Amongst the abovementioned calibrations, that of Topp et al. (1980), known as Topp calibration, is one of the most frequently applied and cited. In this calibration, the dependence of the dielectric constant on the volumetric water content was determined empirically in the laboratory. TDR measurements were conducted to measure the dielectric constant of soils, which are placed in a coaxial transmission line at different degrees of moisture content. A series of 18 experiments were conducted on four inorganic minerals ranging from clay to sandy loam to obtain the relationship between the dielectric constant and the soil volumetric moisture content between 1 MHz and 1 GHz. This calibration was constrained to pass through (1, 81.5),
which is the dielectric properties of pure water at 20 °C (Topp et al., 1980). They also stated that the dielectric constant is weakly dependent on soil density, salinity, and texture, which is contrary to the preceding discussion in Section 2.4.

Although it has been widely used, Topp calibration, like every calibration, has its own limitations. Dirksen and Dasberg (1993) and Dasberg and Hopmans (1992) showed that the Topp equation is valid for soils with low clay content and low specific surface area. Application of this equation to soils of high clay content will often lead to an underestimation of soil water content, more likely due to the bound water portion of the liquid phase, which does not contribute to the real dielectric constant at a frequency of approximately 1 GHz. In contrast, it has also been stated that the deviation from the Topp equation seems to be more due to the lower bulk densities associated with fine-textured soils than to bound water. Furthermore, Ju, Liu, Ren, and Hu (2010) suggested that it is most applicable to a range of bulk density ($\rho_b$) varying between 1.35 and 1.50 g/cm$^3$. Similarly to the Topp calibration, these calibrations are derived experimentally at around 1 GHz, which hints that they may not be suitable for other frequency ranges. To account for the frequency dependence of soil dielectric behaviour in obtaining empirical calibrations, Wensink (1993) conducted experiments over a frequency range between 1 MHz and 3 GHz and proposed the following equations for nominal frequencies:

$$\kappa' = 279.8 - 272.2 \theta \quad f = 5 \text{ MHz}$$  

$$\kappa' = 1.4 + 87.6 \theta - 18.7 \theta^2 \quad f = 50 \text{ MHz}$$  

$$\kappa' = 3.2 + 87.6 \theta - 16 \theta^2 \quad f = 1 \text{ GHz}$$

The calibration proposed by Wensink (1993) for 1 GHz is slightly different to the format shown in Equation 26; however, it adequately described the behaviour of the soil samples tested in their research. This was also the case in Salat and Junge (2010), where a second-degree polynomial described the relationship between the soil dielectric properties and volumetric water content with good agreement.

In addition, despite the suggested insensitivity of the Topp calibration in the range of bulk density ($\rho_b$) varying between 1.35 and 1.50 g/cm$^3$, there have been a few attempts to further improve the performance of these empirical calibrations by considering the dry density of soils. In this context, Ledieu, De Ridder, De Clerck, and Dautrebande (1986) reported a marginal improvement in their calibration between the transit time determined by TDR and volumetric water content by including dry densities in the range of 1.38 to 1.78 g/cm$^3$. Moreover, Malicki, Plagge, and Roth (1996) reported a proportional impact of the dry density on dielectric properties, where the effect of dry density was taken into account as a separate parameter in their calibration:

$$\kappa'(\theta, \rho_d) = 0.819 + 0.168 \rho_d + 0.159 \rho_d^2 + (7.17 + 1.18 \rho_d) \theta$$

It is also emphasised in Dirksen and Dasberg (1993) and Curtis and Narayanan (1998) that the density plays a vital role in characterising the electrical properties of the soil and has to be carefully incorporated in the calibration. Perhaps the most notable practical application in the context of density with regard to dielectric properties is the study by Siddiqui and Drnevich.
(1995), where the real component of the relative dielectric permittivity of soil measured by TDR, in situ and in compaction mould, is used to calculate the dry density and the soil water content. This approach was shown to have enough accuracy for geotechnical purposes and was designated as a standard: ASTM-D6780 (2003) (Yu & Drnevich, 2004). The relationship is as follows:

\[
\frac{V_1 \rho_w}{V_f \rho_d} = c_1 + d_1 (\kappa' - 1) - c_1 \cdot \exp \left[ -f_1 (\kappa' - 1) \right]
\]

(31)

\[
\sqrt[3]{\frac{\rho_w}{\rho_d}} = a + bw
\]

(32)

where a, b, c_1, d_1, and f_1 are soil specific calibration parameters determined by laboratory experimentation, \(\rho_w\) is the density of water, and \(V_f\) and \(V_1\) are the voltage measurements pertinent to TDR. In this method, Equation 31 is solved for dry density \(\rho_d\) and directly determines the dry density of soil. Subsequently, Equation 32 is solved for w and allows the determination of water content based on the calculated dry density from Equation 31 and measured \(\kappa'\). There have also been improvements to this calibration to account for the effects of temperature (Jung, Drnevich, & Abou Najm, 2012).

A general weakness of all the empirical calibrations is that they are most suitable for the corresponding situation in which they were derived or that there exist material-specific parameters which require laboratory calibration. The quality of the calibration, therefore, is strongly reliant on the quality of the experimental data and the fitting procedure. The empirical calibrations are primarily derived in a controlled laboratory environment and often lack the in-situ condition considerations. It is, therefore, crucial to recognise the applicability of a given calibration to specific field conditions and the operational frequency of the geophysical technique. This is the reason why laboratory calibrations are sometimes conducted to characterise soils from specific regions to provide petrophysical information and calibration to be utilised in planning geophysical prospection, data analysis, and modelling.

2.5.2 Mixing models

As mentioned previously, soil is a mixture of different constituents (i.e., solid grains, water, and air). The known dielectric constants of water, air, and solid particles can therefore be equated to the relative dielectric permittivity of soil using dielectric mixing models. This category of modelling describes the soil dielectric properties based on the individual characteristics of its constituents and their volume fraction (Robinson, Jones, Blonquist, & Friedman, 2005). Earlier studies have investigated the applicability of these models to successfully estimate soil water content from relative permittivity measurements (Lichtenecker & Rother, 1931; Roth et al., 1990). This approach, which was initiated from the semi-empirical volumetric mixing model by Lichtenecker and Rother (1931), begins at the grain scale and attempts to reconstruct the sample response based on grain scale properties; it may be written as:

\[
\kappa^\alpha = \sum_{i=1}^{N} V_i \kappa_i^\alpha
\]

(33)
where $V_i$ is the volume fraction of the corresponding constituent $i$, $\alpha$ is a fitting parameter, and $\kappa_i$ accounts for the dielectric property of each individual phase. This model is typically known as the Lichtenecker and Rother Model (LRM).

Equation 33 is common in porous media studies, soil physics, geophysics, remote sensing, and geotechnical applications (see e.g., Alharthi & Lange, 1987; Dobson et al., 1985; Dube, Yadava, & Parshad, 1971; Kraszewski, Kulinski, & Matuszewski, 1976; Lichtenecker & Rother, 1931; Malicki, Plagge, Renger, & Walczak, 1992; Mironov et al., 2004; Nelson, 1988; Schwartz, Evett, Pelletier, & Bell, 2009; Wagner & Scheuermann, 2009). The value of $\alpha$ is controlled partially by the grain dominant orientation and pore geometry as mentioned in Brovelli and Cassiani (2008). For instance, $\alpha = 1$ accounts for situations when the electromagnetic field is parallel to the predominant soil grain orientation and $\alpha = -1$ is adopted when the electromagnetic field is perpendicular to the soil grains. For other orientations, intermediate values are assigned (Birchak, Gardner, Hipp, & Victor, 1974; F. Francisca, Yun, Ruppel, & Santamarina, 2005). For an isotropic soil, Birchak et al. (1974) proposed $\alpha = 0.5$, whereas M. A. Hilhorst (1998) suggested that a value of 0.5 can be considered as an approximation since the compositional and microstructural properties of soil are not taken into account. In another study by Dobson et al. (1985) on a range of soils from sandy loams to silty clay, $\alpha$ was fitted by regression and determined to be 0.65 for a frequency range of 1.4 to 18 GHz. On the other hand, Ole Hørbye Jacobsen and Schjønning (1995) conducted experiments on moist mineral soils and showed that $\alpha$ is a non-constant parameter that varies between 0.4 and 0.8. Moreover, Zakri, Laurent, and Vauclin (1998) suggested that $\alpha$ decreases linearly with soil dry density, while others suggested that it remains as a fitting parameter (Brovelli & Cassiani, 2008; Jung et al., 2012).

In the case of coarse-grained soil, the liquid phase consists primarily of free water due to the low specific surface area, since the bound water volume is estimated to be very small (see Equation 24). Therefore Equation 33 can be rewritten as:

$$\kappa^*\alpha = (1 - n)\kappa^*_s\alpha + (n - \theta)\kappa^*_a\alpha + \theta\kappa^*_w\alpha$$

(34)

where $n$ is the porosity, $\kappa^*_s$ is the permittivity of the solid grains (which is essentially equal to the real part of the complex dielectric permittivity in the case of soil grains), $\kappa^*_a$ is the permittivity of air, $\kappa^*_w$ is the permittivity of water phase (in this case, the free water), and $\theta$ is the volumetric water content. Additionally, for the case where $\alpha = 0.5$ in LRM (Equation 33), it is called the Complex Refractive Index Model (CRIM) (Birchak et al., 1974) or the generalised refractive mixing dielectric model (Mironov, Dobson, Kaupp, Komarov, & Kleshchenko, 2004) and has been utilised in the evaluation of soil dielectric behaviour (e.g., Hailemariam et al., 2016; Huisman et al., 2003; Robinson, Jones, Wraith, Or, & Friedman, 2003; Wagner et al., 2011). For $\alpha = 1/3$, however, it transforms to the Looyenga-Landau-Lifshitz model (Campbell, 1990; Looyenga, 1965; Nelson, 1988).

On the other hand, in the case of a fine-grained soil with high clay content, the water phase is made up of free water and bound water, as previously explained in Sections 2.3.3 and 2.4.2. Considering this fourth phase, the three-phase mixture model can be written as follows:

$$\kappa^*\alpha = (1 - n)\kappa^*_s\alpha + (n - \theta)\kappa^*_a\alpha + \theta_{bw}\kappa^*_bw\alpha + (\theta - \theta_{bw})\kappa^*_fw\alpha$$

(35)
where $\theta_{bw}$ is the volume and $\kappa_{bw}^{*}$ is the dielectric properties of the bound water phase.

The general format of the mixing models essentially follows Equation 33. However, there have been other attempts to link the dielectric properties of soil to its water content and other properties. Equation 36 and 37 denote the Soil Mixing Dielectric Model (SMDM), which equates the real $\varepsilon_m'$ and imaginary permittivity $\varepsilon_m''$ of a moist soil with the bulk (dry) density $\rho_b$, specific density $\rho_s$, and volumetric water content $\theta_v$ (Dobson et al., 1985):

$$
\kappa_m' = \left[1 + \frac{\rho_b}{\rho_s} (\kappa_s' - 1) + \theta \beta' \kappa_{fw}' - \theta_v \right]^{\frac{1}{\alpha}} \tag{36}
$$

$$
\kappa_m'' = \left[\theta \beta'' \kappa_{fw}'' \right]^{\frac{1}{\alpha}} \tag{37}
$$

where $\kappa_s'$, $\kappa_{fw}'$, and $\kappa_{fw}''$ refer to the real relative permittivity of solid soil grains and the real and imaginary permittivity of free water, respectively, $\beta'$ and $\beta''$ are soil-texture-dependent parameters, and $\alpha$ is a constant shape factor equal to 0.65:

$$
\beta' = 1.2748 - 0.00519S - 0.00152C \tag{38}
$$

$$
\beta'' = 1.33979 - 0.00603S - 0.00166C \tag{39}
$$

where S and C are the sand and clay percentages, respectively.

Dobson et al. (1985) proposed to use $\beta'$ and $\beta''$ to account for the bound water content and its contribution to the overall dielectric behaviour of soil through the soil textural composition, since the dielectric properties of bound water are not well known. In addition, Equations 40 and 41 define the Advanced Lichtenecker and Rother Model (ALRM), which equates the real or imaginary part of the relative dielectric permittivity $\kappa$ of a soil as a function of its volumetric water content $\theta$ and the porosity $n$:

$$
\kappa_a(\theta, n) = \theta \kappa_{w}(\theta, n) + (1 - n)\kappa_s(\theta, n) + (n - \theta) \tag{40}
$$

$$
(\theta, n) = A + Bn^2 + C \left(\frac{\theta}{n}\right)^2 \tag{41}
$$

where $\alpha$ is an empirical constant, $A = 0.14$, $B = 0.54$, and $C = 0.62$ (Wagner et al., 2011).

In comparison to the empirical calibration discussed in Section 2.5.1, the mixture models describe the dielectric behaviour of the soils based on the frequency/temperature dependent dielectric behaviour of the individual phases – primarily the liquid phase. This category of calibration, therefore, can be more accurate and applicable to different conditions. However, the main drawback of this category of the models is that the microstructure of the soil is rather simplified, for instance by using the structural parameter, $\alpha$, which is assumed to be a constant value. Under this assumption, the effects of a structure are neglected. Conversely, this category of calibration requires a lot of inputs to estimate the value of the desirable soil parameter. This, in turn, can be time-consuming and it is sometimes very hard to obtain the initial inputs; nonetheless, it may be more accurate and physically sound compared to the empirical calibrations.

The suitability of a given model for a particular application (e.g., water content estimation, environmental studies, remote sensing, archaeological investigations) depends on the
applicability of the model to the specific environmental condition, the availability of previously documented data of the study area, and the soil-specific information, as well as practical considerations such as time and cost. The aim of these models is to be able to provide a way to estimate soil properties such as water content and density by measuring their electrical properties using geophysical techniques.

2.6 Current measurement techniques: w, ρ, κ

Measurement of soil moisture content and density has been of interest to engineering, agriculture, water resource management, and hydrology. The standard method of measuring the moisture content is the thermo-gravimetric method, where a sample of soil is held at 105 °C for 24 hours and the moisture content is calculated based on the weight loss due to the water evaporation from the sample according to AS1289.2.1-2005 (Standards Australia, 2005). The method is destructive to the soil structure, as it requires soil samples to be taken out of the ground and put in the oven, which may not be favourable when the structure of the soil needs to be preserved. Additionally, using traditional soil sampling methods is expensive and time-consuming. Another disadvantage of this method is that sampling makes repeated measurements at the same exact location impossible (Yan, You, Gang, Lei, & Peng, 2011). These measurements also become harder in situ for a large number of points (Robinson & Dean, 1993). Additionally, the traditional methods in agriculture, where high spatial resolution of soil water content is preferable, require a sizeable investment in time and money (Zhang, Fan, Lee, Kluitenberg, & Loughin, 2004).

It is of great advantage to the areas of sustainable land and water management to be able to measure soil moisture using non-destructive methods (Robinson et al., 2008). The neutron probe is an intrusive but non-destructive method widely used for both moisture content and density measurements; however, it is reported in Robinson and Dean (1993) that it cannot return reliable values for near-surface moisture content measurements and requires careful handling due to its radioactive source. Additionally, it cannot be employed for unattended and automatic recordings (Kodikara, Rajeev, Chan, & Gallage, 2013; Robinson & Dean, 1993; Yu & Drnevich, 2004). Furthermore, these common methods of measuring soil water content often cannot provide immediate feedback (Muñoz-Carpena & Dukes, 2015).

Based on the relationship between the soil dielectric properties and individual soil phases, alternative geophysical techniques have been developed which utilise the soil dielectric properties as a proxy to estimate soil water content. TDR, GPR, and remote sensing are non-destructive electromagnetic measuring techniques that are becoming increasingly widespread since they can facilitate accurate and fast measurements of soil water content (Galagedara, Parkin, Redman, von Bertoldi, & Endres, 2005; Noborio, 2001; Steelman et al., 2012; Topp et al., 1980). These techniques are based on measuring the dielectric properties of the soil and they significantly alleviate the drawbacks of otherwise destructive or nuclear-based methods such as oven drying or neutron probes, respectively. For instance, TDR probes, which have been widely used in past researches and experiments (e.g. Jacobsen & Schjønning, 1993; Roth et al., 1992; Topp & Davis, 1985; Topp et al., 1980; Yu & Drnevich, 2004), return an average value of moisture content over the length of the spikes, which may not be suitable for measurements close to the ground surface (Robinson & Dean, 1993). Other techniques which
employ similar principles include Frequency Domain Reflectometry (FDR) probes, capacitive probes, impedance probes, GPR and EM conductivity in the estimation of soil content in various applications (e.g., see Chen et al., 2010; Grote et al., 2003; Huisman et al., 2003; Muñoz-Carpena, Shukla, & Morgan, 2004; Steelman et al., 2012; Wraith, Robinson, Jones, & Long, 2005). The high cost of these methods and the need for probe insertion (except for GPR and EM antennas) impose substantial limitations on the use of these methods and on their accessibility.

To alleviate the high cost of the aforementioned techniques, there have been some developments in low-cost sensors for the estimation of soil water content. Heat pulse soil moisture sensors using single or dual probe designs have been introduced in this context (Bristow, Campbell, & Calissendorff, 1993; Bristow, Kluitenberg, & Horton, 1994; Campbell, Calissendorff, & Williams, 1991; Da Costa et al., 2017, Dias et al., 2016; Dias, Roque, Ferreira, & Siqueira Dias, 2013; Gao et al., 2018; Matile, Berger, Wächter, & Krebs, 2013).

Furthermore, recent developments in capacitive soil moisture sensors have provided low cost means of soil water content measurement (Da Costa et al., 2017; Gao et al., 2018). Nonetheless, they have not eliminated the need for probe insertion. For this purpose, a needle-free heat pulse sensor system has recently been developed (França, Morais, Carvalhaes-Dias, Duarte, & Dias, 2018). Although this sensor has no needle and is inexpensive, burying it in the soil causes soil disturbance (França et al., 2018). None of these developments, however, have focused on non-invasive measurements of near-surface soil water content. Instead, remote sensing applications have been widely used as the primary source of information on surface soil water content. However, they often lack the required resolution for certain applications (Mancini, Hoeben, & Troch, 1999; Ryu & Famiglietti, 2005). It has been suggested that understanding the sub-footprint scale of the variability of remotely sensed soil water content is an important factor to fully utilise these data (Ryu & James Famiglietti, 2005).

There is limited literature that describes soil moisture and density estimation conducted from the ground surface except for a device known as the non-nuclear Soil Density Gauge (SDG) created and used by TransTech System Inc., which is shown in Figure 7.

---

Figure 7 – SDG model 100A schematic (Pluta & Hewitt, 2009)
This gauge is essentially a non-nuclear, non-invasive instrument capable of measuring the density and moisture content of soil based on measuring electromagnetic impedance. An empirical model was developed to measure the wet density and the moisture content of soils with different degrees of saturation. The instrument setup consists of concentric rings that act as transmitting and sensing electrodes. The analysis of the electromagnetic impedance spectroscopy is basically a measure of the material’s dielectric permittivity based on the interaction of the dipole moment of the material under test and the electromagnetic field over a known frequency range (Pluta & Hewitt, 2009).

The SDG is the only available alternative to the current invasive and destructive tests, and therefore given the ongoing demand for soil moisture content and density measurements, this research endeavours to introduce and develop other alternative sensors in the context of non-invasive and non-destructive soil moisture and density measurements.

2.7 Conclusion

This chapter was dedicated to describing the electromagnetic theory and equations which govern wave propagation through the material. The dielectric measurement forms the crux of this research; therefore, the principles of dielectric properties and the different polarisation mechanisms have been discussed. Furthermore, the electromagnetic properties of individual soil phases with respect to frequency and temperature have been studied. We have discussed the parameters which impact the dielectric properties of soils as well as calibrations and models which provide a quantitative link between these parameters. We have reviewed the current techniques of measuring soil geotechnical parameters (i.e., water content and density) as well as dielectric properties and the pertinent geophysical means which are used in this context.

This chapter shows that soil geotechnical properties and other parameters such as textural composition and mineralogy influence the dielectric behaviour of soil. Therefore, empirical and mixture models have been used to describe these relationships. However, these models may only be applicable to the soils and conditions used to derive them. Considering this, there could be instances where site-specific information and calibrations are required prior to planning geophysical prospecting, data analysis, and modelling. Despite the importance of the correlations between the geotechnical and soil electrical parameters in geophysical site characterisation, no regional studies have been conducted on Australian soils to serve as a database that may aid in future investigations and modelling. Furthermore, it was highlighted that unlike to other parameters such as temperature, frequency, water content and salinity, there is no systematic research or adequate experimental evidence to address the effect of dry density on the soil dielectric constant and the use of specific surface area as a more meaningful representation of soil-water interactions within a soil matrix over textural composition (i.e., sand, silt, and clay content).

All of these studies in the context of soil dielectric behaviour aim to provide better and accurate models and calibrations to estimate soil geotechnical properties through the measurement of dielectric properties as a proxy by geophysical means. The use of geophysical means is becoming increasingly popular in soil and site characterisation due to their advantages over conventional thermogravimetric and radioactive methods; however, the need for probe
insertion and the cost of equipment are the major drawbacks which limit the accessibility of these methods which encourage the development of alternative ways for the estimation of soil properties.
3 Physical characterisation of soil recovered from the ANZAC battlefield

This chapter summarises the results of a laboratory experimental investigation on some geotechnical and geophysical characteristics of soil recovered from the iconic ANZAC battlefield in Gallipoli, Turkey. The chapter sets out a framework for geophysical studies in similar areas/regions which assists in future feasibility studies, planning and result interpretation of geophysical investigations.

3.1 Motivation

The ANZAC battlefield has not been physically studied in great detail but only from late 2010, with the approach of the centenary in 2015. The method(s) used in the study of the battlefield was highly multi-disciplinary comprising archaeology, artefact analysis, historical and geophysical techniques, including non-invasive archaeological survey techniques such as GPR. No prior information about site specific soil characterisation was made available to the investigation team. This is particularly crucial considering that access to the site for this sort of studies was highly restricted or very limited for almost a century. This chapter, therefore, aims to provide such soil characterisation and empirical models to facilitate feasibility studies, planning and interpretation of geophysical investigations in this restricted-access study area. In a broader sense, these outputs can be contemplated as a database to assess the applicability of GPR or any other electromagnetic geophysical prospection to nearby/similar sites. Further, the methodology explained in this chapter can also be extended to areas/regions which will be undergoing electromagnetic geophysical investigations. It is important to note that the primarily focus of this research was the development of the models for a diverse range of water contents and frequencies while the dry density of each sample was kept relatively constant.

3.2 Contribution towards manuscript

I was the primary researcher and the author of this work. Together with A/Prof Narsilio, we devised the research plan and I conducted the laboratory measurements and subsequent analyses under the supervision and support of A/Prof Guillermo Narsilio. The XRD tests and analyses were conducted by Ms L Goodall at the Materials Characterisation and Fabrication Platform (MCFP) of the University of Melbourne. Mr Roger Curtain from the Bio21 Institute of The University of Melbourne assisted in producing the ESEM micrographs.

3.3 Published manuscript

This section consists of a paper entitled "Physical characterisation of soil recovered from the ANZAC battlefield", published in Near Surface Geophysics journal. The paper has been inserted in the following pages as published by the journal with page numbers to be consistent with the thesis document.
Physical characterisation of soils recovered from the ANZAC battlefield

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ABSTRACT
As part of a unique tri-nation study to commemorate the centenary of the iconic First World War ANZAC battlefield, this paper summarises the results of a laboratory experimental investigation of some geotechnical and geophysical characteristics of soil recovered from this field in Gallipoli, Turkey. The geophysical characterisation of these samples comprises the determination of the dielectric properties, namely real, imaginary and dielectric dispersion, over a frequency band between 200 MHz and 6 GHz. This characterisation is performed at the samples’ in situ state as well as in a controlled range of water content from oven-dried to saturation. Specific frequencies pertaining to certain in situ geophysical applications and satellite surveys have been targeted as reference frequencies to study the dielectric data. Moreover, attenuation coefficients related to ground-penetrating radar applications are also estimated at 200 MHz for a range of water contents. Microstructure and mineralogy were examined by environmental scanning electron microscopy and X-ray diffraction techniques, respectively. Given the historical and archaeological significance of the ANZAC battlefield, these results can be used for future feasibility studies, planning, and result interpretation of geophysical investigations, including choosing the most appropriate time of the year and geophysical prospecting tools, in this restricted-access study area.

INTRODUCTION AND BACKGROUND
Site investigation using geophysical techniques have been used in different engineering and non-engineering applications to characterise the subsurface, mapping soil and rock conditions, and to gather information about underground features. Such non-engineering applications include for instance archaeological studies (Davis and Annan 1989; Sternberg and McGill 1995; Loewer, Wagner, and Igel 2013; Khakiev et al. 2014). The dielectric properties of soil (influenced by soil water content, salinity, density and mineralogy) and the operational frequency of geophysical surveys play a crucial role in electromagnetic (EM) wave-based geophysical investigations, such as ground-penetrating radar (GPR), EM prospecting, and light detection and ranging (LIDAR) (Topp, Davis, and Annan 1980; Roth et al. 1990; Drnevich et al. 2001; Liu and Mitchell 2009; Lauer et al. 2010; Wagner et al. 2011; Schön 2015). Hence, having information (and building a database) about the dielectric properties of soils over a range of water contents and frequencies may aid future geophysical investigations and modelling. Parameters such as water content and density are relatively easy to measure; therefore, with such database, these and other soil parameters can be linked as proxies to electrical properties (i.e., dielectric permittivity) via site-specific empirical correlations. Furthermore, having a database including important information regarding soil electrical properties will significantly aid in choosing the best season and time of the year to conduct the survey, adopting the right prospection techniques and result interpretation in geophysical and satellite surveys.

The 1915 campaign that took place on Gallipoli Peninsula, Turkey, has immense historical significance. However, the battlefield itself, where the first Australian and New Zealand Army Corp (ANZAC) fought, has not been physically studied in great detail until late 2010. The situation changed for the first time with the approach of the centenary landing in 2015. For almost one hundred years, the ANZAC battlefield (and reserve) has not been studied with modern techniques, with the last (archaeological) survey of the battlefield conducted in 1919 (Sagona et al. 2011). A Joint Historical and Archaeological Survey (JHAS) team was established with members from both sides of the 1915 conflict (Turkey, Australia, and New Zealand) to physically survey the ANZAC battlefield during 2010–2014. The approach for the battlefield study was highly multi-disciplinary: landscape archaeology, artefact analysis, historical, and geophysical, including application of non-invasive archaeological survey techniques such as GPR. The study area (Figure 1) covers approximately 3.7 km² as defined by the Treaty of Lausanne. One of the main objectives was not only to identify and record sites significant to the three nations during

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the 1915 campaign still visible on the landscape (e.g., boundary markers, trenches, dugouts, tunnels, pathways, cemeteries, and memorials) but also to identify those sites with no visible evidence remaining from using other advanced archaeological prospection techniques, including GPR. No prior information about site-specific soil characterisation was made available to the team. It was clear that such information would have been useful to have to decide on the type of prospections, frequency, and even time of the year to plan, and later interpret the geophysical surveys. This is particularly important considering that access to the site for this sort of studies was restricted or very limited for almost a century. Therefore, this article aims to provide such soil characterisation and make it available to facilitate feasibility studies, planning, and interpretation of geophysical investigations in this restricted-access study area.

For instance, in GPR applications, such petrophysical results can help in defining a framework to conduct future geophysical prospecting within this battlefield. In particular, these will help to determine the vertical resolution and effective depth of investigation based on the antenna frequency at different sites. Moreover, results of such petrophysical characterisation can be used to facilitate to properly analyse and interpret forthcoming GPR surveys. In a broader perspective, these results can be contemplated as a database to assess the applicability of GPR or any other geophysical prospection to nearby/similar sites (Society of Exploration Geophysicists of Japan 2014).

**DIELECTRIC PROPERTIES OF SOILS**

Dielectric permittivity \( \varepsilon \) (F/m) is a complex number which describes the behaviour of a material when it is subjected to an electrical field and can be represented as described by Huisman et al. (2003):

\[
\varepsilon = \varepsilon'(\omega) - j\varepsilon''(\omega)
\]

Figure 1: Map of the area: sampling locations, interval between sampling locations, and elevation with respect to the sea level.
where $\varepsilon'$ is the real component of the dielectric permittivity ($F/m$), $j = \sqrt{-1}$ is the imaginary number, and $\varepsilon''$ is the imaginary component of the dielectric permittivity ($F/m$), which are function of the angular frequency $\omega$.

The dielectric constant $\kappa$ of a material is the ratio of its permittivity $\varepsilon$ to the permittivity of vacuum or air ($\varepsilon = 8.85 \times 10^{-12} F/m$); hence, $\kappa = (\varepsilon / \varepsilon_r)$. Therefore, the dielectric constant, which is also known as the relative permittivity $\varepsilon_r$ of the material, is dimensionless and can be written as shown by Santamarina, Klein, and Fam (2001):

$$\kappa = \frac{\varepsilon(\omega)}{\varepsilon_s} = \kappa'(\omega) - j\kappa''(\omega)$$  \hspace{1cm} (2)

where the real and the imaginary dielectric constants are denoted by $\kappa'$ and $\kappa''$, respectively. The out-of-phase (imaginary) component of permittivity $\kappa''$ is in phase with the conductivity $\sigma$. Therefore, losses due to polarisation and conduction are measured together by the imaginary dielectric constant. Thus, considering these losses, an effective imaginary dielectric constant can be expressed as (Santamarina et al. 2001; Schöhn 2015):

$$\kappa''_{\text{eff}}(\omega) = \frac{\varepsilon''(\omega)}{\varepsilon_s} = \frac{\sigma(\omega)}{\sigma_{\text{eff}}}$$  \hspace{1cm} (3)

where $\varepsilon_s = 8.85 \times 10^{-12} F/m$, $\omega$ is the angular frequency, and $\sigma$ is the conductivity of the sample at very low frequency. It is evident that the higher the frequency, the lower the effect of conduction losses. The conductivity of the soil at high frequency can be simply estimated as $\sigma \approx \kappa''_{\text{eff}}(\omega) \times \omega \times \varepsilon_s$ (and the resistivity, as the inverse of conductivity).

Soils generally comprise of three different phases: solid (minerals and particles), liquid (typically water), and gas (typically air), where each phase has its own value for dielectric constant. The dielectric constant of these typical phases has been reported in the literature (Ulaby, Moore, and Fung 1981; Olhoeft 1981; Davis and Annan 1989; Daniels 1996; Schöhn 2015); $\kappa = 1$ for air, $\kappa = (2 - 7)$ for soil solid particles, and $\kappa = 80$ for water. Moreover, the average dielectric constant of soils is related to the dielectric constant of the individual phases, their volume fractions, their spatial distributions, and their orientations relative to the direction of the incident electrical field (Wobschall 1977; Endres and Knight 1991; Robinson and Friedman 2002).

A strong correlation between the volumetric water content and the real dielectric permittivity of soils is typically reported in the related literature where small changes of water content can be determined due to the relatively higher dielectric constant of water (Topp et al. 1980; Roth et al. 1990; Schmalholz et al. 2004). Perhaps, the most widely used empirical correlation is known as the Topp equation, where the apparent dielectric constant of the soil is related to its volumetric water content (Topp et al. 1980). Topp et al. (1980) suggested that the apparent dielectric constant $\kappa$ for low loss and nearly homogeneous materi-
mechanisms will accumulate towards lower frequencies. Thus, a lower frequency of measurement yields a higher value of real dielectric constant (Santamarina et al. 2001). The frequency range used in this work (i.e., 200 MHz to 6 GHz) partially covers the bound water polarisation region. Moreover, in addition to water, soil type is considered an influential parameter on dispersion (Liu and Mitchell 2009). These concepts will be further utilised in the results interpretation section.

The effect of salinity on soil dielectric constant has been proven to mainly affect the imaginary part (and thus soil conductivity), with only a minor influence on the real part of the dielectric constant, except for soils with high moisture content where the real component decreases with salinity due the reduction in the permittivity of saline water. Therefore, soil salinity has a stronger influence on the imaginary part of the dielectric constant, whereas water content primarily affects the real part (Sreenivas, Venkataratnam, and Rao 1995; Schwank and Green 2007; Lasne et al. 2008).

Other soil properties, such as density and organic content, have been shown to have some influence on real dielectric constant. Rinaldi and Francisc (1999) suggested that the real dielectric constant is proportional to dry density. On the other hand, Lauer et al. (2010) mentioned that real dielectric constant is inversely proportional to organic content. This negative effect of soil organic matter on the real dielectric permittivity of tested soils was related to the lower densities of samples associated with their higher organic content. No significant effect of organic content was reported on the imaginary part in the aforementioned research.

Finally, measurements conducted by Salat and Junge (2010) investigated the effect of mineralogy on the dielectric properties of soil focusing on the effect of carbonate content and clay fraction on the real dielectric permittivity at 200 MHz. It was noted that the higher carbonate content was associated with higher densities; hence, a higher real dielectric permittivity. Explicit dependence of the dielectric constant on the mineralogy, however, could not be identified since it was masked by the dry density (Salat and Junge 2010). Moreover, the effect of clay mineralogy and clay percentage on the dielectric dispersion of soil was found to be crucial in frequencies between 50 MHz to 1 GHz (Liu and Mitchell 2009).

While the amount of soil recovered from different locations at the ANZAC battlefield site is relatively small, this experimental work presents dielectric measurements of these soils and, to a limited extent, the effects of the above variables on these measurements.

MATERIAL AND METHODS

Soil samples

Soil samples were collected from the ANZAC battlefield, which is located on the eastern side of European Turkey. Samples were collected over the frontlines areas with approximate locations shown in Figure 1. These areas of interest are today preserved mainly as cemeteries and memorials and connected with roads to facilitate access to visitors and family members of deceased ANZAC soldiers. The geology of the region is related to the Miocene formation, and the soil in the area is classified as Noncalcic Brown and Rendzina soil material (European Soil Portal 1954; Bingöl 1989).

Depths at which the samples were retrieved as well as the elevation with respect to the sea level are summarised in Table 1. Samples were collected and stored in sealed containers to pre­serve their in situ condition (i.e., water content).

Among the aforementioned soil samples, three samples were retrieved preserving their in situ structures, whereas the other samples’ structures were disturbed. Undisturbed samples are: Quinn’s Post (C), Johnston Jolly (E), and Lone pine (F). At Court­ney’s and Steele’s Post, the water content of the soil was relatively high (i.e., 6.2%) within the top horizon (first 0.5 m). The top surface was covered by litter from trees at this location; thus, a soil sample from 0.5 m depth was taken as well as from a depth of 5 m below ground surface.

TESTING PROGRAM AND PROCEDURES

The testing program mainly focuses on dielectric permittivity measurements of the soil samples retrieved from these significant sites. Other physical tests are also conducted to further expand the soil characterisation, to cover a larger range of water

Table 1  Soil samples: location, nomenclature, and natural water content

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample name (depth retrieved)</th>
<th>In-situ gravimetric water content w (%)</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: No.2 Outpost</td>
<td>No.2 Outpost (surface)</td>
<td>1.6</td>
<td>9</td>
</tr>
<tr>
<td>B: The Nek Cemetery</td>
<td>NEK 1 (surface)</td>
<td>2.9</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>NEK 2 (surface)</td>
<td>2</td>
<td>140</td>
</tr>
<tr>
<td>C: Quinn’s Post</td>
<td>Quinn’s Post (surface)</td>
<td>3</td>
<td>128</td>
</tr>
<tr>
<td>D: Courtney’s and Steele’s Post</td>
<td>Steele’s (0.5 m)</td>
<td>6.2</td>
<td>117.5</td>
</tr>
<tr>
<td></td>
<td>Steele’s (5 m)</td>
<td>1.8</td>
<td>113</td>
</tr>
<tr>
<td>E: Johnston Jolly Cemetery</td>
<td>Johnston Jolly (surface)</td>
<td>2.3</td>
<td>120</td>
</tr>
<tr>
<td>F: Lone Pine</td>
<td>Lone Pine (surface)</td>
<td>3.4</td>
<td>122</td>
</tr>
</tbody>
</table>

contents (since these would vary with seasons, i.e., dry and wet) and to aid in interpretation of the results from dielectric measurements. These other physical tests include grain size distribution (Standards Australia 2003, 2009), mineral, compositional, and microstructure characterisation, which have been conducted by using X-ray diffraction (XRD) and environmental scanning electron microscopy (ESEM) techniques, respectively.

The dielectric properties of the soil samples were determined by using a dielectric slim form probe kit (Agilent 85070E). A vector network analyser (FieldFox VNA N9923A) was used to measure the complex reflection coefficient. The complex dielectric permittivity was evaluated over a frequency range of 200 MHz to 6 GHz by means of proprietary software.

Firstly, dielectric constants of all soil samples were measured at their in situ or natural condition. Following these measurements, samples were oven-dried to measure their in situ gravimetric water content (Standards Australia 2005).

Secondly, for varying the water content of disturbed samples, deionised water was added to the soil and by thoroughly mixing the matrix and allowing enough curing time (i.e., at least, 24 hours); homogeneous mixture of each sample was obtained. On the other hand, for the undisturbed samples, they were saturated by carefully submerging them in deionised water (while preserving their structure) and letting them dry over time while conducting the dielectric measurements over this period. Deionised water was used in both scenarios to minimise introducing foreign ions into the soil samples.

Therefore, dielectric constant measurements were conducted for a range of water content from dry to saturated conditions. Once the measurements for undisturbed samples were conducted for the range of water content, these samples were crushed and mixed thoroughly with deionised water to repeat the same measurements but in a disturbed condition. This aids to investigate the effect of structure on the measured dielectric constant values.

While the dielectric constant measurement took place, soil samples were held in PVC containers to minimise the chances of EM interference between metal and the EM waves emitting from the dielectric probe. The probe, connection, and cable were fixed to a frame and instead of moving the probe towards the sample, a lab jack was used to move the samples towards the probe to eliminate or greatly minimise any error originating from the movement of the cable connecting the probe to the network analyser. At the commencement of each dielectric measurement, the probe needs to be calibrated with three different materials and corrected by temperature (Or and Wraith 1999; Ulaby et al. 1981). Once this initial calibration is performed, a quick calibration (QuickCal) can be conducted by measuring the dielectric constant of air (i.e., $\kappa^\prime=1$) prior to each subsequent soil measurement to eliminate any noise or error.

Once the probe is calibrated, the lab jack was used to move the samples towards the probe until a soil penetration of more than 5 mm is achieved and maintained as specified by the manufacturer (Agilent Technologies 2005). For each soil sample, at a given water content, several measurements are conducted at different locations within the sample, and average values are computed for real and imaginary dielectric constants over the frequency band to minimise experimental errors and noise. Figure 2 shows a typical experimental setup and apparatus used in this study.

**EXPERIMENTAL RESULTS AND DISCUSSION**

**Grain size analysis**

Figure 3 shows the grain size distribution for the eight soil samples obtained by sieving and hydrometer tests (including threshold sizes based on the Unified Soil Classification System, 

![Figure 3](https://via.placeholder.com/150)

Figure 3 Grain size distribution of the collected samples with thresholds based on the USCS.

recovered from the ANZAC battlefield, XRD has been conducted on all of the samples. Oven-dried sample powder was initially loaded onto a large holder and mounted such that the sample was flat to the X-ray beam. Each sample was then spiked with a known amount of corundum and backpacked into a sample holder prior to further diffraction analysis. Diffraction data were collected using a Bruker D8 Advance X-ray diffractometer with Ni-filtered Cu Kα radiation (1.54 Å). Data were collected between 5° and 85° (2θ), with a step size of 0.02° and a scan rate of 0.5 seconds per step. An incident beam divergence of 0.26° was used with a 2.5° Soller slit in the diffracted beam. The sample was spun at 15 revolutions per minute. Phase identification was completed using Materials Data, Inc., Jade 9.3 software with the ICDD PDF2 2009 database. Quantitative Rietveld analysis for the determination of amorphous levels was carried out using Bruker Diffracplus Topas software. XRD results are illustrated in Figure 5.

As shown in the figure, the diffraction patterns are similar among all of the samples, which suggest that the mineralogy composition is approximately the same for all of the samples. In general, there are minor differences in the soils from each location. No.2 Outpost and Quinn’s Post show some sharper diffraction peaks suggesting greater crystallinity than other locations perhaps due to the higher sand fraction of these samples as revealed by the grain size. The mineralogy is primarily constituted of quartz with varying quantity. Samples retrieved from Courtney’s and Steele’s Post possesses the highest amount of amorphous material. Johnston Jolly contains a distinct amount of Muscovite among all samples, perhaps due to material borrowing for the levelling of the cemetery construction earlier in the 20th century. Different intensity magnitudes correspond to different amounts of each phase as summarised in Table 3.

Soil microstructure
The scanning electronic microscopy equipment used in this study is a FEI Quanta FEG ESEM. No conductive metallic coating was required in the preparation stage owing to the capability of the ESEM machine in creating low vacuums and applying water vapour as a conductive agent. Powders of dry samples were stucked to carbon tape, and micrographs were obtained by an accompanying voltage of 10 kV. ESEM micrographs of the soil samples are depicted in Figure 4. The grain topography of the soil samples exhibit similarities in microstructures, which consist of semi-rounded to rounded particles and conglomerates.

X-ray diffraction
XRD is an important characterisation tool in identifying and quantifying minerals. To complement the characterisation of soils

<table>
<thead>
<tr>
<th>Soil Sample</th>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
<th>Gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steele’s 0.5 m</td>
<td>0.47</td>
<td>0.28</td>
<td>0.21</td>
<td>0.04</td>
</tr>
<tr>
<td>Lone Pine</td>
<td>0.32</td>
<td>0.32</td>
<td>0.35</td>
<td>0.01</td>
</tr>
<tr>
<td>NEK 1</td>
<td>0.28</td>
<td>0.38</td>
<td>0.29</td>
<td>0.05</td>
</tr>
<tr>
<td>Quinn’s Post</td>
<td>0.25</td>
<td>0.38</td>
<td>0.35</td>
<td>0.02</td>
</tr>
<tr>
<td>NEK 2</td>
<td>0.25</td>
<td>0.43</td>
<td>0.30</td>
<td>0.025</td>
</tr>
<tr>
<td>Johnston Jolly</td>
<td>0.23</td>
<td>0.32</td>
<td>0.41</td>
<td>0.04</td>
</tr>
<tr>
<td>Steele’s 5 m</td>
<td>0.19</td>
<td>0.31</td>
<td>0.50</td>
<td>0.01</td>
</tr>
<tr>
<td>No.2 Outpost</td>
<td>0.19</td>
<td>0.47</td>
<td>0.34</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 2 Soil grain size fractions by mass

Soils from ANZAC battlefield

Soils from ANZAC battlefield


Jolly site), and further identification of the exact clay phase is unlikely to bear a compelling difference on the overall results.

**Dielectric constant**

This section summarises the results of the dielectric constant measurements, starting with the *in situ* state measurements. These are followed by real and imaginary dielectric constants measurement results for a range of water contents (oven dried to saturation) at several frequencies. The dielectric spectrum between 200 MHz to 6 GHz is then investigated for this water content range. The effects of clay content on dielectric behaviour as well as attenuation coefficient related to GPR are discussed at last.

**Dielectric constant at natural water content**

Samples were tested initially in their *in situ* state for dielectric measurements. Natural water contents were subsequently measured by the oven-drying method (Standards Australia 2005). The *in situ*-state dielectric permittivity spectrum measured between 200 MHz to 6 GHz at natural gravimetric water contents \( w \) are summarised and illustrated in Figure 6. Gravimetric water content \( w \) of each sample is mentioned at the corresponding plot.

Due to the low water content of the samples (except “Steele’s 0.5 m”), the real and imaginary dielectric constants are relatively low, and the dispersion tends to be small as well. The reasoning behind this behaviour is that upon applying the EM field, there are no many dipoles (i.e., water molecules) available that can get polarised. In addition, within this range of frequency where most of the dispersion is due to bound water polarisation, samples with low clay content (e.g., No.2 Outpost) exhibit minimal dispersion.

**Real dielectric constant variation with water content at various frequencies**

In addition to the natural water content, real dielectric constants have been measured for water contents ranging from oven-dried to nearly the saturation point (degree of saturation around 90%, exact values shown in the figure). This information may be critical (and useful) when interpreting geophysical results and/or selecting either dry or wet seasons to conduct geophysical prospecting in these study areas. Figure 7 shows the variations of the measured real dielectric constants \( \kappa' \) with volumetric water content \( \theta \) at selected frequencies. The results correspond to disturbed samples.

The real dielectric constant values are presented for frequencies that are common in a variety of geophysical applications. These frequencies are 200 MHz, 500 MHz, and 1 GHz, which
are used in GPR as well as point sensor applications such as time-domain reflectometry probes and LIDAR. Higher frequencies were also used, which are popular in remote sensing applications covering L-band and S-band, as well as, partially, C-band (i.e., 4, 5, and 6 GHz).

As shown in Figure 7, for low volumetric water content samples (i.e., below 10%), the effect of frequency on the real dielectric constant is insignificant. However, the effect of frequency emerges as the volumetric water content increase and the real dielectric constant becomes dependent on the frequency of measurements. This effect is more pronounced for samples with higher clay content (e.g., Steele’s 0.5 m), whereas samples with low clay content (e.g., No.2 Outpost and Johnston Jolly) show marginal sensitivity to frequency (within the range studied here).

The general trend for all of the samples resembles the Topp correlations; however, discrepancies have been observed. The frequency of measurements and other soil characteristics such as mineralogy and grain size distribution can be taken into account to understand these site-specific responses. Generally speaking, higher frequency of measurements (>1 GHz) yields a lower real dielectric constant for a given volumetric water content. This is due to the fact that, as frequency increases, dipoles do not have
enough time to reach maximum polarisation. At the same time, samples with higher sand content exhibit less dependence on the frequency of these measurements because of the relatively small specific surface area of the soil, thus a lower chance of bound water polarisation.

The simultaneous effects of frequency $f$ and volumetric water content $\theta$ on the real dielectric constant of all samples are captured together in Figure 8(a). As the frequency increases, the real dielectric constant decreases at a given water content. Moreover, this effect is more dominant for wet samples compared against dry samples where there exist a higher number of dipolar molecules (i.e., water) within the matrix. Figure 8(b) shows a selected set where trendlines have been fitted for frequencies that are common in geophysical applications. The Topp correlation is also shown (solid black line) which provides a good estimate of the real dielectric constant for dry samples as well as samples with a volumetric water content greater than 0.4. However, this correlation seems to underesti-

![Figure 7](image.jpg)
At frequencies below 1 GHz, the imaginary dielectric constant increases with water content but only up to approximately 30%, beyond which it starts to decrease. This first increase in the imaginary dielectric constant is due to the increase in conductivity $\sigma$ as a result of more ions coming into solution in the porewater, following equation (3). However, once all of the ions available in the soil matrix are dissolved, then the conductivity will decrease as the porewater ion solution concentration decreases following Archie’s law. This water content at which the decreasing trend appears is called critical water content by Santamarina et al. (2001) and seems to be around 30% volumetric water content. This whole increase–decrease behaviour was also reported by Wensink (1993) for clayey soil and suggested for sand and saline water mixture by Lasne et al. (2008). However, as the frequency $f$ increases, hence $\omega$, the effect of conduction losses on the imaginary dielectric constant is reduced (see the second term on the right-hand side of equation 3) and the effects observed in the imaginary dielectric constant become primarily due to the polarisation losses, thus rendering no longer a decrease in the dielectric constant, as observed for frequencies above 1 GHz in the figure.

Imaginary dielectric constant versus water content at various frequencies

Imaginary dielectric constants were also measured simultaneously with the real part. This parameter accounts for losses due to polarisation and conduction as described in equation (3). Figure 9 shows the relationship between the imaginary dielectric constant and the soil volumetric water content at the nominated frequencies for these disturbed samples. Maximum degree of saturation $S$ is included in each plot.

<table>
<thead>
<tr>
<th>Marker</th>
<th>$f$ (GHz)</th>
<th>Equation</th>
<th>$R^2$</th>
<th>Caption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contour lines (8a)</td>
<td>All</td>
<td>$0 = -0.051 + 0.013 f + 0.014 \kappa - 0.01 \kappa^2 + 0.002 f \kappa + 0.003 \kappa^3$</td>
<td>0.94</td>
<td>Equation (5)</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
<td>$\kappa = 242.9 \theta^3 - 231.9 \theta^2 + 123.9 \theta + 2.7$</td>
<td>0.93</td>
<td>Equation (6)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>$\kappa = 163.9 \theta^3 - 155 \theta^2 + 100.1 \theta + 2.7$</td>
<td>0.95</td>
<td>Equation (7)</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>$\kappa = 151.9 \theta^3 - 136.8 \theta^2 + 90.5 \theta + 2.9$</td>
<td>0.95</td>
<td>Equation (8)</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>$\kappa = 142.3 \theta^3 - 118.8 \theta^2 + 79.9 \theta + 2.8$</td>
<td>0.96</td>
<td>Equation (9)</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>$\kappa = 133.5 \theta^3 - 111.6 \theta^2 + 77.2 \theta + 2.8$</td>
<td>0.96</td>
<td>Equation (10)</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>$\kappa = 119.7 \theta^3 - 103.3 \theta^2 + 74.7 \theta + 2.8$</td>
<td>0.96</td>
<td>Equation (11)</td>
</tr>
<tr>
<td>Topp</td>
<td></td>
<td>$\kappa = -76.7 \theta^3 + 146 \theta^2 + 9.3 \theta + 3.03$</td>
<td>0.76</td>
<td>Equation (12)</td>
</tr>
</tbody>
</table>

$\theta = $ Volumetric water content. $f = $ Frequency (GHz). $\kappa' = $ Real dielectric constant.

At frequencies below 1 GHz, the imaginary dielectric constant increases with water content but only up to approximately 30%, beyond which it starts to decrease. This first increase in the imaginary dielectric constant is due to the increase in conductivity $\sigma$ as a result of more ions coming into solution in the porewater, following equation (3). However, once all of the ions available in the soil matrix are dissolved, then the conductivity will decrease as the porewater ion solution concentration decreases following Archie’s law. This water content at which the decreasing trend appears is called critical water content by Santamarina et al. (2001) and seems to be around 30% volumetric water content. This whole increase–decrease behaviour was also reported by Wensink (1993) for clayey soil and suggested for sand and saline water mixture by Lasne et al. (2008). However, as the frequency $f$ increases, hence $\omega$, the effect of conduction losses on the imaginary dielectric constant is reduced (see the second term on the right-hand side of equation 3) and the effects observed in the imaginary dielectric constant become primarily due to the polarisation losses, thus rendering no longer a decrease in the dielectric constant, as observed for frequencies above 1 GHz in the figure.

It is apparent that the imaginary component is also dependent on water content; however, this dependence is less evident in comparison with the relationship between the real component of the dielec-
that the dependence between the imaginary dielectric constant and the frequency decreases at higher frequencies as previously stated.

Similar to the real dielectric constant, the simultaneous effects of water content and frequency on the imaginary part of all samples can be captured together. However, due to the different behaviour of the imaginary component with respect to low and high measurements’ frequencies, these will be divided into two groups.

Figure 10(a) and (b) show the imaginary dielectric constant data for frequencies below and above 1 GHz, respectively. As it
will manifest more strongly due to the effect of free water polarisation as the shape of the contour lines suggests. Comparison between the coefficient of the fitted surfaces (see Table 5) shows that the effect of frequency within this range (i.e., ≥ 1 GHz) is less significant and the effect of water content is dominating.

Lastly, Figure 10(c) summarises the results of imaginary dielectric constant for all the tested soil samples at selected frequencies, including trendline equations for selected frequencies shown by the coloured dashed lines, which are also included in Table 5. It has been shown in the previous section as well as in literature that the relationships between the real dielectric constant and volumetric water content estimation can be highly dependent on many other variables such as mineralogy and clay content; therefore, a single universal calibration is not ideal to be used for different soil types. Alternatively, the results in

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**Figure 10** Simultaneous effects of frequency and water content on the imaginary dielectric constant. The dashed lines correspond to fitted line at the nominated frequencies. (a) \( f < 1 \) GHz. (b) \( f \geq 1 \) GHz. (c) Selected frequencies (0.2, 0.5, 1, 4, 5, and 6 GHz).
Soils from ANZAC battlefield

Dielectric constant

Figure 10(c) show a better linear correlation between imaginary dielectric constant and volumetric water content at higher frequencies (i.e., ≥ 4 GHz shown by the solid black line), which is less dependent on clay content and other influencing variables. This \( \kappa'' \) could be used as a better alternative over \( \kappa' \) for correlating soil water content, especially when dealing with soils with high clay content.

Higher frequency of measurement (i.e., ≥ 4 GHz) of imaginary dielectric constant returns similar values. Therefore, a linear calibration between the volumetric water content and the imaginary dielectric constant is suggested as equation (21), which is shown by the solid black line.

Real and imaginary dielectric dispersion (200 MHz – 6 GHz)

Dielectric dispersion for real and imaginary parts is plotted for all of the samples between 200 MHz and 6 GHz in Figure 11. Results of measurements for undisturbed samples are also included, which shows similar results to the disturbed (i.e., mixing method) samples. Dashed lines illustrate the pattern of variation of the dispersion against the volumetric water content. The general trend for the imaginary dispersion is similar among all soils and manifest the shape of the plots observed in Figure 9, whereas the real part dispersion has a proportional trend until it reaches a plateau close to the saturation point. Close to the saturation point, due to the increase in the free water, the dispersion is dominant by the free water molecules rather than soil and water matrix. Hence, the real dielectric dispersion does not change significantly.

The imaginary dielectric dispersion over the same range of water content reaches a maximum and further reduces toward the saturation point. This phenomenon can be explained as follows: as the water content increases, for a given amount of ions in soil, the conductivity increases hence the dispersion. Nonetheless, as the water content keeps increasing for a constant amount of ions available, the conductivity decreases, and this leads to a decrease in the magnitude of imaginary dielectric dispersion.

Table 5 Summary of Figure 10 fitted trendline and surface equations

<table>
<thead>
<tr>
<th>Marker</th>
<th>( f ) (GHz)</th>
<th>Equation</th>
<th>( R^2 )</th>
<th>Caption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contour lines (10a)</td>
<td>&lt; 1 GHz</td>
<td>( 0 = 0.05 – 0.08 f + 0.002 \kappa' + 0.015 \kappa'' + 0.06 f \kappa'' ) + 0.082 ( f^2 + 0.013 f^3 \kappa'' – 0.07 f^3 \kappa'' )</td>
<td>0.55</td>
<td>Equation (13)</td>
</tr>
<tr>
<td>Contour lines (10b)</td>
<td>≥ 1 GHz</td>
<td>( 0 = – 0.02 + 0.023 f + 0.01 \kappa' – 0.017 f^2 + 0.06 f \kappa'' + 0.005 f^3 \kappa'' )</td>
<td>0.82</td>
<td>Equation (14)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \kappa'' = – 66.4 0^3 – 88.6 0^2 + 94 0 + 0.8 )</td>
<td>0.65</td>
<td>Equation (15)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \kappa'' = 15.6 0^3 – 77.7 0^2 + 53 0 + 0.5 )</td>
<td>0.69</td>
<td>Equation (16)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \kappa'' = 2.2 0^3 – 37.4 0^2 + 29.5 0 + 0.3 )</td>
<td>0.73</td>
<td>Equation (17)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \kappa'' = 43.9 0^3 – 30.4 0^2 + 18.5 0 + 0.003 )</td>
<td>0.85</td>
<td>Equation (18)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \kappa'' = 49.2 0^3 – 28 0^2 + 17.8 0 – 0.07 )</td>
<td>0.86</td>
<td>Equation (19)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \kappa'' = 56.6 0^3 – 28.1 0^2 + 17.8 0 – 0.13 )</td>
<td>0.86</td>
<td>Equation (20)</td>
</tr>
<tr>
<td></td>
<td>≥ 4 GHz</td>
<td>( \kappa'' = 15.01 0 – 0.12 )</td>
<td>0.84</td>
<td>Equation (21)</td>
</tr>
</tbody>
</table>

\( \theta = \text{Volumetric water content}. \ f = \text{Frequency (GHz)}. \ \kappa'' = \text{Imaginary dielectric constant}. \)

Attenuation coefficient

The attenuation coefficient is a crucial parameter in adopting the correct method in geophysical surveys. It depends on a number of parameters ranging from soil type, water content, conductivity, and the measurements frequency of geophysical survey. For the samples recovered from the ANZAC battlefield, the coefficients of attenuation are calculated at 200 MHz from dry condition to saturation. This is a typical frequency that is used in archaeological GPR prospections. The attenuation coefficient in decibel per metre (dB/m) is calculated as follows:

\[
\alpha = \frac{8.868 \omega}{c_0} \sqrt{\frac{\kappa'-\kappa''}{2}} \sqrt{(1 + \tan^2 \delta) - 1} \tag{5}
\]

where \( c_0 \) is the speed of light (2.998 × 10^8 m/s), \( \omega \) is the angular frequency, and \( \delta = \kappa'' / \kappa' \), which is known as tangent loss (Salat and Junge 2010).

Figure 13 shows the attenuation coefficient variation with volumetric water content. The coefficient of attenuation for dry samples varies between zero and 27, with the highest value corresponding to the soil with the highest clay fraction. The highest attenuation coefficient value is approximately 230 (dB/m). Generally, at a given water content, the clay fraction and the...
coefficient of attenuation are proportional. However, beyond about 30% volumetric water content, conductivity $\sigma$ drops, and the attenuation coefficient decreases accordingly. This is tentatively explained by assuming that $\sigma$ is the sum of the porewater conductivity, which increases with water content until all the salts in the soil are dissolved into the water and then decreases because the concentration of the dissolved salts starts decreasing (Lasne et al. 2008; Wensink 1993).

The depth of penetration is inversely proportional to the attenuation coefficient, and it is typically referred to in GPR surveys. Basically, soils with higher conductivity, generally clays, exhibit larger coefficient of attenuation, and depth of penetration will be lower accordingly. On the contrary, samples with higher sand contents have a lower coefficient of attenuation leading to greater penetration depth for GPR surveys.

The operational frequency of the geophysical methods affects the depth of penetration with an inversely proportional relationship. The attenuation coefficient is analysed against the frequency of measurements for dry and 30% volumetric water content in Figure 14.

![Graphs showing dispersion magnitudes from 200 MHz to 6 GHz versus volumetric water content $\theta$.](image)

**Figure 11** Real and imaginary dispersion magnitudes from 200 MHz to 6 GHz versus volumetric water content $\theta$. 

Soils from ANZAC battlefield

Figure 12 Dielectric spectra from 200 MHz to 6 GHz at dry conditions (Volumetric water content $\theta = 0\%$) and at wet conditions ($\theta = 30\%$) for the soil samples from the eight sites. (a) Real dielectric spectrum. (b) Imaginary dielectric spectrum.

Figure 13 Attenuation coefficient at 200 MHz against volumetric water content (Clay content is colour coded). 30% volumetric water content border shown by a dashed black line.

At 30% volumetric water content, the attenuation rate resembles the shape of attenuation curve for a thin layer of water using the Debye equation as described by Koh and Kelley (2008). This shows that, for the tested soils at this water content, the attenuation coefficient is controlled by free water absorption. On the other hand, the curvature of dry conditions for ANZAC sites with high clay content is opposite, which suggests a different controlling mechanism when working with dry sites.

CONCLUSIONS

Geophysical and geotechnical characterisations have been conducted on soil samples recovered from eight sites at the ANZAC battlefield: No.2 Outpost, The NEK Cemetery, Quinn’s Post, Courtney’s and Steele’s Post, Johnston Jolly Cemetery, and Lone Pine. Due to the limited amount of soil allowed to be recovered from this region, only limited testing could be carried out, including grain size distribution, mineralogy, and grain topography. Geophysical testings included measurements of real and imaginary dielectric constants as well as computation of dielectric dispersion for a range of water contents (i.e., oven-dried to saturation point) within frequencies varying between 200 MHz and 6 GHz—which cover a range of field geophysical survey techniques (from GPR to remote sensing). The most important findings are summarised as follows:

• Soils from the ANZAC battlefield are mainly classified as clayey sand to sandy clay.
• The mineralogy of the samples is primarily comprised of quartz. Samples retrieved from Johnston Jolly contains a distinct higher amount of muscovite than other samples, perhaps due to material borrowing for the levelling of the cemetery construction earlier in the century.

• Dielectric properties of sites with higher clay content exhibits higher dependence on the frequency of measurement.

• Higher frequency of measurements (i.e., ≥ 4 GHz) tends to show a dielectric constant that is less dependent on frequency for both real and imaginary parts of dielectric constant.

• Real dielectric dispersion is strongly proportional to clay content in these sites.

• Site-specific empirical correlations between dielectric properties and volumetric water content and frequency were drawn from the characterisation. These correlations are helpful to plan further geophysical studies in this region, given that the generic universal correlations may not be accurate for these soils.

• Attenuation coefficients (hence the penetration depths) in GPR prospections show a wide range of values depending on the in situ water content condition. This will affect the seasons in which GPR prospection should be carried out as well as adapting a proper frequency range for the prospection.

• Geophysical prospection on the sites containing soil strata with higher clay content is recommended to be conducted towards the drier seasons of the year. On the other hand, when dealing with sites with soil strata comprising primarily of sand, wetter seasons will be also appropriate to conduct surveys. Nonetheless, generally dry seasons are suggested to be more suitable given the lower attenuation coefficient calculated for these sites.

• Vertical resolution and the depth of penetration can be determined by the provided attenuation coefficients for each site. Therefore, a suitable frequency could be adapted considering the time of the year (dry or wet season), which has impact on the likely soil water content conditions.

The information and analysis summarised in this article can be used by other researchers for the purpose of feasibility studies and planning to conduct geophysical surveys in the ANZAC sites. Essentially, the applicability of particular geophysical prospecting (e.g., GPR) to this site can be assessed based on the result of this petrophysical characterisation. Furthermore, other important aspects of geophysical prospecting such as appropriate time of the year (i.e., season) to conduct a survey, effective survey depth and vertical resolution can be determined accordingly. Lastly, the suggested site-specific empirical calibrations can be used to link soil parameters such as water content, as proxies to dielectric permittivity to further facilitate result interpretation for future geophysical studies in this iconic region.

ACKNOWLEDGEMENT

The authors would like to thank the Government of Turkey, Australia and New Zealand for supporting the Joint Historical and Archaeological Survey (JHAS) project, which provided the opportunity to acquire soil samples from the ANZAC battlefield; Prof. A. Sagona (JHAS leader) and Mr. C. Ogley for facilitating this work; Mr. R. Curtain from the Bio21 Institute of The University of Melbourne for assisting in producing the ESEM micrographs; and Dr. A. Stickland and Ms. L. Goodall for facilitating the XRD testing and analysis. XRD was performed at the Materials Characterisation and Fabrication Platform (MCFP) at the University of Melbourne and the Victorian Node of the Australian National Fabrication Facility (ANFF). This experimental work was primarily undertaken at the Geotechnical, Soil and Water Laboratory at The University of Melbourne.

REFERENCES


4 An Improved soil mixing dielectric model based on soil specific surface area

Following from the previous chapter, this chapter summarises the results of a laboratory experimental investigation on some geotechnical and geophysical characteristics of soil recovered from different geological formations in Melbourne. These data were combined with the data from the previous chapter and were used to modify the Dobson soil mixing dielectric model. More importantly, the data from this chapter have been used to develop new frequency- and site-specific mixture model as well as empirical relationships linking soil dielectric properties with its geotechnical parameters.

4.1 Motivation

Despite the existence of ‘universal’ models that are utilised in soil science, remote sensing and geotechnical applications that link the dielectric properties of soil to its water content, site and frequency specific dielectric models are typically desirable, for example for more accurate soil water content estimations. The provision of such models and calibrations, however, requires conducting separate measurements at each frequency, which makes this a resource-demanding exercise. Thus, here we have used the data collected from sites of particular interest for Australia to re-calibrate the Dobson soil mixing dielectric model. These models can aid in providing ground true data and models for an effective application of geophysical techniques in agriculture and hydrology disciplines for water resource and crop management. Furthermore, new frequency and site-specific models have been developed now using soil specific surface area as an input parameter governing the soil water dielectric behaviour.

4.2 Contribution towards manuscript

I was the primary researcher and the author of this work. The laboratory testing was partially conducted by graduate students Daniel Langley, Nick Withers and Daniel Popec under my direct supervision. I devised the research plan and carried out the data analysis and model development under the supervision and support of A/Prof Guillermo Narsilio.

4.3 Submitted manuscript

This section consists of a manuscript entitled "An Improved soil mixing dielectric model based on soil specific surface area", submitted to IEEE Transactions on Geoscience and Remote Sensing journal. The manuscript has been inserted in the following pages in a format which is consistent with this thesis.
An Improved Soil Mixing Dielectric Model Based on Soil Specific Surface Area

Authors: A. Orangi¹, G. A. Narsilio¹

¹The University of Melbourne, Department of Infrastructure Engineering, Parkville, VIC 3010.

1 Abstract

A new Soil Mixing Dielectric Model that accounts for the Specific Surface Area (SSA) of the soil is introduced (MSMDM-SSA). The dielectric properties of samples of different soil types collected from sites of interest to Australia were measured in the laboratory at different volumetric water contents. The data were used to evaluate and recalibrate the Dobson’s semi-empirical Soil Mixing Dielectric model (SMDM) for these Australian soils at 500 MHz, 1 GHz and 6 GHz, frequencies commonly used in geophysical explorations, and results were compared to the new model. The new MSMDM-SSA model showed superior predictive performance than other available models. The SSA fundamentally captures both textural and mineralogical soil composition, which are important for dielectric properties estimations. In addition, simple but robust site-specific empirical calibrations for these Australian soils have been developed. The improved models can be specifically used for soils from these regions as well as for soils with similar characteristics when planning and conducting geophysical prospections utilising Time Domain Reflectometry probes, Ground Penetrating Radars and remote sensing techniques.

2 Introduction

Soil water content is a crucial parameter in a range of engineering, agricultural, water resource management and climate science applications. Time Domain Reflectometry (TDR), Ground Penetrating Radar (GPR) and remote sensing are non-destructive electromagnetic measuring techniques that are becoming increasingly widespread which can facilitate accurate and fast measurements of soil water content (Galagedara, Parkin, Redman, von Bertoldi, & Endres, 2005; Noborio, 2001; Steelman, Endres, & Jones, 2012; Topp, Davis, & Annan, 1980). These techniques are based on measuring the dielectric properties of soils to indirectly measure soil moisture content without altering the soil structure or using nuclear-based methods such as neutron probes.

The Soil Mixing Dielectric Model (SMDM) developed by Dobson, Ulaby, Hallikainen, and El-rayes (1985) is based on the Lichtenecker and Rother (1931) model (typically known as LRM) which is commonly used to link the dielectric properties of soil to its water content in geotechnical and environmental applications, remote sensing studies and soil physics (Malicki, Plagge, Renger, & Walczak, 1992; Valery L Mironov, Dobson, Kaupp, Komarov, & Kleshchenko, 2004; Wagner & Scheuermann, 2009). The SMDM model was developed based on five soil samples over two frequency ranges namely; 0.3 GHz to 1.3 GHz and 1.4 GHz to 18 GHz and requires input parameters such as soil density and soil textural composition (i.e., sand and clay contents). On the other hand, empirical calibrations, which require fewer input parameters than the above mixing model, are widely used in geophysical prospections, such as those developed by Topp et al. (1980) and Roth, Malicki, and Plagge (1992). Despite the existence of these ‘universal’ models that link the dielectric properties of soil to its water
content, site and frequency specific dielectric models are typically desirable for more accurate soil water content estimations. The provision of such models and calibrations, however, requires conducting separate measurements at each frequency, which makes this a resource-demanding exercise.

Using the above universal models instead of site-specific ones can result in erroneous estimations in some instances (Comegna et al., 2013). Thus, here we have used data collected from sites of particular interest for Australia to re-calibrate Dobson et al.’s SMDM and to introduce new mixing models. To serve this purpose, soil samples were recovered from the iconic ANZAC battlefield site in Gallipoli, Turkey as well as from the different geological formations encountered in Victoria, Australia.

The ANZAC battlefield site is significant to Turkey, Australia and New Zealand, parts of the 1915 conflict. However, this region has not been physically studied in great detail but only between 2010-2014 by a Joint Historical and Archaeological Survey (JHAS) team, who amongst others, used non-invasive archaeological survey techniques such as GPR. Yet, at the time of the survey, no information was available about the dielectric characterisation of soils of this iconic region to assist with planning (Orangi & Narsilio, 2017). The models and calibrations developed in this present work can facilitate feasibility, planning and interpretation of geophysical investigations in this restricted-access study area. For instance, in GPR applications, such models can aid in result analysis and defining a framework to conduct future geophysical prospections within this battlefield. On the other hand, the state of Victoria has suffered from the Millennium Drought, the worst on record drought in south-eastern Australia, extending between 1997 and 2009. The Millennium Drought significantly and adversely affected agricultural production (CSIRO, 2012; Van Dijk et al., 2013). The information and models provided in the present study can also aid in providing ground truth data and models for an effective application of remote sensing techniques in agriculture, and in hydrological studies, for water resource and crop management (Liu, Van Dijk, de Jeu, & Holmes, 2009). Further, these models can be utilised as the bases for estimation and monitoring of soil water content and salinity, irrigation management which ultimately control crop health and production (e.g., Brown et al., 1993; Chen, Chen, Xu, & Yu, 2010; Dalton, Herkelrath, Rawlins, & Rhoades, 1984; Dobson & Ulaby, 1986; Grote, Hubbard, & Rubin, 2003; O’Brien, 1992; Steelman et al., 2012; Ven Chow, David Maidment, & Larry Mays, 1988).

However, there have not been any studies to characterise the dielectric properties of any of the above regions or to provide site-specific calibrations using soil textural parameters, that could be used in future geophysical prospections. There is only one study conducted by Orangi and Narsilio (2017) on the ANZAC soils where empirical calibrations were developed at certain frequencies without considering soil textural composition. Thus, in this work, a new SMDM based on Specific Surface Area (instead of Dobson et al.’s sand and clay contents) is introduced. The Specific Surface Area, SSA, has been suggested as the parameter ultimately controlling the dielectric properties of the water phase within a soil, thus a better representative of soil texture (Friedman, 1998; Fripiat, Cases, Francois, & Letellier, 1982; Hallikainen, Ulaby, Dobson, El-rayes, & Wu, 1985; Regalado, 2006; Robinson, Cooper, & Gardner, 2002). Furthermore, SSA has been recently recognised as a fundamental parameter controlling the
dielectric behaviour of soils with respect to water content and dry density (Orangi, Narsilio, Wang, & Ryu, 2019). In addition to the newly developed mixture model, an improved version of Dobson et al. (1985)’s Soil Mixing Dielectric Model (SMDM) for the ANZAC battlefield and Victorian soils at the frequencies typically used on different geophysical prospections and remote (satellite) sensing, i.e., 500 MHz, 1 GHz and 6 GHz is also presented. Finally, following up the same approach as (Dobson et al., 1985) and the recent findings reported in (Orangi et al., 2019), we have used the SSA to provide simple but robust polynomial calibrations at the same frequencies.

3 Theory and background: Soil dielectric permittivity

Geophysical techniques using electromagnetic waves typically rely on directly or indirectly measuring the soil dielectric permittivity or often referred to as permittivity. Dielectric permittivity, $\varepsilon$, is a complex number with a real component, $\varepsilon'$, and an imaginary component, $\varepsilon''$. The real component represents the polarisability of the material, while the imaginary component captures the energy loss when a material is subjected to an electromagnetic field:

$$\varepsilon = \varepsilon' - j\varepsilon''$$  \hspace{1cm} \text{Equation 1}

where, $j = \sqrt{-1}$. The energy loss occurs due to polarisation as well as conduction. Thus, if Equation 1 is further expanded and normalised by the permittivity of vacuum $\varepsilon_0$ ($\approx 8.85 \times 10^{-12} \text{F/m}$) then it can be rewritten as follow:

$$\kappa = \kappa' - j \left(\kappa'' + \frac{\sigma_{\text{DC}}}{\omega\varepsilon_0}\right)$$  \hspace{1cm} \text{Equation 2}

where $\kappa$ is the relative permittivity, $\kappa'$ is denoted as dielectric constant, $\kappa''$ represents the loss through polarisation, and $\frac{\sigma_{\text{DC}}}{\omega\varepsilon_0}$ represents the loss due to conduction. $\sigma_{\text{DC}}$ and $\omega_0$ is the angular frequency equal to $2\pi f$ with $f$ being the frequency in Hz. These two losses are collectively known as the loss factor. As Equation 2 suggests, at lower frequencies the effect of conduction losses $\sigma_{\text{DC}}$ will be dominant whereas at higher frequencies the polarisation losses $\kappa''$ are dominant.

Each phase within the matrix of an unsaturated soil (solid, liquid, and gas) has distinct dielectric properties. Furthermore, within the liquid phase of the soil, typically water, one can distinguish free water and bound water (Or & Wraith, 1999; Santamarina, Klein, & Fam, 2001). Free water is essentially the water molecules that are not affected by the solid particles’ molecular forces, hence, they can freely move within the soil matrix when subjected to external forces such as electromagnetic fields. Conversely, bound water includes the water molecules which are tightly bounded to the solid particles due to osmosis and matric forces (Hallikainen et al., 1985). Due to the significant forces acting upon bound water molecules, they exhibit substantially different dielectric properties to that of free water (Boyarskii, Tikhonov, & Komarova, 2002; Friedman, 1998; Fripiat et al., 1982; Hoekstra & Doyle, 1971; Ishida & Makino, 1999; Jones & Or, 2002; Regalado, 2006; Robinson et al., 2002). From an electromagnetic perspective, therefore, soil is a four-component dielectric mixture of solid, free water, bound water and air. Based on the significant difference between the dielectric properties of water and that of solids and air, the dielectric properties of a soil are greatly affected by water and its interaction with other phases. The interaction between water and solid particles apportions the water phase into free and
bound components. Table 1 summarises the dielectric properties of the individual phases at a reference 1 GHz frequency.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Material</th>
<th>$\kappa'$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid</td>
<td>Solid particles</td>
<td>2-15</td>
<td>(Daniels, 1996; Davis &amp; Annan, 1989; Wagner et al., 2013; Ulaby, Moore, &amp; Fung, 1981; Wagner &amp; Scheuermann, 2009)</td>
</tr>
<tr>
<td>Liquid</td>
<td>Free water</td>
<td>80*</td>
<td>(Daniels, 1996; Davis &amp; Annan, 1989; Schön, 2015; Udo, 2007)</td>
</tr>
<tr>
<td></td>
<td>Bound water</td>
<td>10-50*</td>
<td>(Dobson et al., 1985; Or &amp; Wraith, 1999; Pennock &amp; Schwan, 1969)</td>
</tr>
<tr>
<td>Gas</td>
<td>Air</td>
<td>1</td>
<td>(Daniels, 1996; Davis &amp; Annan, 1989; Schön, 2015; Ulaby et al., 1981)</td>
</tr>
</tbody>
</table>

* at 1 GHz

Moreover, the dielectric permittivity of water is frequency dependent while the other phases dielectric properties are frequency independent within the microwave (300 GHz <) regions (Wagner et al., 2013). Temperature is another parameter which affects the dielectric properties of water, however, will not be considered in this work since all the testing was conducted in the laboratory at around 20°C.

In view of the frequency dependent dielectric behaviour of water, these properties are normally described by the modified Debye equations:

$$\kappa'_{fw} = \kappa_{w0} + \frac{\kappa_{w0} - \kappa_{w\infty}}{1 + (2\pi f \tau_w)^2}$$  \hspace{1cm} \text{Equation 3}

$$\kappa''_{fw} = \frac{2\pi f \tau_w (\kappa_{w0} - \kappa_{w\infty})}{1 + (2\pi f \tau_w)^2} + \frac{\sigma_{DC}}{\omega \varepsilon_0}$$  \hspace{1cm} \text{Equation 4}

where $\kappa_{w\infty}$ is the high frequency limit of water permittivity equal to 4.9, $\kappa_{w0}$ is the low frequency limit of water permittivity equal to 80.1, $\tau_w$ is relaxation time for free water and $\sigma_{DC}$ is the effective conductivity of water. The graphical representation of the relative permittivity of water (i.e., Equations 3 and 4) are shown in Figure 1 where the frequency dependency of dielectric properties of water is captured by dielectric relaxation, $\Delta \kappa$. 

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Figure 1. The frequency-dependent behaviour of free water dielectric properties at 20 °C based on Debye (Black dash line) and modified Debye (Blue dash line) equations. $\kappa_{\infty}$: the high frequency limit of water permittivity, $\kappa_{\omega_0}$: the low frequency limit of water permittivity, $\sigma_{DC}$: the effective conductivity of water and $\Delta \kappa$: dielectric relaxation. L, S, C represent remote sensing application frequency bands. The operational frequency ranges for common geophysical techniques are also shown. Adapted from (Robinson et al., 2008).

3.1 Dielectric mixture models

In order to link the dielectric properties of soil to the dielectric properties of its constituent, there exist physical theoretical mixture models and material specific empirical equations in the literature. The general format of the theoretical mixture models is based on the refractive volumetric mixing model suggested by Lichtenecker and Rother (1931) (typically known as LRM):

$$\kappa^\alpha = \sum_i V_i \kappa_i^\alpha$$ \hspace{1cm} (Equation 5)

where $V_i$ represents the volume fraction of each phase and $\alpha$ is a parameter that varies between 1 and -1. When applied to a moist soil, this may be written as follow:

$$\kappa^\alpha = V_s \kappa_s^\alpha + V_a \kappa_a^\alpha + V_{fw} \kappa_{fw}^\alpha + V_{bw} \kappa_{bw}^\alpha$$ \hspace{1cm} (Equation 6)

where the subscripts $s$, $a$, $fw$ and $bw$ correspond to solid, air, free water and bond water, respectively. Since the properties of the bound water phase are not particularly well known, Dobson et al. (1985) suggested to adopt the following approximation to account for the contribution of bound water to the dielectric properties of the matrix:

$$\theta^\beta \kappa_{fw}^\alpha = V_{fw} \kappa_{fw}^\alpha + V_{bw} \kappa_{bw}^\alpha$$ \hspace{1cm} (Equation 7)

where $\theta$ is the volumetric water content, $\beta$ is a textural parameter that depends on the composition of the soil and $\alpha$ is known as the shape factor, usually derived as a fitting parameter.
According to (Emmerich, Bonitz, & Kupfer, 2011) accuracy have initially been adapted to a particular frequency \( f \) and for ionic conductivity losses based on soil texture.

\[
\kappa' = \left[ 1 + \frac{\rho_b}{\rho_s} (\kappa_s \alpha_s^a - 1) + \theta \beta' \kappa'_w^\alpha - \theta \right]^{1/\alpha}
\]

Equation 8

\[
\kappa'' = \left[ \theta \beta'' \kappa''_w^\alpha \right]^{1/\alpha}
\]

Equation 9

where \( \kappa_s \approx 4.7, \beta' \) and \( \beta'' \) are soil type dependent textural composition parameters which were determined experimentally by Dobson et al. (1985) as follow:

\[
\beta' = 1.2748 - 0.00519S - 0.00152C
\]

Equation 10

\[
\beta'' = 1.33979 - 0.00603S - 0.00166C
\]

Equation 11

where \( S \) and \( C \) are the sand and clay percentages, respectively.

The dielectric properties of the water phase can be estimated based on the modified Debye equation (given in Equations 3 and 4). Equation 4 was further modified by Dobson et al. (1985) and accounts for ionic conductivity losses based on soil texture.

\[
\kappa''_w = \frac{2\pi f \tau_w (\kappa_w - \kappa_w^{00})}{1 + (2\pi f \tau_w)^2} + \frac{\sigma_{eff}}{2\pi \varepsilon_0} \left( \frac{\rho_s - \rho_b}{\rho_s \theta} \right)
\]

Equation 12

The second term on the right-hand side of Equation 12 is an empirical parameter accounting for direct effective conductivity of soil, derived based on soil textural composition and dry density. Dobson et al. (1985) suggested that for the frequency range between 1.4 GHz and 18 GHz:

\[
\sigma_{eff} = -1.645 + 1.939\rho_b - 0.0225622S + 0.01594C
\]

Equation 13

and for the frequency range between 0.3 and 1.3 GHz:

\[
\sigma_{eff} = 0.0467 + 0.2204\rho_b - 0.004111S + 0.006614C
\]

Equation 14

On the other hand, according to Archie’s Law, the conductivity of a soil-water mixture (with no surface layer conduction) can be expressed as follow:

\[
\sigma_{eff} = a \sigma_w S_s c \left( \frac{\rho_s - \rho_b}{\rho_s} \right)^m
\]

Equation 15

where \( a, c \) and \( m \) are fitting parameters, \( S_s \) is the degree of saturation and \( \sigma_w \) is the fluid conductivity. We will be adapting Archie’s Law format in order to modify the SMDM in later sections.

Apart from the SMDM, there exist other mixing models which are essentially based on the initial Lichtenecker and Rother (1931) model (given in Equation 5), where different parameters have been introduced such as temperature and other fitting parameters in order to improve the accuracy of the models (Mironov et al., 2004; Mironov, Kosolapova, & Fomin, 2009; Wagner, Emmerich, Bonitz, & Kupfer, 2011). Considering all the required inputs for these mixing models, it is possible that not all of these parameters are readily available for specific soils or poorly suited to a particular frequency (Hallikainen et al., 1985). For certain applications,
therefore, it is preferable to use empirical models such as (e.g., Dasberg & Hopmans, 1992; Jacobsen & Schjønning, 1993; Roth et al., 1992; Topp et al., 1980) or more advanced models such as the semi-empirical calibration by Hallikainen et al. (1985). The latter model uses some physical parameters (i.e., textural composition parameters) of the soils in the establishment of the multipliers of the empirical calibration. The general format of the empirical calibrations is as follow:

\[ \kappa' = A + B \cdot \theta + C \cdot \theta^2 + D \cdot \theta^3 \]  

Equation 16

There are numerous empirical calibrations derived for different soil types in the literature. Table 2 shows selected empirical calibrations that are used in this context.

<table>
<thead>
<tr>
<th>Calibration</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>Number of soil samples and soil types used for calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topp et al. (1980)</td>
<td>3.03</td>
<td>9.3</td>
<td>146</td>
<td>-76.7</td>
<td>4 samples, inorganic minerals ranging from clay to sandy loam</td>
</tr>
<tr>
<td>C. Roth et al. (1992)</td>
<td>2.87</td>
<td>-11.10</td>
<td>276</td>
<td>-272</td>
<td>9 samples, clayey sand, clayey silt, silty sand, sandy clay, silty clay, clayey silt</td>
</tr>
<tr>
<td>Jacobsen and Schjønning (1993)</td>
<td>2.9</td>
<td>39.6</td>
<td>81</td>
<td>-76</td>
<td>5 samples clayey sand, silty sand with minimal organic content</td>
</tr>
<tr>
<td>Dasberg and Hopmans (1992)</td>
<td>2.7</td>
<td>38.4</td>
<td>44</td>
<td>-48</td>
<td>2 samples, sandy and clayey loam</td>
</tr>
</tbody>
</table>

Amongst the abovementioned calibrations, Topp et al. (1980) is the most frequently applied and cited. This calibration was derived based on measurements on non-organic soil samples using Time Domain Reflectometry at 1 GHZ (Topp et al., 1980). Although Topp et al.’s calibration was initially taken as ‘universal’ and applicable to all soil types within a measurement frequency range between 1 MHz and 1 GHz, it is now known that this calibration is not suitable for at lower (or higher) frequencies particularly for fine-grained soils, due to the significant presence of bound water. Bound water polarisation has minimal effects on the soil dielectric permittivity at around 1 GHz, however, the effects of bound water polarisation increases with decreasing frequency. This effect is notorious in clays and some silts (the dielectric permittivity increases with decreasing frequency) but is minimal for sandy soils for
which the effects of bound water are negligible (Dasberg & Hopmans, 1992; Dirksen & Dasberg, 1993; Or & Wraith, 1999). Thus, frequency specific models that also consider soil types are desirable and more accurate for certain applications.

We have focused on 500 MHz, 1 GHz and 6 GHz frequencies in this present work because of their significance for in-situ geophysical investigations (the operational frequency ranges for common geophysical techniques alongside the dielectric relaxation behaviour of free water were shown in Figure 1). For instance, 500 MHz and 1 GHz correspond to point sensors such as TDR as well as Ground Penetrating Radar surveys, while 1 GHz and 6 GHz are dominant in remote sensing applications for L- and C-bands.

Based on the preceding discussion, the aim of this work is to develop and provide new models and calibrations which are derived based on frequency and meaningful soil physical input parameters. Thus, in this paper, we have first evaluated the performance of the SMDM against experimental data for each soil group tested (i.e., ANZAC soils and Australian soils). Secondly, we have improved the accuracy of the SMDM by providing site-specific functions for textural composition parameters (i.e., $\beta'$ and $\beta''$) as well as effective conductivity $\sigma_{eff}$ for each individual soil group at the nominal frequencies of 500 MHz, 1 GHz and 6 GHz. This approach was further refined by introducing Specific Surface Area as a new input parameter for $\beta'$ and $\beta''$ as well as effective conductivity $\sigma_{eff}$. Lastly, we suggest simple polynomial calibrations for the Australian soils that are based on using the Specific Surface Area at the nominal frequencies in these new and improved models.

4 Material and methods

This section elaborates on the soil samples characteristics and the experimental procedure adopted throughout this work to obtain the dielectric properties of the soil samples.

4.1 Soil sample characterisation

Soil samples were collected from two distinct regions of the world. Nine samples were collected from the ANZAC battlefield site located in Gallipoli, Turkey and another five samples were retrieved from distinct geological formations across Victoria, Australia. Table 3 summarises the geotechnical characteristics of the soil samples.
Table 3. Characterisation of soil samples.

<table>
<thead>
<tr>
<th>Soil Group</th>
<th>Sample</th>
<th>D&lt;sub&gt;50&lt;/sub&gt; (mm)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
<th>SSA* (m&lt;sup&gt;2&lt;/sup&gt;/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANZAC Soils†</td>
<td>No. 2 Outpost</td>
<td>0.032</td>
<td>18</td>
<td>48</td>
<td>33</td>
<td>NA†</td>
</tr>
<tr>
<td></td>
<td>Steel C</td>
<td>0.075</td>
<td>18</td>
<td>31</td>
<td>49</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Johnston Jolly</td>
<td>0.047</td>
<td>23</td>
<td>37</td>
<td>38</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>NEK B</td>
<td>0.021</td>
<td>25</td>
<td>45</td>
<td>28</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Quinn’s Post</td>
<td>0.024</td>
<td>25</td>
<td>42</td>
<td>31</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>NEK A</td>
<td>0.02</td>
<td>28</td>
<td>40</td>
<td>31</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Lone Pine</td>
<td>0.014</td>
<td>32</td>
<td>36</td>
<td>32</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Steel B</td>
<td>0.015</td>
<td>34</td>
<td>35</td>
<td>27</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Steel A</td>
<td>0.0036</td>
<td>47</td>
<td>31</td>
<td>20</td>
<td>NA</td>
</tr>
<tr>
<td>Australian Soils</td>
<td>Brighton Group Sand (BG)</td>
<td>0.32</td>
<td>0</td>
<td>3</td>
<td>97</td>
<td>8‡</td>
</tr>
<tr>
<td></td>
<td>Silurian Mudstone (SM)</td>
<td>0.018</td>
<td>20</td>
<td>51</td>
<td>29</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Coode Island Silt (CIS)</td>
<td>0.011</td>
<td>25</td>
<td>56</td>
<td>19</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>Basaltic Clay (BC)</td>
<td>0.0005</td>
<td>63</td>
<td>29</td>
<td>8</td>
<td>257</td>
</tr>
<tr>
<td></td>
<td>Bentonite (BENT)</td>
<td>0.001†</td>
<td>81</td>
<td>19</td>
<td>0</td>
<td>526</td>
</tr>
</tbody>
</table>

*European Standard spot test: Water-based methylene blue (a detailed procedure in Kandhal and Parker (1998) and Santamarina, Klein, Wang, & Prencke, 2002)
†Due to the limited amount of soil allowed to be collected at this site, SSA measurements could not be conducted
‡BET method (Brunauer, Emmett, & Teller, 1938)
†D<sub>80</sub>

It is worthwhile mentioning that the ANZAC soils were collected from a relatively small area, rendering similar mineralogy mainly composed of quartz (Orangi & Narsilio, 2017). The geology of the ANZAC soils region corresponds to the Miocene formation, and the soil in the area is classified as Noncalcic Brown and Rendzina soil material (Bingöl, 1989; European Soil Portal, 1954). On the other hand, the Australian soils (from metropolitan Melbourne, except the Bentonite which was sourced from a mine) are rather from different geological formations and are quite distinct: the Brighton Group Sand (BG) corresponds to range in age from the late Miocene into the Pliocene, the Silurian Mudstone (SM) is a highly weathered clay form Silurian age, the Coode Island Silt (CIS), as is locally known, is really a clay from the Holocene age. The Basaltic Clay (BC) is derived from the weathering of basaltic lava of Late Oligocene to Middle Miocene (Geoscience Australia, 2018; School of Historical & Philosophical Studies, 2008). The different mineralogical formation of the Australian soil group, therefore, allows for the evaluation of utilising the Specific Surface Area in the new models.

4.2 Soil sample preparation

Soil samples were crushed and thoroughly mixed with deionised water until a homogeneous mixture was obtained. Samples were allowed to cure for at least 24 hours in sealed containers (For soils with higher clay content this curing duration often extended to 48 hours or 7 days). Subsequently, the samples were remixed, subsequently, to ensure a homogeneous mixture was attained. The soils were then transferred into non-ferromagnetic (PVC) containers of known volume to determine soil density and to measure the soil dielectric properties without interference. The process was repeated to obtain samples of different moisture content by varying the initial amount of deionised water used to generate the mixtures. This was the
procedure used for the Australian soils. However, since a limited amount of soil was allowed to be collected from the ANZAC battlefield site by the local authorities, the samples were firstly prepared at the highest possible water content (when no free drainage was visible). Dielectric measurements took place over time as the sample(s) dried out. Following these procedures, the dielectric measurements for each soil sample at different water contents were obtained.

It is important to note that the Australian soil samples were prepared at a range of dry densities for a given gravimetric water content. This approach provided samples with different volumetric water contents as well as allowing an evaluation of the effects of dry density on the dielectric properties of soil by grouping soils with similar volumetric water content. For the ANZAC soil samples, however, we attempted to conduct the dielectric measurements at relatively constant dry densities due to the available amount of soil samples, as explained in Chapter 3. For the purpose of this study, however, we did not directly investigate the dry density effects in our models, however, densities of the samples are calculated and considered in the developments of the models. The effects of dry density on dielectric properties of soils have been investigated in a separate study and will be discussed in Chapter 5 (Orangi et al., 2019).

4.3 Dielectric measurement

The measurements of the dielectric properties of the soil samples were conducted using a 2.2mm Agilent coaxial slim form probe connected to an N9923 FieldFox Vector Network Analyser. For each measurement, a dielectric spectrum was produced based on measuring the reflection coefficient (Keysight Technologies, 2017). Prior to measurements, the system was calibrated through a 3-step calibration against air, a shorting block and water. Thereafter, before each successive measurement, the calibration was refreshed against air to account for any movement in the probe and cable, thus minimising the corresponding errors. For each measurement, the samples were placed on a lab jack and moved towards the probe until penetration of at least 10mm into the soil was maintained. For each sample, at least three measurements were undertaken at different locations to ensure the representativeness of the values obtained. Subsequently, the gravimetric water content, \( w \), was determined using the common oven drying method (Standards Australia, 2005). For this purpose, we needed to adopt two different approaches as follow. For the Australian soils, once the dielectric measurements concluded, a subsample was collected from the exact location of measurements (near the points where the dielectric probe was inserted). This is to ensure that subsamples are highly representative of the soil which was subjected to the incident electromagnetic field. For the ANZAC soils, however, due to the different approach used to measure the dielectric permittivity at different moisture contents, at each measurement, the mass of wet soil and the container was recorded and at the end of the last measurement, the sample was oven dried to calculate the total gravimetric water content. The intermediate water contents were calculated, subsequently, based on each wet weight measurement. In both cases, the gravimetric soil water contents were converted to volumetric soil water content by using the measured samples’ dry density \( \rho_d \), and the density of water \( \rho_w \) (i.e., \( \theta = \frac{\rho_d}{\rho_w} w \)).
5 Results and discussion
The dielectric measurements at 500 MHz, 1 GHz and 6 GHz frequencies for varying volumetric water content are presented next. Firstly, the dielectric constant and loss factor variations for the ANZAC and Australian soils against volumetric water content will be examined. This will be followed by evaluating the SMDM (i.e., Dobson et al., 1985) for both soil groups at the above nominal frequencies. Based on these experimental data, we modify the SMDM’s textural parameters (i.e., $\beta', \beta''$) and adapt Archie’s Law to modify the functions related to the effective conductivity, $\sigma_{eff}$, for each soil group at individual frequencies to improve the accuracy of the SMDM. Next, we suggest using the Specific Surface Area as an underpinning parameter to derive $\beta'$, $\beta''$ and $\sigma_{eff}$ for the dielectric constant and loss factor at the individual frequencies. This new model is exemplified with data from the Australian soils. Lastly, we derive simple yet robust and soil type dependent calibrations for specific frequencies of interest.

5.1 Measured dielectric properties versus volumetric water content
The variation of the dielectric measurements as a function of volumetric water content is shown in Figure 2 for both soil groups at the nominal frequencies, showing the expected general increasing trend. Generally speaking, the soil samples from ANZAC exhibits a slightly higher dielectric constant $\kappa'$ compared to the Australian soils at all frequencies which could be attributed to the higher proportion of sand (i.e., quartz) of the ANZAC soils than that of the Australian Soil group (except to the Brighton group sand – Refer to Table 3). Furthermore, as the frequency increases the dielectric constant for all the soils decreases which corresponds to the water relaxation effect (see Figure 1). The discrepancies between the dielectric constant of both soil groups decrease as the frequency increases due to the reduction of bound water polarisation and water relaxation effects and their relative contribution to the dielectric constant as observed in Figure 2a-6GHz.
Figure 2. Measured variation of the dielectric constant ($\kappa'$) and loss factor ($\kappa''$) versus volumetric water content ($\theta$) for ANZAC (circular markers) and Australian (triangular markers) soil samples at 500 MHz, 1 GHz and 6 GHz. The Australian soils samples are shown in different colours; BG (orange): Brighton Group Sand; SM (Grey): Silurian Mudstone; CIS (Yellow): Coode Island Silt; BC (Red): Basaltic Clay and BENT (Green): Bentonite.

In relation to the loss factor $\kappa''$, an overall increasing trend with water content can be observed for all frequencies, due to the increase in water polarisation for both soil groups. However, for three of the Australian soils shown in different colours in the lower pane of Figure 2 (i.e., Coode Island Silt, Basaltic Clay and Bentonite) which have the highest Specific Surface Area (and perhaps salinity), two different responses can be observed depending on the frequency of measurement. Firstly, for low frequency (i.e., 500 MHz and 1 GHz), apart from the overall increasing trend, an upward shift in the data is observed. Conversely, for measurements at 6 GHz frequency, a single (without the upward shift) increasing trend can be seen. It is suggested that at lower frequencies (i.e., 500 MHz and 1 GHz), losses due to surface conduction and ionic conductivity are significant (Equation 2), and soils with high SSA (and salinity content) do present high surface conduction. Moreover, for soil with a high content of (precipitated) salts, as the volumetric water content increases beyond 20%, salts are dissolved and the ions in solution significantly contribute to increasing the ionic conductivity, thus increases the loss factor which exhibits as an upward shift in the data. The shift is more prominent for the 500 MHz than for the 1 GHz measurements since the relative contribution of conductivity to the loss factor diminished as the frequency increases (refer to the second term in the right-hand side of Equation 2). In contrast, for measurements at 6 GHz frequency, since the contribution of conductivity has been minimised and the loss primarily occurred because of water molecule polarisations, a single (without the upward shift) increasing trend is manifested. This variation of dielectric constant and the loss factor with frequency, confirms that measurements at higher frequencies become less dependent on soil types, thus, fewer uncertainties would be involved.
in estimating the water content from dielectric measurements. In the next section, we will be evaluating the accuracy of advanced dielectric constant models against the experimental data.

5.2 Modelled dielectric constant versus experimental data

In this section, the Soil Mixing Dielectric Model (SMDM) presented by Dobson et al. (1985) is evaluated for each soil group at the nominal frequencies. The upper pane of Figure 3 shows the SMDM predictions of the dielectric constant, exhibiting good correlation but some discrepancies for both soil groups to the measured data. At lower frequencies (i.e., 500 MHz and 1 GHz), the SMDM generally underestimates the dielectric constants for most of the ANZAC samples. On the other hand, for the Australian soils, the model mainly overestimates the dielectric constant at lower water contents, while it increasingly underestimates the values as the water content increases. SMDM slightly overestimates the dielectric constant for the wetter samples. At higher frequencies (i.e., 6 GHz), it is observed that the errors within the model predictions have been significantly reduced compared to the lower frequencies as evidenced by the Coefficient of Correlation $R^2$ and Root Mean Square Error RMSE values computed. However, there exist some discrepancies for some of the soil samples following a pattern similar to what it was discussed previously. The reduced errors are essentially due to the effects of water phase relaxation as explained earlier.

![Figure 3](image)

Figure 3. Results of the modelled versus measured dielectric constant ($\kappa'$) data at 500 MHz, 1 GHz and 6 GHz. a) Modelled data using Dobson Soil Mixing Dielectric Model (SMDM). b) Modelled data using the Modified Soil Mixing Dielectric Model (MSMDM).

To reduce errors between the modelled and measured data, we have optimised the textural composition parameter (i.e., $\beta'$ in equation 10) for each soil group and frequency following the framework suggested in Dobson et al. (1985). In this approach, the textural composition is a
function of sand and clay contents ($S$ and $C$ respectively) of the soil (which captures the silt content as well). Table 4 summarises the new optimised functions for $\beta'$. 

<table>
<thead>
<tr>
<th>Frequency</th>
<th>ANZAC soils</th>
<th>Australian soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 MHz</td>
<td>$\beta' = 1.08 - 0.065S - 0.643C$</td>
<td>$\beta' = 1.206 - 0.2105S - 0.4035C$</td>
</tr>
<tr>
<td>1 GHz</td>
<td>$\beta' = 1.087 - 0.04241S - 0.5793C$</td>
<td>$\beta' = 1.204 - 0.2246S - 0.2814C$</td>
</tr>
<tr>
<td>6 GHz</td>
<td>$\beta' = 1.111 - 0.03464S - 0.5183C$</td>
<td>$\beta' = 1.255 - 0.2769S - 0.2059C$</td>
</tr>
</tbody>
</table>

A Modified Soil Mixing Dielectric Model (MSMDM) is thus suggested for the nominal frequencies using the newly optimised parameters for $\beta'$ as per Table 4. With the new site and frequency specific textural composition, the performance of the model has been significantly improved for all frequencies as shown in the lower pane of Figure 3 by the $R^2$ and RMSE values. There persists, however, discrepancies between the modelled and the measured data particularly at the higher water contents (i.e., higher dielectric constants) which suggest that there exist other soil-water interactions that the model is still unable to fully capture. These may be due to the inefficiency of using only the textural composition (i.e., sand, silt and clay contents) in accounting for the volume of bound water in soils as well as other experimental errors. In the next section, the efficiency of the model for loss factor estimation is discussed.

5.3 Modelled loss factor versus experimental data

In the modelling of the loss factor $\kappa''$ based on SMDM, besides the $\beta''$ parameter, another parameter is required to account for the conductivity of the sample that plays a role in controlling the loss behaviour (Dobson et al., 1985). This was highlighted in the Theory and background Section (see Equation 2) and illustrated in Figure 1 using the modified Debye equation (Equation 4). As a result, Dobson et al. (1985) introduced the effective conductivity parameter $\sigma_{eff}$ show in Equation 4, which was derived based on textural composition and the dry density of the sample (refer to Equations 13 and 14). The results of the comparison of the modelled and measured loss factor for both soil groups using the SMDM are summarised in the upper pane of Figure 4.

As was observed and discussed in Figure 1, at lower frequency ranges, the effects of surface and ionic conduction dominate over the effects of polarisation loss. As the frequency increases, however, the polarisation losses become the dominant component in determining the loss factor. Based on the results shown in the upper pane of Figure 4 the SMDM seems to underestimate the loss factor. The underestimation becomes more significant as the water content increases probably due to the increase of the number of dissolved ions in the mixture as the water content increases, thus, increasing the soil electrical conductivity (recall Equation 4). These results suggest that the SMDM is, therefore, unable to capture the effects of the ionic and surface conduction at 500 MHz and 1 GHz where the effects of conduction losses are stronger than polarisation losses. On the contrary, at 6 GHz, the correlation between the modelled and measured data improves dramatically, once again presumably due to the minimised effect of the conductivity and losses at higher frequencies. There are, however, some errors and
underestimation for the data at 6 GHz for the Coode Island Silt, Basaltic Clay and Bentonite samples at increasing water content, that may be attributed to salinity as well as experimental errors.

Figure 4. Results of the modelled versus measured loss factor (κ") at 500 MHz, 1 GHz and 6 GHz. a) Modelled data using Dobson Soil Mixing Dielectric Model (SMDM). b) Modelled data using the Modified Soil Mixing Dielectric Model (MSMDM).

In view of the errors observed, similar to the modification applied to the dielectric constant shown in the previous section, we have optimised the textural composition parameter β" (equation 11) for both soil groups at the given frequencies. Moreover, the effective conductivity parameter σ_{eff} used in the SMDM has been modified and derived based on Archie’s Law (Refer to Equation 15). As a result, the loss factor component of free water in the MSMDM model can be expressed as follow:

\[ \kappa''_{fw} = \frac{2\pi f \tau_w (\kappa_w - \kappa_{wo})}{1 + (2\pi f \tau_w)^2} + \frac{(n)^\alpha}{2\pi \sigma_{eff}} \]  

Equation 17

where n is porosity and the rest of the parameters were defined in Equation 4.

Based on the optimisation conducted on the two soil groups, new functions for the textural composition parameter β", as well as the newly introduced parameter “α”, which is partly accounting for the conductivity of the sample, have been derived and summarised in Table 5.
The lower pane of Figure 4 shows the new correlations between the modelled and measured loss factor. For the ANZAC soils, across the three frequencies shown, there has been a significant improvement to the modelled data as captured by the increase in $R^2$ and decrease in RMSE values. For the Australian soils, the predictions across all frequencies have improved significantly, however, the model improvements at 500 MHz and 1 GHz frequencies are not as significant and there still exist some errors in the modelled data. The different salinity levels as well as different mineralogical composition, leading to significantly different Specific Surface Area, may be responsible for some of the errors in the MSMDM. The model was unable to fully capture these effects particularly at lower frequencies where the effect of conduction is still dominant over polarisation for samples with high salinity levels and Specific Surface Area (e.g., Coode Island Silt, Basaltic clay and Bentonite samples, circled in red, green and black lines in the lower pane of Figure 4, at 500 MHz, respectively). On the other hand, the MSMDM predictions for the ANZAC soils have improved across all frequencies likely due to their similar mineralogical composition (as well as low salinity and Specific Surface Area) resulting in similar responses to the modification to the SMDM. The different responses of two soil groups in this regard suggest that the Specific Surface Area could be another important factor in driving the textural composition parameters. Therefore, in the next section, we investigate the efficacy of utilising Specific Surface Area (SSA) in deriving the textural composition parameter and effective conductivity.

### 5.4 Improved Soil Mixing Dielectric Model using soil Specific Surface Area

In the study conducted by Dobson et al. (1985), the $\beta$ parameters were introduced in view of the complexity and ambiguity involved in defining the complex dielectric properties of bound water and its volume fraction. The $\beta$ parameters, therefore, were optimised against sand and clay contents in the above-mentioned study and generic relationships were introduced in predicting dielectric constant and loss factor. It was, however, shown in the previous section, that while valuable, these generic parameters felt short for the soil samples tested in this research. Hence, the newly developed $\beta$ parameters were introduced using the experimental data leading to a significant improvement in the predictions of dielectric properties of these soils. On the other hand, it has been shown in the literature that the volume of bound water is directly proportional to the Specific Surface Area (Friedman, 1998; Hallikainen et al., 1985;
Ishida & Makino, 1999; Or & Wraith, 1999; Santamarina et al., 2001). This can arguably question whether using only textural composition through sand, silt and clay contents is an adequate measure in accounting for the volume of bound water through $\beta'$ and $\beta''$. We, therefore, propose introducing the Specific Surface Area of the soil as an input parameter in mixing models that not only captures the textural composition of soils but also the effects of mineralogy on the bound water volume and the overall soil dielectric behaviour. For instance, two clayey soil samples with a similar amount of clay, one made up of montmorillonite minerals and the other with illite minerals, will have significantly different Specific Surface Areas of approximately 30 m$^2$/g and 570 m$^2$/g, respectively (Santamarina et al., 2002). Thus, they will show different capacities for bound water volume that leads to substantially different dielectric properties. Using only sand, silt and clay contents to capture the $\beta$ parameter for these two clayey soils will, however, result in similar $\beta$ values which obviously does not reflect the true dielectric behaviour of these soils.

In view of the effects of the Specific Surface Area on the bound water volume, we suggest deriving the $\beta$ parameters by using the Specific Surface Area of the soils. We exemplify this new model using the data pertinent to the Australian soils where direct measurements of SSA were conducted\(^1\). The newly developed $\beta'$ functions based on Specific Surface Area used to estimate the dielectric constant $\kappa'$ are summarised in Table 6.

![Table 6. Modified $\beta'$ parameter utilising Specific Surface Area, SSA (m$^2$/g) for the Australian soils at the nominal frequencies (MSMDM – SSA)](image)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Australian soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 MHz</td>
<td>$\beta' = -3.91 \times 10^{-4} \text{SSA} + 1.196$</td>
</tr>
<tr>
<td>1 GHz</td>
<td>$\beta' = -1.71 \times 10^{-4} \text{SSA} + 1.059$</td>
</tr>
<tr>
<td>6 GHz</td>
<td>$\beta' = 2.26 \times 10^{-5} \text{SSA} + 1.089$</td>
</tr>
</tbody>
</table>

Figure 5a shows the modelled dielectric constants using the MSMDM with the $\beta'$ functions that are based on the site-specific soil textural composition obtained in the previous section (same as Figure 3a) versus those derived from the MSMDM with $\beta'$ functions (Figure 5b) based on just SSA functions given in Table 6. The figure shows that there has been a slight improvement in the modelled results for the 500 MHz measurements where the effect of bound water on the soil dielectric properties is greater compared with the 1 GHz and 6 GHz measurements. In addition, there is essentially no changes in the prediction accuracy for these higher frequencies, since the polarisation of the bound water is minimised at around 1 GHz, presumably the cut off frequency of bound water. These observations suggest that using the

\(^1\) Due to the restricted amount of soil allowed to be retrieved from the ANZAC region, the SSA of these samples could not be measured directly with methods such as Methylene blue adsorption or Nitrogen absorption techniques. The estimation of SSA through indirect empirical correlations based on particle size distribution (e.g., Ersahin et al., 2006) does not capture the mineralogical composition. This obviously imposed significant limitations on establishing relationships between $\beta$ parameters and SSA for the ANZAC soils, and thus these data cannot be used for further verification of the model.
more fundamental SSA input in deriving the $\beta'$ functions is useful particularly for the lower frequencies where the mineralogical effects seem to be important.

Figure 5. Results of the modelled versus measured dielectric constant data at 500 MHz, 1 GHz and 6 GHz. a) MSMDM using textural composition (i.e., sand and clay contents), b) MSMDM using Specific Surface Area.

A similar approach was adopted for the loss factor, finding the $\beta''$ functions based on the Specific Surface Area of the soils and introducing an “a” parameter, shown in the equation for the loss factor of free water (Equation 17). Figure 6a are the same results as shown in the previous section (Figure 4a) for and “a” parameter. Moreover, Figure 6 compares the results between the MSMDM using the (optimised) sand and clay contents for finding $\beta''$ and the newly modelled loss factor that utilises the Specific Surface Area and the “a” parameters.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Australian Soils</th>
</tr>
</thead>
</table>
| 500 MHz   | $\beta'' = -0.001798SSA + 0.7508$  
|           | $a = -0.001819SSA + 0.1089$      |
| 1 GHz     | $\beta'' = -0.001593SSA + 0.7588$  
|           | $a = -0.001566SSA + 0.1549$      |
| 6 GHz     | $\beta'' = -0.000205SSA + 1.02$   
|           | $a = 0.003951SSA - 0.6099$       |
Figure 6 shows that the predictions by the new model tend to be more accurate likely due to the prominent effects of surface and ionic conduction especially at low frequencies (e.g., 500 MHz) on the factor loss. More importantly, the most significant prediction improvements at 500 MHz were achieved for the Basaltic Clay (SSA = 257 m²/g) and the Bentonite Clay (SSA = 526 m²/g) samples, which are in fact of highest Specific Surface Area soils among the tested Australian Soil group. These are highlighted in Figure 6 by the red and green dashed lines, respectively.

Despite the improvements observed in the R² values at 500 MHz and 1 GHz, there exist some discrepancies in the modelled data. This highlights that mixing models, in general, are less capable to predict the dielectric behaviours at low frequency due to different relaxation mechanism involved, which are not trivial to be captured. Nonetheless, a significant accuracy improvement has been achieved for the soil samples showing the highest Specific Surface Areas. For instance, Figure 7 shows a comparison of the modelled dielectric results for the Bentonite soil sample using the Soil Mixing Dielectric Model (SMDM), Modified Soil Mixing Dielectric Model (MSMDM) as well as the MSMDM using Specific Surface Area at 500 MHz. For the dielectric constant predictions, a consistent accuracy improvement can be observed from the SMDM to the other two models, however, using the Specific Surface Area did not bear a significant improvement on the modelled data (as previously described). On the other hand, a significant improvement in the modelled results can be obtained by using the MSMDM over SMDM. For the loss factor, while further refinements can still be made, a significant improvement in the accuracy of the modelled or predictive values can be observed with the
MSMDM using the SSA, with a significant reduction in the root mean square error (RMSE) and a two-fold increase in the coefficient of correlation ($R^2$).

**Figure 7.** Comparison among the different models in predicting dielectric constant ($\kappa'$) and loss factor ($\kappa''$) for Bentonite samples at 500 MHz by a) SMDM, b) MSMDM, and c) MSMDM using Specific Surface Area. The use of SSA as input in mixing models increases accuracy and reduces error (see variations in $R^2$ and RMSE).

### 5.5 Utilising the Specific Surface Area in deriving robust calibrations

It has been shown that using the SSA as input in mixing models generally results in a better estimation of the soil dielectric properties. Empirical polynomial correlations similar to ones developed by (Malicki, Plagge, & Roth, 1996; Roth et al., 1990; Topp et al., 1980) can also be derived using SSA, as a way to capture both textural and mineralogical soil composition important for dielectric properties estimations. In this section, we utilised the Australian soil data to develop simple but robust semi-empirical correlations between soil dielectric properties and volumetric water content at the nominal frequencies using samples’ Specific Surface Area. Essentially, at each frequency, individual polynomial correlations were generated for each soil sample dielectric constant and loss factor as a function of volumetric water content and SSA. The general form follows:

$$\kappa = (a_0\text{SSA} + a_1)\theta^2 + (b_0\text{SSA} + b_1)\theta + (c_0\text{SSA} + c_1)$$  \hspace{1cm} \text{Equation 18}

where SSA is the soil Specific Surface Area in $\text{m}^2/\text{g}$. The main difference to the previous correlation (e.g., Roth et al., 1990; Topp et al., 1980) is that the multipliers are a function of SSA instead of purely empirical based multipliers.

The measured data from all of the Australian soil samples were used to calibrate Equation 18. Table 8 summarises the results of the above procedure.
Table 8. Semi-empirical polynomial correlations based on Specific Surface Area, SSA (m$^2$/g) (Poly – SSA)

<table>
<thead>
<tr>
<th>Frequency</th>
<th>$\kappa' = (a_0 \cdot \text{SSA} + a_1) \theta^2 + (b_0 \cdot \text{SSA} + b_1) \theta + (c_0 \cdot \text{SSA} + c_1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a_0$</td>
</tr>
<tr>
<td>500 MHz</td>
<td>$-0.2602$</td>
</tr>
<tr>
<td>1 GHz</td>
<td>$-0.2209$</td>
</tr>
<tr>
<td>6 GHz</td>
<td>$-0.1747$</td>
</tr>
<tr>
<td>500 MHz</td>
<td>$0.3626$</td>
</tr>
<tr>
<td>1 GHz</td>
<td>$-0.1631$</td>
</tr>
<tr>
<td>6 GHz</td>
<td>$-0.0817$</td>
</tr>
</tbody>
</table>

Figure 8 shows the modelled dielectric properties of the Australian soils using the correlations provided in Table 8 versus the experimental measurements. For comparison purposes, the predictions made by the commonly used Topp calibration (Topp et al., 1980) have been provided for the dielectric constant (i.e., real component). For the loss factor, since according to Hailemariam, Shrestha, Wuttke, and Wagner (2016) there is no calibration similar to Topp et al. (1980), we have used the equation proposed by Hallikainen et al. (1985) at 1.4 GHz that is based on Sand $S$ and Clay $C$ contents, the closest available to the measured 1 GHz frequency:

$$\kappa'' = (0.356 - 0.003S - 0.008C) + (5.507 + 0.044S - 0.002C)\theta + (17.753 - 0.313S + 0.206C)\theta^2$$

Equation 18

And for the 6 GHz frequency (Hallikainen et al., 1985):

$$\kappa'' = (-0.123 + 0.002S + 0.003C) + (7.502 - 0.058S - 0.116C)\theta + (2.942 + 0.452 + 0.543)\theta^2$$

Equation 19

Both models show good agreement with measured data at all frequencies (Figure 8-upper pane), whereas the Topp tends to overestimate the dielectric constant ($\kappa'$) at higher water contents, the polynomial calibration underestimates the data, the errors increase with frequency. Generally speaking, although the predictions based on the Specific Surface Area show good agreement with the measured data, they possess slightly larger errors in comparison with the Topp predictions, except at 6 GHz. Thus, the newly provided calibrations for the dielectric constant did not yield any advantages over the Topp calibration.
On the other hand, the loss factor predictions by the new polynomial calibrations at 500 MHz, shows two clusters: one with underestimation of the values, and another leading to a significant overestimation, which corresponds to measurements in the samples with the highest Specific Surface Areas. This suggests that using only Specific Surface Area for the low-frequency modelling is not adequate to capture this behaviour (whereas in the previous section, the simultaneous use of SSA in $\beta''$ and “a” parameters showed a significant improvement). Moving to the 1 GHz frequency results, the equation from Hallikainen et al. (1985) that is based on sand and clay contents (for 1.4 GHz) generally underestimates the measured data whereas the new polynomial calibration based on SSA (Poly-SSA) provides an improved estimation for all of the samples except the Coode Island Silt. This underestimation may be due to the salinity of these soil samples whose influence is still present at the 1 GHz frequency. Similarly, for the 6 GHz frequency, the Hallikainen et al. (1985) calibration underestimates the data while the new polynomial calibration (Poly-SSA) predicts the data with a good agreement for all of the soil samples where the effects of salinity and direct conductivity towards the loss factor are envisaged to be minimised

The use of SSA in the estimation of the dielectric constant does not show a significant advantage over the Topp calibration, however, for the estimations of the loss factor, we have provided a robust calibration for higher frequencies which perform significantly better than the (probably only) available empirical model in the literature.
6 Conclusion

Experimental data of dielectric measurements on nine soil samples were initially used to evaluate the performance of the Dobson et al.’s Soil Mixing Dielectric Model (SMDM) at specific frequencies (500 MHz, 1 GHz and 6 GHz) relevant to common geophysical testing techniques. It was shown that the SMDM is unable to fully describe the behaviour of the tested soils. Thus, we modified the textural composition parameters in the SMDM. The resulting Modified Soil Mixing Dielectric Model (MSMDM) is shown to have superior predictive performance.

More importantly, we have introduced soil Specific Surface Area as a new alternative input parameter in the mixing models. The Specific Surface Area fundamentally captures both textural and mineralogical soil composition, which are important for dielectric properties estimations. As a result, the newly introduced mixture model (MSMDM-SSA) generally provides a better prediction of dielectric constant and the loss factor particularly for low-frequency measurements compared to SMDM (and MSMDM). The performance of the new models at low frequency, however, can be improved with further research.

We have also used the Specific Surface Area as an input parameter in deriving empirical polynomial calibrations for the Australian soils. It was shown that the improvements made in the predictions of dielectric constant were not significant compared with the commonly used Topp calibration. However, the predictions of the loss factor using the Specific Surface Area using the polynomial models are superior to the existing calibrations. Soil Specific Surface Area is shown to be a robust parameter which can be used in the modelling of soil dielectric properties.

The models developed in this work can be utilised in planning and interpretation of geophysical prospections using Time Domain Reflectometry probes, Ground Penetrating Radars and remote sensing.

7 Acknowledgements

Graduate students D. Popec, D. Langley, and N. Withers are thanked for their help with the experimental work. N. Morgan from Geotechnical Engineering Pty Ltd, W. Withers from Withers Civil Contractors, and Arumpo Bentonite Pty Ltd provided representative soil samples. The experimental work was carried out in the Geotechnical, Soil and Water Laboratory at The University of Melbourne.
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5 Experimental investigation of dry density effects on dielectric properties of soil-water mixtures with different specific surface areas

This chapter investigates the effects of dry density or the degree of compaction on the dielectric properties of soils. To achieve this goal, a laboratory experimental program is undertaken to examine the dielectric properties of different soil types, ranging from sand to clay, with distinct specific surface areas at different volumetric water content and dry density levels. In addition, the results of the experimental work are evaluated based on the use of two relatively simple mixture models (De Loor and Birchak). The introduction of surface specific area and the potential role of bound water on the dielectric behavior of soils is offered as an explanatory model of the observed results.

5.1 Motivation

The use of electromagnetic (EM) techniques in quantifying the temporal and spatial variations in soil water content and other geoenvironmental parameters is becoming increasingly popular worldwide. Among the soil parameters that influence soil dielectric properties, dry density or the degree of soil compaction has received little attention in the literature, unlike the effects of water content which are relatively well documented. To date, the limited studies that attempted to evaluate the dry density effects on the soil dielectric properties have produced equivocal results that can mislead interpretation of the soil water content using EM techniques. Thus, the objective of this chapter is to experimentally examine the effect of soil dry density or degree of compaction on the dielectric properties of different soil types, ranging from sand to clay at different volumetric water content. This will ultimately provide new comprehensive experimental evidence to offer an explanation on the current controversy that exists around the results of the limited studies on the effect of dry density on the soil dielectric constant. In addition, a comparison is made between the experimental data and the physically based mixture models, namely De Loor model and Birchak model, leading to refining the dielectric properties of bound water and the geometrical component used in the Birchak model.

5.2 Contribution towards manuscript

I was the primary researcher and the author of this work. The laboratory testing and experimentation were conducted by graduate students Daniel Langley, Nicholas Withers and Daniel Popec under my direct supervision. I developed the research plan and carried out the data analysis under the supervision and support of A/Prof Guillermo Narsilio, A/Prof Dongryeol Ryu and Prof Yu-Hsing Wang while undertaking a fellowship at the Hong Kong University of Science and Technology.

5.3 Submitted manuscript

This section consists of a manuscript entitled "Experimental investigation of dry density effects on dielectric properties of soil-water mixtures with different specific surface areas", published in Acta Geotechnica journal. The paper has been inserted in the following pages as published by the journal with page numbers to be consistent with the thesis document.
Experimental investigation of dry density effects on dielectric properties of soil–water mixtures with different specific surface areas

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Abstract
The dielectric constant of soil is used to estimate its water content in a range of applications. Unlike the widely known effect of water content on the soil dielectric constant (consistent direct proportionality), only a limited number of studies have reported the effects of soil dry density, however, with equivocal results. This paper, therefore, investigates the effects of dry density or degree of compaction on the dielectric constant of five different soil types. The results of the experimental work for the soils ranging from sand to Bentonite clay with distinct specific surface areas were evaluated based on the use of two simple mixture models (De Loor and Birchak). The effects of dry density on the soil dielectric constant were found to be soil type dependent. This is demonstrated by the experimental data and further proven by the modified De Loor model. The behavior is shown to be defined by the changes in the free water, bound water, and solid particle volume fractions, ultimately controlled by the soil specific surface area. The dielectric constant changes from being directly proportional to dry density to inversely proportional at a threshold specific surface area of between 122 and 147 m²/g. Supported by the experimental observations, parametric analysis has revealed that the range for the dielectric constant of bound water was found to be 9–37, while the geometrical parameter a in the Birchak model was found to be 0.4–0.8.

Keywords Bound water • Compaction • Dry density • Soil dielectric constant • Specific surface area

1 Introduction
Spatiotemporal variation of the near-surface soil water content is of paramount significance in a multitude of hydrological and geoenvironmental applications. An accurate, reliable and fast estimation of this soil variable is crucial, for instance, in rigorous interpretation of remote sensing data [1, 12, 15, 25, 73], quality control of road infrastructure sub-bases [104], addressing issues pertinent to land surface hydrology [58, 66], management of agricultural and irrigation practices [36, 93], water resource management, and more broadly, soil science. Within this context, the use of electromagnetic (EM) techniques for in situ investigations is becoming increasingly popular worldwide in quantifying the temporal and spatial variations in soil water content and other geoenvironmental parameters based on dielectric properties (i.e., dielectric permittivity). This, in turn, has significantly increased the availability of near-surface soil water content data [23, 39]. Furthermore, EM techniques can be conducted over a large site within a reasonable timeframe, providing qualitative and quantitative information pertinent to the subsurface [34, 40, 81]. Given the importance and significant utilization of EM techniques in studying near-surface soil, understanding the geoenvironmental factors underpinning the changes in dielectric properties of soils can enhance the innovative use of geophysical techniques to evaluate the subsurface soil and water conditions. For example, geophysical methods such as time-domain reflectometry (TDR) and ground-penetrating radar (GPR) have been widely used to examine the soil water content and other soil geoenvironmental parameters such as salinity and electrical conductivity [e.g., [14, 17, 34, 88]].
Among the soil parameters that influence soil dielectric properties, dry density has received little attention in the literature. Unlike the effects of water content on the dielectric properties of soil which are relatively well documented [e.g., [72, 90, 100]], the effect of dry density or degree of soil compaction has not been studied widely. To date, the limited studies which attempted to evaluate the dry density effects on the soil dielectric properties have produced equivocal results that can mislead interpretation of the soil water content. For example, some studies have pointed to a directly proportional trend between the dielectric constant and density for dry samples [19, 50]. This proportionality assumes the dominance of the solid phase in determining the overall dielectric properties of the soil matrix. Furthermore, the widely used ‘Topp’ correlation between the dielectric constant and volumetric water content is reported to be independent of dry density between 1.35 and 1.50 g/cm$^3$, which suggests an insignificant dry density effect on the soil samples tested in deriving this correlation [90]. On the other hand, Leduc, De Ridder [51] reported a marginal improvement made on their calibration by including the dry density in the range of 1.38–1.78 g/cm$^3$, whereas Ghezzehei [32] showed that the errors in volumetric water content estimation using a three-prong TDR waveguide could be up to 10% due to soil compaction around waveguides. In addition, Malicki et al. [53] reported a proportional impact of the dry density on dielectric properties, where the effect of dry density was taken into account as a separate parameter in their calibration. In contrast, for fine-grained soils, as the water content increases, it has been suggested that if the water content is large enough, the medium dielectric constant is defined primarily by the liquid phase and subsequently by the solid (or gas) phase [27, 65, 101]. Moreover, a small number of studies have reported that an inversely proportional trend could exist in the presence of clays. Without adequate experimental evidence, this trend is suggested to be a result of the interaction between the clay particles and water molecules which considerably impact the electrical properties of soil water [42]. It is envisaged that this inversely proportional relationship is due to the dominance of the water phase over the solid phase due to the volume fraction of the bound water in the soil matrix. The bound water volume is proportional to the dry bulk density, the thickness of bound water surrounding the soil solid particles, and the soil specific surface area. Furthermore, Curtis and Narayanan [16] hinted that the effect of density on the soil dielectric constant can be either directly or inversely proportional and suggested further research was needed.

The effect of dry density on the dielectric properties of soil could, therefore, vary for different soils in contrast to the consistent proportional effects of the water content. This, in turn, may affect the results of the interpretation of the geophysical investigations of different sites which contain soils with distinct characteristics, such as expansive soils which normally have higher specific surface area. Furthermore, utilizing empirical calibrations for TDR probes to estimate the soil volumetric water content, which is normally obtained without accounting for the effect of soil dry density, could lead to inaccurate estimations when the density of the sample in the laboratory is different to the in situ condition.

The preceding literature suggests that there has not been any systematic research or adequate experimental evidence to address the effect of dry density on the soil dielectric constant. Thus, the objective of this study is to experimentally examine the effect of soil dry density or degree of compaction on the dielectric properties of different soil types, ranging from sand to clay at different volumetric water content. This will ultimately provide new comprehensive experimental evidence to offer an explanation on the current controversy that exists in regard to the results of the limited studies on the effect of dry density on the soil dielectric constant. In addition, a comparison will be made between the experimental data and the physically based mixture models, namely De Loo model and Birchak model [8, 18]. Furthermore, utilizing the experimental data, the parameter which controls the variation of the soil dielectric constant against dry density is introduced and subsequently, a threshold will be established based on a parametric study. This will eventually aid in defining an improved range for the bound water dielectric constant and the geometry factor used in the Birchak model, where the latter is normally used as a fitting parameter in the literature (e.g., [13, 45, 60, 71]).

This paper is organized as follows: In Sect. 2, the background of dielectric permittivity of the soil matrix and two dielectric mixing models is introduced and utilized to demonstrate the soil dielectric behavior against dry density. Section 3 presents the typical geotechnical characterization of soil samples and a description of the methodology adopted to achieve the objectives. Section 4 introduces the results, discussion, and the subsequent analysis which ultimately leads to establishing a threshold for the newly discovered controlling parameter, the specific surface area, and modified ranges suggested for the geometric parameter and the dielectric constant of bound water. Finally, Sect. 5 summarizes the findings of this study and concludes with recommendations for future work.
2 Dielectric Permittivity: Background and Models

Dielectric permittivity describes the behavior of a material under an electromagnetic field. From a macroscopic perspective, permittivity is the polarizability of a material under an electromagnetic field. Usually, the complex permittivity of the material is normalized by the dielectric permittivity of air (i.e., \( \varepsilon_0 \approx 8.85 \times 10^{-12} \text{ F/m} \)) and is known as the relative complex permittivity \( \kappa^* \) and expressed as follows [77, 79]:

\[
\kappa^* = \kappa'(\omega) - j\left(\kappa''(\omega) + \frac{\sigma_{\text{dc}}}{\omega \varepsilon_0}\right)
\]

where \( \kappa' \) is the real part of the relative complex permittivity, denoted as the dielectric constant, \( \kappa'' \) is the imaginary part representing the polarization loss, and \( \sigma_{\text{dc}} \) is the ohmic loss at a very low frequency. The polarization and ohmic losses are measured together as relative loss factor or imaginary part, and \( \omega \) is the angular frequency. Within an unsaturated soil matrix, each phase has a distinct dielectric constant \( \kappa' \) value. The dielectric constant of the gas phase (typically air) is 1, the solid phase (typically solid and minerals) dielectric constant varies between 2 and 7, and the liquid phase (typically water) shows a dielectric constant of approximately 80 [4, 59, 79, 92]. Water in soil exists in the forms of free and bound water, where the latter refers to the water molecules close to the solid particles. These water molecules are rotationally hindered by the solid particles and exist at a lower energy state [60, 94]. Since the dielectric behavior of bound water is used throughout this study, a better understanding of the dielectric behavior of this phase will aid in understanding the experimental results. Thus, the next section describes some physical and dielectric properties of this constituent of the soil matrix.

2.1 Dielectric behavior of bound water

In unsaturated conditions, particularly for fine-grained soil, as the soil becomes wet, the water molecules start adsorbing to the solid particles and are known as bound or adsorptive water [106]. As the water content increases, these successive water molecules are yet to be attracted to the solid particles; however, they are unable to bound tightly to the particles surface [24, 74, 80]. Further increase in the distance between the water molecules and the solid particles surface reduces the attractive forces that are experienced by the water molecules. These water molecules are termed as free water (which may include the capillary water as well) [80]. Defining the boundary between the bound and free water, however, has remained a challenging task [11, 24, 68, 94, 103] and, however, has been attended using techniques such as Nuclear Magnetic Resonance [82]. From an electromagnetic perspective, the definition of bound water essentially refers to the water molecules whose mobility is hindered by the bounding forces exerted by the solid particles when subjected to an electromagnetic field, hence exhibiting different dielectric properties to those of free water [11, 44, 46, 60, 67, 89]. The dielectric constant of water molecules near soil solid particles is low due to the van der Waals forces experienced by the water molecules near these particles. These forces prevent the water molecules from being rotationally free against an electromagnetic field, hence causing a lower dielectric constant above the megahertz range [11, 31, 41, 44, 67, 69]. It is generally accepted that the dielectric constant of water is proportional to the distance from a charged surface and it exponentially varies from a low value to its bulk value over a distance equivalent to one to several water molecule diameters where the dielectric properties of the bound water are essentially similar to those of free water with no further increase with the wetness of the soil [11, 41, 56, 64]. Past experimental research shows that the dielectric constant of rotationally hindered water (i.e., bound water) near the solid surface is somewhere between that of ice and water—between 3.2 and 80—in the kilo to gigahertz frequency range [11]. This was furthered refined by Pennock and Schwan [62] to 10–50 for TDR frequencies near 1 GHz for hemoglobin-bound water. Moreover, Dobson et al. [20] reported a narrower range of 20–40 between 1.4 and 18 GHz for soils ranging from sandy loam to Silty clay. Additionally, Or and Wraith [60], based on the harmonic averaging method proposed by Bockris et al. [10], computed the effective dielectric constant of bound water as a function of distance from the solid surface to be 6, 10 and 14 for the first, second and third molecular thickness of bound water. For the purpose of calculation, they used 12 as a single value for this parameter. However, other works such as Robinson et al. [69] suggested an average value for the dielectric constant of these phases based on the thickness of the water covering the solid particles. In other words, they treated the free and bound water as a combined phase with an equivalent dielectric constant which is a function of the water shell thickness covering the solid particles.

Soil suction is another way to broadly estimate the extent of bound water in the soil matrix [38]. Soil suction essentially describes how tightly the water molecules are attracted to the solid particles’ surface and is a result of adsorption forces and capillary forces in the matrix [91]. The relationship between soil suction and water content is explained by soil water characteristic curve (SWCC) which is correlated with soil mineralogy and specific surface area and can aid to evaluate the state of the liquid phase in the...
matrix [26, 29, 30, 33, 52, 63], but cannot be directly and easily used to distinguish the proportion of bound to free water fractions. It is important to clarify that an accurate quantitative consideration of bound water remains a challenging task due to; firstly, the issues in characterizing the bound water state on the soil surface and secondly, the uncertainties associated with the interface influence [11, 94, 103]. However, since the present study investigates the effect of dry density assuming separate phases for the free and bound water, the approach suggested in Or and Wraith [60], alongside the experimental data produced in this work. The first model, known as the four-component De Loor [18] model, is given by Dobson et al. [20] as:

$$\kappa' = \frac{1}{3 + (\theta_0 - \theta_{bw})\left(\frac{\kappa_{bw}}{\kappa_{f}} - 1\right) + \theta_{bw}\left(\frac{\kappa_{bw}}{\kappa_{f}} - 1\right) + (n - \theta)(\frac{\kappa_{f}}{\kappa_{bw}} - 1) + 2(n - \theta)(\kappa_{bw} - \kappa_{f})}$$

(4)

The second model is the four-component Birchak model which is expressed as:

$$\kappa'' = (1 - n)\kappa_{f}'' + (n - \theta)\kappa_{bw}'' + \theta_{bw}\kappa_{bw}'' + (\theta - \theta_{bw})\kappa_{f}''$$

(5)

This model includes an empirical component $x$ that accounts for the geometry of the medium with respect to the direction of the applied electric field against the soil constituents and varies between 1 and -1 for parallel and series arrangements, respectively [8]. For an isotropic soil, Birchak et al. [8] proposed $x = 0.5$, whereas Hillhorst [37] suggested that a value of 0.5 is considered as an approximation since the compositional and microstructural properties of soil are not taken into account. In another study by Dobson et al. [20] on a range of soils from sandy loams to Silty clay, $x$ was fitted by regression and determined to be 0.65 for a frequency range of 1.4 to 18 GHz. On the other hand, Jacobsen and Schjønning [43] conducted experiments on moist mineral soils and showed that $x$ is a non-constant parameter and varies between 0.4 and 0.8. Moreover, Zakri et al. [105] suggested that $x$ decreases linearly with soil dry bulk density while others suggested that it remains as a fitting parameter [13, 45]. The latter approach that was also adopted by Or and Wraith [60] was implemented in this work. On the other hand, Blonquist et al. [9] have suggested an alternative approach where instead of bound water being responsible for the reduced observed permittivity, the material structure (i.e., pore connectivity) is accountable for a dissimilar dielectric behavior and suggested further research to differentiate between the contribution of bound water and microstructure to soil permittivity. In this work, however, we did not directly examine the samples internal structure. Instead, we have...
used the specific surface area as a simple measure which can capture both to some extent and help to shed light on this topic. Other parameters in the models are as follows: $\theta$ is the volumetric water content and $n$ is the porosity. It is noted that the porosity is $n = 1 - \frac{\rho_s}{\rho}$ where

$$\rho_d = \frac{\text{mass of soil solid particles}}{\text{volume of soil specimen}}$$

and $\rho_s$ is the density of the soil solid particles. Moreover, subscripts $s$, $bw$, $fw$, and $a$ correspond to solid, bound water, free water, and air, respectively. The value of the dielectric constant for solid particles is calculated based on Dobson et al. [20] and estimated to be 4.67 considering the density of soil particles to be 2.65 g/cm$^3$:

$$\kappa_s = (1.01 + 0.44\rho_s)^2 - 0.062$$  \hfill (6)

The dielectric constant of the free water molecules follows the Debye equation [20]:

$$\kappa_{fw} = \kappa_{fw0} + \frac{\kappa_{fw0} - \kappa_{fw0c}}{1 + (2\pi \tau_w)^2}$$  \hfill (7)

where $\kappa_{fw0c}$ is the high-frequency limit of the free water dielectric constant equal to 4.9. The lower frequency limit of the water dielectric constant $\kappa_{fw0}$ is a function of temperature and is estimated to be 80.36 at 20 °C and $2\pi \tau_w$ is

$$0.58 \times 10^{-10} [92, 102].$$

The volume of the free water $\theta_{fw}$ is simply the difference between the total volumetric water content $\theta$ and the volume of the bound water $\theta_{bw}$ and is given by Eq. (8):

$$\theta_{fw} = \frac{\rho_d}{\rho_w} \theta - \theta_{bw}$$  \hfill (8)

where $\rho_w$ is the density of water in soil and $w$ is the gravimetric water content. It is important to note that the density of water is assumed to be constant at 1 g/cm$^3$ in this work; however, one must be aware that the density of water is a function of the water content and vary for the adsorbed bound water layer. The magnitude of the van der Waals forces on the nearby water molecules increases with the proximity to the soil particle surfaces, leading to an increase in density and in pressure of the water in the vicinity of the solid particles [6, 56, 106]. Zhang and Lu [106] have suggested that for the bound water (adsorptive water) the density of water can be as high as 1.825 g/cm$^3$ due to structural changes of water, and that the water density reduces as the thickness of the bound water increases. As the thickness of the water layer reaches the capillary water, however, the density is very similar to that of free water and is relatively constant [106]. Due to this density variation, some errors may arise in estimating the volumetric content of free water using Eq. (8). The errors associated with the volume of free water can affect the estimation of the overall dielectric constant of the soil due to the distinct difference between the dielectric constant of free water to that of other phases. However, since the volume of free water is directly estimated based on Eq. (3) (irrespective of the density of water) and used in Eq. (8); thus, it is envisaged that the errors involved in the estimation of the free water volume are minor. Considering the aforementioned discussion, at any given temperature and total volumetric water content $\theta$, the volumes of bound and free water are calculated according to Eqs. (3) and (8) and the thickness of the bound water layer $x(T)$ used in Eq. (3) is estimated to be constant and equal to 4.65 Å at 20 °C, according to Eq. (2). Furthermore, the bound water dielectric constant is 12 following the study by Or and Wraith [60]. With the above description, the application of the De Loor and Birchak models to calculate the dielectric constant of soil is relatively straightforward, except for the $x$ parameter which has to be obtained for each sample as a fitting parameter similar to the published results (e.g., [13, 45]).

We have used two models which consider the soil as a four-phase element which will aid us in the later stages of the analysis where the dielectric properties of the bound water phase will be estimated. To demonstrate how each of the abovementioned models describes the effect of dry density on the soil dielectric constant, $x = 0.6$ is chosen for the Birchak model. Although this might not be the best fit, 0.6 is close to the values suggested in other works (e.g., [20, 43, 60, 71]) and serves the purpose of this demonstration.

Prior to demonstrating the effect of dry density using the models, it is worthwhile to illustrate this effect using a simple soil phase diagram as shown in Fig. 1. This figure depicts the effect of an increase in dry density on the soil dielectric constant that is the result of competition between two concurrent phenomena. Essentially, at a constant volumetric water content, an increase in the dry density will increase the volume of water, and thus reduce the free water volume fraction (as shown in Fig. 1b with the circled 1). Thus, this will make a positive contribution to the overall dielectric constant of the soil matrix, owing to a higher $\kappa_{fw}$ in comparison with $\kappa_{bw}$. On the other hand, the same increase in the dry density will increase the volume of bound water based on Eq. (3) and thus reduce the free water volume fraction (as shown in Fig. 1b with the circled 2). This will cause the overall dielectric constant of the liquid phase to reduce, owing to the fact that $\kappa_{bw}$ is significantly smaller than $\kappa_{fw}$.

The dielectric constant response of the soil at a constant volumetric water content to the variation in dry density is, therefore, a consequence of an interplay between these two aforementioned scenarios shown by circled 1 and 2 in
As shown in Fig. 2a, b, for the sample with a volumetric water content ranging from 45 to 75%. As such, for low water content, the effect of dry density is observed to be proportional to the dielectric constant. This suggests that a model behavior in predicting the changes in the dielectric constant against dry density becomes simpler. Figure 2 shows the effect of the dry density on the dielectric constant for two soils with contrasting specific surface areas of 75 and 500 m²/g using the De Loor and the Birchak models at volumetric water contents ranging from dry to 75%. As shown in Fig. 2a, b, for the sample with a relatively lower specific surface area (SSA = 75 m²/g), the overall trends captured by both models is proportional to dry density except for soils with lower water content and dry density (for the De Loor model).

By contrast, for the soil with a specific surface area of 500 m²/g, the De Loor model describes the dry density effect differently based on the volumetric water content (denoted as water content hereafter) as can be seen in Fig. 2c. As such, for low water content, the effect of dry density is observed to be proportional to the dielectric constant. On the other hand, when the water content increases, the effect of dry density becomes inversely proportional to the dielectric constant. This suggests that a different mechanism may prevail for wet soils than for drier samples. Furthermore, when the volumetric water content increases beyond 50%, due to the dominance of the water phase (described with this model), the relationship switches to be directly proportional again. This second change in the model behavior might be due to the fact that the underlying assumptions of this model are not strictly valid if the total volume of water within the matrix exceeds one-third of the total volume [19]. With the Birchak model depicted in Fig. 2d, the model behavior is very similar to the De Loor model, generally with higher predicted values of dielectric constant. The main difference is, however, that beyond a certain volumetric water content, the effect of the dry density remains inversely proportional.

The aforementioned scenarios, essentially underpinned by the variation of the volume fractions of the bound, free water, and solid content, due to the change in the dry density where the specific surface area of the soil, seem to play a dominant role in the overall response. To investigate the above hypothesis explained by the phase diagram and supported by the models, an experimental program was designed to examine the effect of the degree of compaction, hence dry density, on the dielectric behavior of various soil samples.

### 3 Experimental materials and methods

A holistic approach was adopted toward linking the soil dry density and dielectric properties of soil, which is explained in the following sections.

#### 3.1 Soil samples

The tested soil samples used in this laboratory investigation ranged from sand to Bentonite clay. Four of these samples were obtained from distinct Melbourne (Australia) geology formations locally known as Brighton Group Sand, Silurian Mudstone (extremely weather residual soil), Coode Island Silt (which is really a clayey material, but locally known this way), and Basaltic Clay [please refer to the USCS included in Table 1]. In addition, a Bentonite clay, referred to as Bentonite herein, was sourced from a mine at Mildura in Victoria, Australia. Table 1 summarizes the typical geotechnical properties of the soil samples which were determined as follows: Grain size distribution including sieve analysis [5] and hydrometer tests [83], liquid limit
509, and plastic limit tests \[85\] were conducted to classify
510 the soil in accordance with the Unified Soil Classification
511 System (USCS). In addition, the standard Proctor
512 compaction test \[83\] was performed to obtain the optimum
513 water content and the corresponding dry density for each
514 sample. The specific surface area for the soil samples was

![Fig. 2 Hypothetical illustration of the effect of dry density \( \rho_{\text{dry}} \) on the dielectric constant \( \kappa' \), described by the De Loor and Birchak models at 1 GHz for two soils with different specific surface areas SSA at nominal different volumetric water contents \( \theta \) increasing at 5% increments. 
a The De Loor model for a soil with SSA = 75 m\(^2\)/g. 
b The Birchak model for a soil with SSA = 75 m\(^2\)/g. 
c The De Loor model for a soil with SSA = 500 m\(^2\)/g. 
d The Birchak model for a soil with SSA = 500 m\(^2\)/g. Values of volumetric water content above 55% could be unrealistic, nonetheless, are included for the demonstration purpose.]

<table>
<thead>
<tr>
<th>Material (abbreviation)</th>
<th>USCS</th>
<th>( D_{50} ) (mm)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
<th>( w_{\text{opt}} ) (%)</th>
<th>( \rho_{\text{dry(opt)}} ) (g/cm(^3))</th>
<th>PL(^a) (%)</th>
<th>LL(^a) (%)</th>
<th>SSA(^a) (m(^2)/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brighton Group Sand (BG)</td>
<td>SP</td>
<td>0.32</td>
<td>0</td>
<td>3</td>
<td>97</td>
<td>9</td>
<td>2.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Silurian Mudstone (SM)</td>
<td>CL</td>
<td>0.018</td>
<td>20</td>
<td>51</td>
<td>29</td>
<td>13</td>
<td>1.82</td>
<td>21</td>
<td>32</td>
<td>25</td>
</tr>
<tr>
<td>Coode Island Silt (CIS)</td>
<td>CH</td>
<td>0.011</td>
<td>25</td>
<td>56</td>
<td>19</td>
<td>16</td>
<td>1.59</td>
<td>23</td>
<td>67</td>
<td>71</td>
</tr>
<tr>
<td>Basaltic Clay (BC)</td>
<td>MH</td>
<td>0.0005</td>
<td>63</td>
<td>29</td>
<td>8</td>
<td>27</td>
<td>1.40</td>
<td>40</td>
<td>69</td>
<td>257</td>
</tr>
<tr>
<td>Bentonite (Bent)</td>
<td>CH</td>
<td>0.001(^*)</td>
<td>81</td>
<td>19</td>
<td>0</td>
<td>37</td>
<td>0.97</td>
<td>44</td>
<td>167</td>
<td>526</td>
</tr>
</tbody>
</table>

\( *\)European Standard spot test: water-based methylene blue (a detailed procedure in Kandhal and Parker \[47\] and \[78\])

\( ^*\)D\(_{50}\)

\( ^*\)\[57\]
3.2 Experimental procedure

3.2.1 Sample preparation

For each soil type, specimens with distinct gravimetric water content \( w \) and dry density \( \rho_{\text{dry}} \) were prepared. To obtain homogeneous samples at specific gravimetric water contents, based on the amount of dry soil, an adequate amount of deionized water was added to a soil batch and thoroughly mixed. The batch was allowed to equilibrate at least for 24 h in a sealed container (clayey samples were thoroughly mixed and allowed to homogenize for at least 7 days). Deionized water was used to minimize the introduction of any foreign ions to the mixture. As the focus of this study is to investigate the effects of the dry density or compaction on the soil dielectric properties, the soil compaction test procedure [i.e., 83] was adapted to serve this purpose. That is, at given water content, instead of applying 25 blows per layer, which is the standard compaction proctor test [83], each subsample or specimen was prepared with a different number of blows per layer, and on non-dielectric (plastic) molds. Thus, to obtain a low dry density specimen, 5 (or lower) blows per layer for 3 consecutive layers was adopted and the blow counts were increased incrementally (mostly by 5), to achieve higher values of dry density for the subsequent specimens. Once all the soil layers are compacted in the mold, the excessive soil was removed. Thus, the volume of the sample was equal to the volume of the mold. (Two sizes of molds were used throughout the testing program, of around 1000 cm\(^3\) and 500 cm\(^3\), respectively.) Subsequently, the filled mold was weighed to determine the total mass of the specimen. Each prepared specimen was followed by dielectric measurement (to be explained later), and a small portion of soil was taken out for gravimetric water content measurement by oven drying at 105 °C for at least 24 h and until sample weight did not change [84]. The subsample for oven drying measurement was retrieved from the vicinity of the soil–sensor contacts to ensure that the oven-dried water content is good representations of the specimen. By knowing the specimen total mass and volume, the bulk wet density was determined. Subsequently, the volumetric water content was calculated \( \theta = \frac{w}{\rho_{\text{dry}}} \). In this way, at a given gravimetric water content, several specimens having different dry densities and volumetric water contents were obtained. Later, another series of specimens with the same gravimetric water content of the previous series of specimens) were prepared at different dry densities, following the approach stated above. This procedure was repeated multiple times to obtain a number of individual samples at a range of gravimetric and volumetric water contents and different dry densities.

3.2.2 Soil dielectric measurements

The soil dielectric properties were measured with open-ended coaxial line technique using a Keysight N1501A dielectric slim form probe, of 200-mm length and 2.2-mm diameter [49], connected to a N9923A FieldFox Vector Network Analyzer that is able to measure the dielectric spectrum over the frequency band of 500 MHz to 6 GHz. Due to their broadband capabilities and nondestructive nature, open-ended coaxial probes such as the slim form probes are common for dielectric characterization of soils [95] The open-ended coaxial probes were used in similar studies that investigated the relationships between different soil geoenvironmental parameters and soil dielectric properties (e.g., [7, 22, 28, 35, 61, 75, 76, 98, 99]). The experimental setup is shown in Fig. 3.

Prior to the commencement of the dielectric measurement, a three-step calibration was performed where the probe was calibrated against air, a dielectric shorting block, and deionized water at a known temperature. During the calibration and the subsequent measurements, the coaxial cable and the probe remained undisturbed to minimize noise and errors. Therefore, a lab jack was used to raise the specimens toward the probe instead of inserting the probe directly into the specimen. During the measurements, a probe penetration of at least 10 mm was maintained while ensuring a firm contact between the tip of the probe and the specimen, and no air bubbles were trapped to minimize any adverse effect of air (which has significant dielectric properties) on the measurements [54]. In addition, since each dielectric measurement was conducted as soon as the probe-soil contact was maintained, shrinkage of the clayey samples which could create air gaps in the soil–probe contact is not expected in such short timeframe. In the case of specimens with high bulk densities, a hole of slightly smaller diameter than the probe was pre-drilled and the probe was simply pressed hard against the sample in the pre-drilled hole to ensure good coupling [35, 98]. The soil disturbance caused by pre-drilling is expected to be similar to that caused by probe insertion. Following measurement, the coefficient of reflection \( S_{11} \) was measured and converted to real and imaginary dielectric spectrums over 500 MHz to 6 GHz by means of proprietary software [48]. Based on [96, 98], for an open-ended coaxial probe, the depth of penetration and the distribution of electrical field are more than 14 mm inside the specimens; hence,
615 problems due to the soil texture are not expected. The soils tested herein having a mean grain size $D_{50}$ ranging from 616 0.018 mm for the Silurian Mudstone to 0.001 mm for the Basaltic Clay (and Bentonite with $D_{80} = 0.001$ mm) which are significantly smaller than the probe diameter, except the Brighton Group Sand ($D_{50} = 0.32$ mm) which is slightly larger than the 0.3 mm grain size recommended by the manufacturer. Errors associated with the electromagnetic measurements were minimized by triplicating each measurement in a triangular pattern, such that the measurements were representative of the entire specimen. Before each subsequent measurement (after the three-step calibration), a QuickCal feature was used to calibrate the dielectric measurement setup to ensure the errors were minimized. This was achieved by leaving the probe in air and calibrating the system against the dielectric properties of air. The temperature during all the measurements was around 20 °C.

4 Experimental results, analysis, and discussion

In the spectrum of 200 MHz to 6 GHz, the results associated with the approximately 1 GHz (0.977 GHz) frequency are employed in this work, since it is envisaged that the bound water polarization is cut off at approximately 0.8 GHz to 1 GHz and the dielectric constant becomes primarily dependent on the amount of bound and free water exist in the specimen [60, 97, 100]. Therefore, the bound water polarization is minimized. Thus, the effect of dry density on the dielectric constant is maximized since there is an insignificant contribution to the dielectric constant of the soil arising from the bound water relaxation. Indeed, Maxwell–Wagner or interfacial polarization effects are minimized in the GHz range [3, 28]. Moreover, 1 GHz frequency is a common frequency used in TDR, GPR, and remote sensing (L-band) applications where the results of this study may be helpful [70]. Thus, the selection of 1 GHz for the analyses presented in this study. Figure 4 shows examples of dielectric properties spectra obtained for the Brighton Group Sand, Coode Island Silt, and Bentonite at different volumetric water contents which justify and support the selection of the results at the 1 GHz frequency. It is shown that below 1 GHz the pronounce effects of Maxwell–Wagner and tightly bound water polarization exist particularly for the Coode Island Silt and Bentonite specimens (this does not exist for the Brighton Group Sand due to the minimal amount of tightly absorbed water). However, beyond around 1 GHz frequency these effects become less pronounced and there are minimal effects of bound water relaxation and other loss effects. This pattern is captured more strongly by the imaginary component, as recognized in [97]. Moreover, the dispersion of the dielectric properties, which is due to the induced polarization caused by physically bound water relaxation,
is clearly observed for the Coode Island Silt and Bentonite samples. The high specific surface area of some of the soil samples used in this work suggests a relatively high proportion of physically bound water for these samples. This hypothesis, in turn, supports the adoption of the four-phase model and 1 GHz for the subsequent analysis [as hinted in [2]].

The results of the experimental program are summarized next.

4.1 Soil dielectric constant based on the water shell thickness

To establish a better understanding of the change in the dielectric constant of the tested soils based on the water shell thickness $\delta$, in cm surrounding the solid particles, Fig. 5 is constructed where the water shell thickness $\delta$ is calculated as per:

$$\delta = \frac{\theta}{\rho_{\text{dry, SSA}}}$$  \hspace{1cm} (9)

In this analysis, the dielectric measurements of the samples are plotted against the water shell thickness $\delta$ around the solid particles based on Eq. (9). Obviously, for samples with lower SSA, the thickness of the water shell (including free water and bound water) is larger. The

Fig. 4 Dielectric properties spectra from 500 MHz to 1 GHz at different volumetric water contents; a Brighton Group Sand, b Coode Island Silt, c Bentonite

Fig. 5 Measured dielectric constant versus the water shell thickness ($\delta$) estimated based on Eq. (9) at 1 GHz. Symbols correspond to the different soil samples; open square: Bentonite, open triangle: Basaltic Clay, times symbol: Coode Island Silt, plus symbol: Silurian Mudstone, and open circle: Brighton Group Sand. The shaded area highlighting the sharp transition is the region which is likely to be the bound water thickness (equivalent to one to two monolayers) which is in agreement with the calculated value. Trend lines are shown as dashed lines in this figure.
important highlight of Fig. 5 is a sharp transition in the
dielectric constant for samples with higher SSA (Coode Island Silt, Basaltic Clay, and Bentonite) from a smaller
water shell thickness (low water contents) where most of
the water is considered as bound (hence a very low
dielectric constant) to a larger water shell thickness (higher
water contents) where the electrical forces experienced by
the water molecules from the solid particles are dramati-
cally reduced. Thus, a rapid variation in the dielectric
constant occurs thereafter. This transition range, which is
depicted in the gray area in Fig. 5, is in good agreement
with the theoretical prediction [i.e., \( x(T) = 4.65 \, \text{Å} \), equiva-
 lent to 1–2 water molecule thickness made by Eq. (2)]. In
contrast, for samples with lower SSA, there is a smooth
transition from low to high water content due to the neg-
ligible amount of bound water from the insignificant SSA
of the Brighton Group Sand and Silurian Mudstone. To
complement the above explanations, the data for each soil
sample are accompanied by the dashed trend lines.

Based on Fig. 5, it is postulated that the water phase
adjacent to the soil particles can be treated as a separate
phase having a considerably lower dielectric constant as
opposed to the approaches adopted by Friedman [31].

Thus, in this work, the soil is treated as a matrix comprising
4 phases, namely solid, air, bound water, and free water
with different dielectric constants, analogous to the
approaches adopted in and Or and Wraith [60].

### 4.2 Dry density effects on the dielectric constant
of soil water mixtures

For each of the samples shown in Table 1, the prepared
specimens were grouped based on similar volumetric water
content (±2%) to solely investigate the effect of dry
density on the dielectric constant. This enables analyzing
the effect of dry density independent of volumetric water
content on the specimens on the dielectric constant. As
such, for each soil sample, the effect of dry density was
evaluated for specimens where the volumetric water con-
tent is considered constant. The next section describes this
behavior for Brighton Group Sand, the Silurian Mudstone,
and the Coode Island Silt.

#### 4.2.1 Brighton Group Sand, Silurian Mudstone, and Coode Island Silt samples

Figure 6 shows the variation of the dielectric constant with
dry density for Brighton Group Sand (SP) shown in
Fig. 6a, Silurian Mudstone (CL) shown in Fig. 6b, and
Coode Island Silt (CH) shown in Fig. 6c at nominal water
content. The maximum bound water volume attained
throughout the experimentation, based on Eq. (3), is esti-
imated to be 0.0002%, 2.4%, and 5.2% for the Brighton
Group Sand (negligible SSA), Silurian Mudstone
(SSA = 25 m²/g), and Coode Island Silt (SSA = 71 m²/g),
respectively. Based on the models’ interpretation provided
in 2, it is hypothesized that an increase in the dry density of
these specimens will have a direct proportional impact on
the dielectric constant of these samples. The reason behind
this can be explained again as follows: An increase in the
dry density of the specimens causes an increase in the
dielectric constant owing to solid particles replacing voids which were primarily filled with air ($\kappa'_S > \kappa'_w$). On the other hand, this will increase the bound to free water volume fraction at a given water content, thus reducing the overall dielectric constant of the liquid phase ($\kappa'_w < \kappa'_w$). However, owing to the relatively small SSA, the variation made to the bound to free volume fraction is considered small. Therefore, an increase in the dielectric constant of the matrix due to the additional solid particles is dominant over the reduction of the dielectric constant of the matrix as a result of an increase in the bound to free water volume fraction. Hence, an overall increase in the dielectric constant of the matrix is expected.

It is noted that the increasing trend effect on the dielectric constant caused by the dry density is gradually reduced from the Brighton Group Sand to Silurian Mudstone and the Coode Island Silt. We consider that this slightly different behavior is caused by the increased volume of the bound water, which leads to a decrease in the free water volume where $\kappa'_w < \kappa'_w$. This, to some extent, offsets the increasing effect of the solid content arising from $\kappa'_S > \kappa'_w$ as the SSA increases. Thus, an increasing trend exists, however, with a reduced magnitude, especially for drier water content where the competition between the solid and liquid phase is more evident.

Both the De Loor and the Birchak models describe the proportional effect of dry density on the dielectric constant for these samples in a similar pattern to the experimental data. It is noted that the Birchak model needs to be fitted using the $\alpha$ parameter to describe the data more accurately. The adjustments to $\alpha$ made for the Brighton Group Sand, Silurian Mudstone, and the Coode Island Silt sample varied in the range of 0.2–0.73, 0.48–0.66, and 0.48–0.91, respectively. Typically, the predictions made by the De Loor models showed some discrepancies with the measured data and increases for higher water content whereas the Birchak model, in view of $\alpha$, could be modified to describe the data with a better agreement. This is, however, could detract from the usefulness of this model due to the requirement of the modifying of the fitting parameter for each dataset based on its water content and dry density, as was also suggested in Or and Wraith [60]. The response of the Basaltic Clay (MH) and the Bentonite (CH) samples is described next.

### 4.2.2 Basaltic Clay and Bentonite samples

Since the specific surface areas of the Basaltic Clay (MH) and the Bentonite (CH) samples are much larger than the Brighton Group Sand, Silurian Mudstone, and the Coode Island Silt samples, the bound water volume fraction could be higher. The maximum and minimum amounts of bound water that existed in the tested specimens based on the obtained dry densities and total volumetric water content were 14% and 19% for the Basaltic Clay and varied between 0.5 and 24% for the Bentonite, according to Eq. (2). Despite the SSA for the Bentonite being twice that of the Basaltic Clay sample, due to the lower dry density of the Bentonite specimens ($0.6 \text{ g/cm}^3 < \rho_{\text{dry}} < 1 \text{ g/cm}^3$), the bound water fraction was not significantly larger. Figure 7 shows the dielectric constant versus dry density for the measurements and the predictions made with the De Loor and the Birchak models of the Basaltic Clay. For better visualization, the data for the Basaltic Clay sample are divided into two groups and shown in Fig. 7a, b. For all the tested water content, a clear decreasing trend for the measured dielectric constant against dry density is illustrated. It is noted that the dry specimen and specimens with low water content, most likely containing only bound water, could not be prepared and tested due to the difficulty

![Image](Acta Geotechnica)

**Fig. 7** Dielectric constant $\kappa'$ at 1 GHz versus dry density $\rho_{\text{dry}}$ for the Basaltic Clay specimens (SSA = 257 m$^2$/g) at nominal different volumetric water contents $\theta$ (water in all of the specimens is suggested to exist in both forms of bound and free water). Markers: measurements, solid blue lines: the De Loor model, and dashed red lines: the Birchak model
arising from the hardness of dry clay clogs which made the 
breaking up of the clogs and preparing a homogeneous dry 
Sample extremely difficult. The lowest water content 
Specimen, therefore, was 19% which contain both bound 
and free water based on the achieved dry densities. 
Moreover, Fig. 8 depicts the data for the Bentonite 
samples which are also shown in two groups for clarity. It 
was observed that due to the loose structures of the spec-
imens at very low water content and dry density, even a 
small disturbance caused by moving the specimens around 
for conducting the pertinent dielectric measurements sig-
nificantly altered the sample properties. Hence, just two 
sets of specimens were prepared to carry out the analysis at 
a low water content of 0.6 and 8%, as shown in the 
enlarged inset in Fig. 8a. Figure 8a shows an increasing 
trend with dry density for all of the volumetric water 
content except 41.8%. For $\theta = 41.8\%$ (filled circle 
symbols) as shown by the measured data and described by 
both models, there is a decrease followed by an increase in 
the dielectric constant with increasing dry density. In 
contrast, in Fig. 8b, it is noted that there is an inversely 
proportional relationship between the measured dielectric 
constant and dry density at water content greater than 43%. 
This suggests that below 43%, water primarily exists in the 
bound form in the Bentonite sample within the tested dry 
density range. Thus, the decreasing–increasing pattern 
observed for $\theta = 41.8\%$ can be explained as follows: As 
the dry density increases from 0.85 to 0.92 g/cm$^3$, there is a 
decrease in the dielectric constant which suggests that this 
increase causes absorption of free water by the solid par-
ticles, hence giving a reduction in the dielectric constant. 
However, a further increase in dry density increases the 
dielectric constant of the matrix which shows that the 
removal the air voids by the solid particles is the dominant 
scenario (recalling the explanation to the effect in Fig. 1). 

The increasing trends observed in Fig. 8 exist due to the 
dominance of the solid phase over the liquid phase at water 
contents at which the proportion of bound water over free 
water is high (i.e., specimens with low water content). 
Therefore, it is assumed that no change is induced to the 
bound liquid phase by the additional solid particles. Con-
versely, as the water content increases, an inversely pro-
portional trend between the dry density and the dielectric 
constant emerges for both samples, as shown in Figs. 7 and 
8. As the water content increases, the liquid phase will exist 
in both free and bound water forms. Thus, at a given vol-
umetric water content, an increase in the dry density gen-
erates an increase in the dielectric constant of the soil 
matrix due to an increase in the solid content ($\kappa_s < \kappa'_s$). 
However, as the dry density increases, there will be a 
concurrent decrease in the dielectric constant of the soil as 
a result of a transformation of some of the free water 
molecules to bound water ($\kappa'_w$): refer to Eq. (3). 
The overall response of the dielectric constant of the soil 
matrix is, therefore, a consequence of the competition 
between these two mechanisms in which the latter pre-
vailed; hence, a decrease in the total dielectric constant of 
the matrix is observed. 

With regard to the performance of the models for the 
Basaltic Clay sample, Fig. 7a shows that for the specimen 
with 19% volumetric water content (square symbols— 
containing both bound and free water), the dielectric con-
stant decreases with increasing dry density. This trend was 
also captured by the models; however, both models 
underestimated the dielectric constant. Moreover, the De 
Loor model shows a gentler decrease in the dielectric 
constant values, whereas the Birchak model describes a 
decreasing gradient comparable to the measured data. In 
addition, the fitted $\alpha$ parameter for the Birchak model has 

![Fig. 8 Dielectric constant $\kappa'$ at 1 GHz versus dry density $\rho_{dry}$ for the Bentonite specimens (SSA = 526 m$^2$/g) at nominal different volumetric water contents $\theta$: a $\theta = 0.6\%$, 8%, 35.2%, 38.5%, and 41.8% - Primarily bound water. An enlarged view of $\theta = 0.6\%$ and 8% is shown in the inset (a.1) in (a) for better visualization. b $\theta = 44.3\%$, 47%, and 54.7%, and 59.2%—free and bound water. Markers: measurements, solid blue lines: De Loor model, and dashed red lines: Birchak model.](image-url)
to be chosen as 1 to achieve the highest correlation coefficient, nevertheless, the fit quality is still suboptimal. This was also observed in Dirksen and Dasberg [19] where for some of their samples, even the highest value of the fitting parameter (i.e., α = 1) could not accurately reproduce the relationship between the dielectric constant and water content. The specimens with 24% (diamond symbols), 28% (triangle symbols), and 30% (cross symbols) water content also showed a clear decreasing trend for the Birchak model and the measured data, however, with a slightly less decreasing trend for the De Loor model. Moving to a higher water content of 38% (filled circle symbols) in Fig. 7b, decreasing trend is observed with dry density and the dielectric constant for the measured data and the Birchak model; however, the De Loor model shows the opposite (increasing) trend between the dry density and the dielectric constant. Similarly, for the higher water content of 43% (hollow circle symbols), and 45% (plus symbols), the measured data show a decreasing trend with dry density as predicted by the Birchak model, however, the De Loor model produced an increasing trend for both water content values. This discrepancy may be due to the fundamental assumptions used in the De Loor model, as this model is not strictly valid when the volume of the liquid phase of the soil matrix exceeds one-third of the total volume of the soil matrix [19]. Furthermore, both models underestimate the dielectric constant as depicted for the lower water content.

For the Bentonite specimens, as shown in Fig. 8a (in particular, the enlarged view in the inset of Fig. 8a (i.e., a.1)), the De Loor and Birchak models could accurately predict the dielectric constant at 0.6% water content (square symbols) when α = 1. However, significant discrepancies were observed for higher water content, even at a still low volumetric water content of 8% (diamond symbols). This suggests that there is a substantial interaction between the solid and liquid phases that these models are unable to describe. Additionally, an increasing trend was also observed with the measured data for the specimens with 35.2% (triangle symbols) and 38.5% (cross symbols) water content, although according to the calculation, it was assumed that the liquid phase exists in both free and bound water forms; hence, a decreasing trend was expected. This is suggested to be caused by the estimations made in Eq. (2) for the calculation of the thickness of the bound water and the errors involved in the SSA measurements which may have led to an underestimation of the total volume of bound water. In Fig. 8b, the measured dielectric constant variation is inversely proportional to the dry density. For the water content shown in Fig. 8b, the De Loor and Birchak models behavior is different. For 44.3% (plus symbols) and 47% (hollow circle symbols) specimens, both models could predict the overall trend, nonetheless with significant discrepancies against the measured data. Furthermore, at a higher water content of 54.7% (star symbols) and 59.2% (hollow triangles symbols), the specimens show a clearly different behavior for De Loor and Birchak models. The De Loor shows an increasing trend with dry density while the Birchak model presents an inversely proportional relationship. Similar behavior of the De Loor model is shown in Fig. 2, where the dielectric constant predictions by the De Loor model above a certain water content were consistently proportional to the dry density, despite a high SSA of 500 m$^2$/g. Conversely, with the Birchak model, as shown in Fig. 2 for the same sample, this trend is inversely proportional, provided that the liquid phase consists of both free and bound water.

It was observed that for the Basaltic Clay and the Bentonite samples, an increase in the dry density has a different impact on the dielectric constant of the specimens based on the state of the liquid phase. For specimens where the liquid phase consists of mainly bound water, a directly proportional trend between the dry density and dielectric constant exists which is identical to the Brighton Group Sand, Silurian Mudstone, and Coode Island Silt specimens. This is caused by the additional solid content replacing the air voids, thereby having a lower dielectric constant. However, when the liquid phase consists of free and bound water, the additional solid content absorbs fractions of free water, hence reducing the volume fraction of free water and increasing that of bound water, besides removing the air voids. For these soil samples, the change in the volume fraction of the bound water is prevalent over the additional solid content; hence, they exhibit the opposite behavior (recalling Fig. 1 for a physical interpretation). The variable which defines the line where the soils dielectric properties exhibit a different response to an increase in the dry density is, therefore, suggested to be the specific surface area SSA. The next section describes the investigation of the threshold for the SSA where the variation of the soil dielectric properties against dry density is different for samples such as the Basaltic Clay and the Bentonite to sand, Silt or, in general, samples with low SSA.

### 4.3 Contrasting effect of dry density on the soil dielectric constant based on the SSA

It is suggested by the models, as per Fig. 2, and further proven by the new experimental data that the effect of dry density on the soil dielectric properties is soil type dependent. The experimental data for the Basaltic Clay (SSA= 257 m$^2$/g) and Bentonite samples (SSA= 526 m$^2$/g) show that the effect of dry density on the dielectric constant is different to the other samples. Identifying the threshold for the SSA where the effect of dry density on the dielectric constant switches from a directly proportional trend to an
inversely proportional trend is thus of scientific and practical importance. This section, therefore, provides insights on establishing this threshold.

Based on the two models and analyzing the state of water in the soil matrix, two scenarios are considered:

1. $\theta \leq \theta_{bw\text{max}}$: This is when all the water that exists in the soil matrix is less than the maximum capacity of the matrix for the bound water ($\theta_{bw\text{max}}$); hence, the volume of free water is (nearly) zero [87]. It is important to note that defining the boundary for $\theta_{bw\text{max}}$ is difficult and depends on the soil mineralogy (which can be linked to the SSA) and soil matrix potential [55, 87].

   For some soils, the capillary forces could prevail over the effects of the adsorption forces, thus, the ‘effective’ bound water layer thickness may be extended beyond two layers of water molecules. These can also include unbound water which are trapped in the pores [68, 106].

   When all the water the molecules are considered as bound water from an electromagnetic perspective, the Birchak model may be written as:

$$\kappa' = (1 - n)\kappa_a' + (n - \theta)\kappa'_bw + \theta_{bw\text{max}}\kappa'_bw \quad (10)$$

Rearranging this equation, it can be written as follows:

$$\kappa' = \rho_d \times \left[ \frac{(\kappa'_a - 1)}{\rho_s} + \text{SSA} \times x(T) \times (\kappa'_bw - 1) \right] + 1 \quad (11)$$

In this equation, the multiplier of the dry density $\rho_d$ (i.e., the highlighted part of Eq. (11)) is always a positive value unless the SSA becomes a negative number which is not possible. This also confirms that when the water in soil exists only in the form of bound water, the increase in the dry density results in an increase in the dielectric constant of the matrix, as observed in the experimental data.

2. $\theta > \theta_{bw\text{max}}$: In this case, water in the soil is manifested in terms of both free and bound water; hence, the four-phase Birchak model can be rewritten as follows:

$$\kappa' = \rho_d \times \left[ \frac{(\kappa'_a - 1)}{\rho_s} - \text{SSA} \times x(T) \times (\kappa'_bw - 1) \right] + \theta \times (\kappa'_bw - 1) + 1 \quad (12)$$

The dry density multiplier (i.e., the bold part of Eq. (12)) can be a positive or negative value based on the SSA. The SSA which is defined herein as the SSA threshold will vary based on the fitting parameter $\alpha$ and the estimated value of the dielectric constant of bound water $\kappa'_bw$. Rearranging the dry density multiplier in Eq. (12), and recalling the thickness of the bound water $x(T)$ given by Eq. (2), and solving for SSA, gives:

$$\text{SSA} = \frac{\theta \rho_s}{-d_T + T \ln \left( \frac{\rho_d}{\rho_s} \times (\kappa'_bw - \kappa'_bw) \right)} \quad (13)$$

As such, at a given volumetric water content where $\theta > \theta_{bw\text{max}}$, the relationship between the dielectric constant and the dry density is inversely proportional, whereas for soils with a SSA smaller than the threshold a direct proportional relationship exists. The next section provides a quantitative insight and establishes the threshold for the SSA.

### 4.4 Threshold for the specific surface area: SSA$_{\text{threshold}}$

Based on Eq. (13), a parametric investigation for this threshold against $\alpha$ and the dielectric constant of bound water is presented in Fig. 9. The thickness of the bound water $x(T)$ was set at 4.65 Å based on Eq. (2), and according to Eq. (7), the dielectric constant of free water $\kappa'_fw$ is 80.1 at 20 °C. With the Birchak model, $\alpha$ is considered as a fitting parameter which varies for different soils. Moreover, the dielectric constant of the bound water fraction is another fitting parameter. This is similar to the work by Dirksen and Dasberg [19] where suggested values of $\kappa'_bw$ such as 10 (or lower or higher) were unable to

![Fig. 9 Parametric analysis on the SSA threshold based on the variation in the fitting parameter $\alpha$ and the real dielectric constant of bound water $\kappa'_bw$ at 1 GHz. Highlighted text boxes demonstrate the most likely ranges of $\alpha$, 0.4–0.8, (box a with the solid line margins) and the real dielectric constant of bound water, 9–37, (box b with dashed line margins). Dashed red lines correspond to the SSA of the tested soil samples accompanied for the soil samples](image-url)
describe the soil dielectric behavior. Considering these parameters which are not constant, the threshold for the specific surface area SSA_threshold where the dry density effect shifts will, therefore, vary. Thus, for each value of the fitting parameter $\alpha$ (which varies between -1 and 1 as shown in Fig. 9 in 0.2 steps), a threshold for the SSA is calculated based on different values of the dielectric constant of bound water which ranges from 3 to 50 according to the literature. Essentially for each set value of $\alpha$ (i.e., $-1, -0.2, -0.4$, etc.) and using $\kappa'_{bw}$ varying between 3 and 50, Eq. (13) is solved for SSA_threshold. The following observations can be made from Fig. 9: It is shown that for a given value of $\alpha$, the SSA_threshold increases with the dielectric constant of the bound water. This trend illustrates that a higher estimated value of the dielectric constant of bound water, corresponds to a higher SSA_threshold for the presence of the inversely proportional trend between dry density and dielectric constant. Moreover, due to the significantly large values of SSA_threshold calculated for the Birchak model for $\alpha = -0.4$ to $\alpha = -1$ (for SSA larger than 1000 m²/g) it is suggested that a series-type arrangement of soil constituents might not occur in soils. Similarly, for the parallel-type arrangement, when $\alpha = 1$, the SSA_threshold falls below 71 m²/g for the whole range of the bound water dielectric constant, which suggests that the inversely proportional relationship can exist in the Coode Island Silt sample. Nonetheless, this was not the case with the experimental results associated with the Coode Island Silt with SSA of 71 m²/g. Hence, the lower range for SSA_threshold is defined as 71 m²/g based on the experimental data. In contrast, the Basaltic Clay and Bentonite have shown a decreasing trend with dry density; therefore, defining an upper limit for the SSA_threshold larger than the SSA of any of these two samples cannot be justified. Thus, an upper limit of the SSA_threshold is suggested to be set at 257 m²/g. These lower and upper limits are highlighted in Fig. 9 by the gray box with solid margins marked as “a”. Box “a” represents the range where SSA_threshold lies (71 m²/g < SSA_threshold < 257 m²/g) according to the experimental results and analysis. A similar method can be used to refine the dielectric constant of bound water at 1 GHz; it can be seen from Fig. 9 that, for $\kappa'_ {bw}$ greater than 37, the Basaltic Clay falls below the threshold which was not the case based on the experimental data; hence, 37 is suggested as the upper limit for the dielectric constant of the bound water. Moreover, when $\kappa'_ {bw}$ is less than 9 and $\alpha$ is 0.8, the threshold is smaller than the Coode Island Silt specific surface area which suggests that the inversely proportional trend may exist in samples such as the Coode Island Silt. Nonetheless, this is contrary to the experimental data. As a result, the lower limit of the $\kappa'_ {bw}$ is envisaged to be 9. The lower and upper bands for the real dielectric constant of bound water are delimited by another box with the dashed line margins (9–37) marked as “b”.

The aforementioned discussion was based on a comparison made between the experimental results and the output of the Birchak model using Eq. (13). As a result, the dark gray area which is captured by both “a” and “b” boxes in Fig. 9 highlights the range where SSA_threshold lies, the range for $\kappa'_ {bw}$ as well as the range for the $\alpha$ parameter. Thus, it is postulated that the SSA_threshold is between 71 and 257 m²/g, the bound water real dielectric constant falls between 9 and 37 which is a narrower range than currently suggested in the literature, and the $\alpha$ parameter varies between 0.4 and 0.8 (as opposed to the $-1$ to 1 range found in the literature).

Based on the proposed ranges for $\alpha$ and the real dielectric constant of bound water, Fig. 10 attempts to construct a narrower range where the SSA_threshold exists. According to the current literature, 0.6 is a good approximation for $\alpha$ which describes the behavior of the majority of soil types with good agreement. Considering $\alpha = 0.6$, the threshold for the SSA varies between 122 and 147 m²/g, as depicted in Fig. 10. It is suggested, therefore, that extra attention be paid to the dry density, in particular for soils with SSA larger than the SSA_threshold when dielectric properties are employed in research and investigations as proxies of soil geoenvironmental parameters. To accurately establish this threshold, the same methodology adopted in this work can be followed, employing soils having specific surface areas within the suggested range.
5 Conclusions

The effect of soil dry density or degree of compaction on the dielectric constant of five different soil samples was experimentally investigated. Compacted specimens at different gravimetric water content were prepared by modifying the compaction test procedure, subsequently followed by dielectric measurements. Specimens with similar volumetric water content were grouped to specifically explore the effect of dry density on the dielectric constant. Essentially, the effect of an increase in the dry density or degree of compaction at a constant volumetric water content manifests itself in two concurrent scenarios. At a constant volumetric water content, increasing the dry density (i.e., removing air voids) causes a positive contribution to soil dielectric constant owing to a higher dielectric constant of the solid phase in comparison with that of the gas phase (i.e., air). Secondly, in the presence of free water and at a fixed volumetric water content, an increase in the dry density may increase the volume fraction of the bound water, thus reducing the free water volume fraction. Bound water volume fraction has not been measured directly in this work, but arises as a plausible explanation of the overall observed trends from the model proposed herein. This likely reduction of free water volume fraction imposes a reduction on the overall dielectric constant of the liquid phase, in view of the fact that the dielectric constant of bound water is significantly smaller than that of free water. Based on the competition between these two scenarios, therefore, two distinct types of behavior were observed: when the water phase in the soil matrix primarily is present in the form of bound water, there is a directly proportional relationship between the soil dielectric constant and the dry density, irrespective of the soil type. Conversely, when water in soil consists of both free and bound water, the relationship between the dry density and the real dielectric constant becomes soil type dependent. As such, for soil samples with low specific surface area SSA, this relationship remains directly proportional, whereas for soils with large SSA, this relationship changes to an inversely proportional correlation. Thus, the specific surface area of the samples was proven to be the governing parameter which controls this relationship. Within this context, the threshold for defining whether a sample is considered to have a high or low specific surface area is suggested to be between 71 and 257 m²/g, with a refined range between 122 and 147 m²/g, based on the geometric parameter z = 0.6 (in the Birchak model). However, further testing conducted on soil samples with similar SSA is required to more accurately define this threshold. Furthermore, it was also found that the dielectric constant of bound water is likely to be in the range of 9 to 37, which is a narrower range compared to the values quoted in the current literature. Additionally, based on the experimental data, it is suggested that the most likely possible range of z for soils is between 0.4 and 0.8.

To address some of the limitations discussed in this work, future studies may include direct measurements of the bound water content with techniques such as nuclear magnetic resonance as well as other techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) which are more precise at characterizing internal structure and mineralogy. Furthermore, spectrum analyses over kHz and MHz frequency ranges can provide insights on the effect of densification on the electromagnetic relaxation mechanisms.

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6 A Laboratory study on non-invasive soil water content estimation using capacitive based sensors

This chapter focuses on the development of a new technique for soil water content estimation. For this purpose, a laboratory experimental program is designed to develop new sensors which enable a cost-effective way to estimate soil water content non-invasively with implications on an array of applications such as engineering, agriculture and hydrology.

6.1 Motivation

Soil water content is an important parameter. The current techniques of measuring soil water content are either time and labour consuming, expensive or they utilise radioactive materials. Motivated by the importance of soil water content and the drawbacks of its current measurement techniques, this chapter aims to develop new an alternative method to enable non-invasive water content estimation of different soil types through low cost and capacitive-based sensors. These sensors have shown promising potential in estimating near surface soil water content, with implications in diverse fields including agriculture, hydrology, geoenvironmental engineering, bushfire protection management and road construction. It is important to note that the sensor performance is highly dependent on its coupling with the soil surface. The soil sensor coupling was effectively maintained during experimentations by using a weight which was added to the sensor by non-ferromagnetic spacers between the weight and the sensor. In this way, we believe, that the elevated weight was outside the zone of influence of the sensor, thus having negligible impacts on the capacitive readings.

6.2 Contribution towards manuscript

I was the primary researcher and the author of this work. The laboratory testing was partially conducted by graduate students Daniel Langley, Nicholas Withers and Riley Fullerton under my direct supervision. A/Prof Narsilio developed the research plan, with inputs from myself and others. I and carried out the data analysis under the supervision and support of A/Prof Guillermo Narsilio and a/Prof Dongryeol Ryu.

6.3 Published manuscript

This section consists of a paper entitled "A Laboratory study on non-invasive soil water content estimation using capacitive based sensors", published in Sensors journal. The paper has been inserted in the following pages as published by the journal with page numbers to be consistent with the thesis document.
A Laboratory Study on Non-Invasive Soil Water Content Estimation Using Capacitive Based Sensors

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Abstract: Soil water content is an important parameter in many engineering, agricultural and environmental applications. In practice, there exists a need to measure this parameter rather frequently in both time and space. However, common measurement techniques are typically invasive, time-consuming and labour-intensive, or rely on potentially risky (although highly regulated) nuclear-based methods, making frequent measurements of soil water content impractical. Here we investigate in the laboratory the effectiveness of four new low-cost non-invasive sensors to estimate the soil water content of a range of soil types. While the results of each of the four sensors are promising, one of the sensors, herein called the “AOGAN” sensor, exhibits superior performance, as it was designed based on combining the best geometrical and electronic features of the other three sensors. The performance of the sensors is, however, influenced by the quality of the sensor-soil coupling and the soil surface roughness. Accuracy was found to be within 5% of volumetric water content, considered sufficient to enable higher spatiotemporal resolution contrast for mapping of soil water content.

Keywords: agriculture; capacitive sensors; dielectric constant; remote sensing; surface soil water content

1. Introduction

Soil water content is a parameter with implications in an array of engineering, hydrology, climate science, water resource management, remote sensing and agricultural applications [1–6]. The challenge of increasing water use in agriculture, which is known to be the largest consumer of water resources (e.g., see [7]), can be alleviated by better-informed irrigation decisions and smart farming systems that are based on accurate measurements of soil water content [8–10]. In addition, accurate and rapid measurements of soil water content can enhance site assessments in a broad range of civil engineering applications such as road construction, since the soil moisture is an important parameter to derive the strength and the integrity of the infrastructure [11]. Furthermore, in bushfire management, the fuel availability estimates used for issuing warnings are partly based on the soil moisture deficit [12].

Surface soil moisture comprises only 0.05% of the Earth’s total fresh water. Although this value is small, the amount of soil moisture is imperative in agriculture for crop development, irrigation management, crop type selection and plant stress [13–16]. Additionally, spatiotemporal variations of near surface soil water content are of paramount significance in a number of applications due to its very large inhomogeneity [17–19]. As such, the near surface soil water content is an integral hydrological and meteorological parameter for ground truthing remotely sensed data, mapping variable sources of streamflow, developing large scale surface water and energy balance models and improving the land component of climate models, including global circulation models [17,20–26]. In precision agriculture, it is the soil water content in the root zone, not the near surface water content, that determines the amount of water available to a plant. However, the water available to the plant often can be inferred...
from near surface soil water content information (e.g., see [19,27–30]). Nonetheless, with the current soil water content measurement techniques measuring the surface soil water content become difficult to assess its spatiotemporal variability [31,32].

Soil water content can be directly measured using the oven drying method which is accurate and inexpensive; however, it is time-consuming and labour-intensive. In addition, there are indirect techniques which utilise other soil parameters as a proxy to estimate soil water content. Neutron probes are commonly used for these indirect techniques; however, there are limitations associated with their use. These limitations are primarily due to the probes containing radioactive materials and include the high cost of equipment, the requirement of a certificate to operate, the inability to use as a continuous monitoring tool and unreliability to estimate near surface soil water content [2,20,33]. Furthermore, the common methods of measuring soil water content often cannot provide immediate feedback [34]. The disadvantages of traditional soil water measurement methods associated with time and cost are exacerbated by the large spatial extent of measurements required for irrigation management in agriculture and motivate the development of cost-effective and non-invasive alternatives [35,36].

Alternative techniques which address some of the limitations of traditional methods include dielectric methods. In these, the electrical properties of soil are utilised as a proxy to estimate soil water content. For example, Time Domain Reflectometry (TDR) probes, Frequency Domain Reflectometry (FDR) probes, capacitive probes, impedance probes, Ground Penetration Radar (GPR) and Electromagnetic conductivity (EM) antennas have been used to estimate water content in various applications (e.g., see [10,37–41]). However, the accessibility of these methods is limited by the high cost of equipment and difficult result interpretation. Furthermore, despite the non-invasive nature of GPR and EM antennas, the requirement of probe insertion into the soil makes the TDR, FDR, capacitive and impedance probes labour intensive, particularly for hard or dense soils. Additionally, by being invasive, repeated measurements at the same location can make the measurements unreliable [42]. To compensate for the high cost involved in some of the aforementioned methods, there exist other common low-cost sensors which, although invasive, demonstrate good performance. The heat pulse soil moisture sensors using single or dual probe designs have been introduced in this context [43–50]. Furthermore, recent developments in capacitive soil moisture sensors have enabled low cost means in soil water content measurement [49,50]. Nonetheless, they have not eliminated the need for probe insertion. For this purpose, a needle-free heat pulse sensor system has recently been developed [51]. Although this sensor has no needle and is inexpensive, burying it in the soil causes soil disturbance [51]. None of these developments, however, have focused on non-invasive measurements of near surface soil water content. Instead, remote sensing applications have been widely used as the primary source of information of surface soil water content. However, they often lack the required resolution for certain applications [31,52]. It has been suggested that understanding the sub-footprint scale of the variability of remotely sensed soil water content is an important factor to fully utilise these data [31].

Motivated by the importance of soil water content and the drawbacks of its current measurement techniques, particularly for near surface soil water content, this research aims to develop a new non-invasive, low cost and capacitive-based technique for estimating near surface soil water content. We hypothesise that given the accuracy of the relationship between soil water content and its dielectric properties, which is widely known, the surface soil water content can be estimated from the surface using a non-invasive capacitive sensor (since capacitance is linked to the dielectric constant and the sensor geometry). To evaluate this hypothesis, we first compared three new non-invasive capacitive sensors developed to estimate soil volumetric water content and we examined their performance for four different soil types and for a range of water contents. Subsequently, based on the comparative performance of these three sensors, a fourth sensor was designed and manufactured to substantially reduce the limitations of the previous versions. The sensors, particularly the fourth one, demonstrated great potential in detecting variation in soil water content from the ground surface. Moreover, it is concluded that the soil-sensor coupling and roughness of the soil sample surface play an important influencing role in the performance of the sensors.
To address the objective of this research, this manuscript is organised as follows: In Section 2, an overview of dielectric permittivity and soil moisture is introduced. Sections 3 and 4 comprise descriptions of the materials and methodologies used. The results, analyses and discussion are presented in Section 5. In Section 6, we discuss potential practical applications of the sensors as well as the limitations of the research. Finally, summaries of the findings and recommendations for future work are presented in Section 7.

2. Theory and Background: Dielectric Permittivity and Soil Moisture

Current non-destructive soil water content estimation techniques such as GPR and TDR are based on measuring the dielectric permittivity of soil. The dielectric permittivity, \( \varepsilon \) (F/m), is a complex number which measures the degree to which a material is polarised when it is subjected to an electrical field and it can be represented as shown by [41]:

\[
\varepsilon = \varepsilon' - j\varepsilon''
\]  

where \( \varepsilon' \) is the real component of the dielectric permittivity (F/m), \( j = \sqrt{-1} \) is the imaginary number and \( \varepsilon'' \) is the imaginary component of the dielectric permittivity (F/m) known as the dielectric loss. The ratio between a material’s dielectric permittivity and that of air (\( \varepsilon_0 \approx 8.85 \times 10^{-12} \) F/m) is known as the relative dielectric permittivity, \( \kappa \) and can be written as:

\[
\kappa = \frac{\varepsilon}{\varepsilon_0} = \kappa' - j\kappa''
\]  

where \( \kappa' \) is known as the dielectric constant and \( \kappa'' \) is known as the loss factor. In an unsaturated soil, water has the highest dielectric constant (\( \kappa' \approx 80 \)), which is noticeably larger than the dielectric constant of minerals (2 < \( \kappa' \) < 7) and of air (\( \kappa' = 1 \)). The bulk dielectric permittivity of soil, a mixture of these three elements is, therefore, influenced mostly by the water content. Indeed, a strong correlation between the soil volumetric water content and the (real) dielectric constant is reported in the literature. There are several studies which investigated the correlation between soil volumetric water content and its real dielectric constant, considering parameters such as soil type, salinity, density, temperature and frequency of measurements (e.g., [53–57]). Within this context, Topp, Davis and Annan [53] performed TDR measurements on four types of soil to propose what it is today the most commonly used empirical model: for a low-loss homogenous material (i.e., low or negligible \( \kappa'' \)), the correlation between the apparent dielectric constant, \( \kappa' \) and its volumetric water content, \( \theta \), is:

\[
\theta = 4.3 \times 10^{-6} \kappa'^3 - 0.00055 \kappa'^2 + 0.0292 \kappa' - 0.053
\]  

Further, capacitance, \( C \), is the ability of a material to store an electrical charge. The capacitance of a capacitor is related to the dielectric constant of the dielectric material used as the insulator [58] such that:

\[
C = \kappa g \varepsilon_0
\]  

where \( \kappa \) is the relative dielectric permittivity, \( g \) is a geometric constant and \( \varepsilon_0 \) is the permittivity of a vacuum (F/m). Measurement of soil permittivity through capacitance methods was first introduced by Dean, et al. [59], who developed a capacitance sensor operating at a frequency of 150 MHz for the purpose of creating a cost-effective and safe in situ method [58]. Furthermore, due to their relatively low cost and ease of operation, capacitive sensors are becoming increasingly popular among researchers and practitioners [60]. Most importantly, the relationship between water content and the dielectric constant of a soil is widely accepted to be accurate [42,58]. We compare four new capacitive sensors developed to non-invasively estimate the soil volumetric water content by utilising the relationship between the volumetric soil water content and the dielectric constant (Equation (3)) and the relationship between the capacitance and the dielectric constant (Equation (4)).
3. Materials and Methods

This section describes the experimental framework including the material and methods used to address the objectives of this research.

3.1. Tested Soils

Four different soil types collected from Victoria, Australia, whose characteristics are summarised in Table 1, are used for testing. Soils are selected to cover a range of grain sizes and textures based on grain size distribution analysis according to Australian Standards [61,62]. In addition, the plasticity index (Plastic Limit, PL and Liquid Limit, LL) were determined following Australian Standards [63,64]. The Organic Matter (OM) was measured using the Loss on Ignition (LOI) method described in the American Society for Testing and Materials (ASTM) standards [65]. The salinity of the samples was estimated using the conductivity, $\sigma$, of the samples at saturation point ($\sigma = \kappa'' \cdot \omega \cdot \varepsilon_0$), where $\kappa''$ is the loss factor (see Equation (2)) and $\omega$ is the angular frequency, as proposed by Santamarina and Fam as well as Narsilio, et al. [66,67].

<table>
<thead>
<tr>
<th>Soil Sample</th>
<th>Location</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
<th>PL (%)</th>
<th>LL (%)</th>
<th>OM (%)</th>
<th>Salinity (dS/m)</th>
<th>USCS Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brighton Group Sand</td>
<td>Brighton, VIC</td>
<td>&lt;1</td>
<td>2</td>
<td>97</td>
<td>NA</td>
<td>NA</td>
<td>0.08</td>
<td>1.5</td>
<td>SP</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>Melbourne, VIC</td>
<td>&lt;1</td>
<td>14</td>
<td>85</td>
<td>NA</td>
<td>NA</td>
<td>0.37</td>
<td>2.3</td>
<td>SM</td>
</tr>
<tr>
<td>Silty Clay (Camb)</td>
<td>Camberwell, VIC</td>
<td>48</td>
<td>42</td>
<td>10</td>
<td>19</td>
<td>28</td>
<td>0.18</td>
<td>3.0</td>
<td>CL</td>
</tr>
<tr>
<td>Clayey Silt (Bun)</td>
<td>Buninyong, VIC</td>
<td>13</td>
<td>70</td>
<td>17</td>
<td>30</td>
<td>39</td>
<td>0.33</td>
<td>1.6</td>
<td>ML</td>
</tr>
</tbody>
</table>

PL—plastic limit; LL—liquid limit; OM—organic matter; SP—poorly graded sand; SM—fine-grained silty sand; CL—low to medium plasticity silty clay; ML—low to medium plasticity clayey silt.

Based on the unified soil classification system (USCS) described in the Australian Geotechnical Site Investigations standard [68], the first soil is classified as a poorly graded sand (SP) denoted in this manuscript (and locally known) as Brighton Group Sand; the second soil as a fine-grained silty sand (SM) referred to as Silty Sand in this manuscript; the third soil as a low to medium plasticity silty clay sample (CL) denoted as Camb Clay in this manuscript and the fourth sample is classified as a low to medium plasticity clayey silt (ML) referred to as Bun Silt in this manuscript. These clay samples belong to the Silurian Melbourne geological formation, which contains primarily illite and kaolinite minerals. Based on the estimated values of salinity, the Brighton Group Sand and the Bun Silt are considered as non-saline soils whereas the Silty Sand and Camb Clay samples are considered as moderately saline according to Agriculture Victoria [69].

3.2. Dielectric Probe: Benchmark Dielectric Measurements

The complex dielectric properties of soil samples can be measured by means of an open-ended coaxial line technique [70]. In this work, a 2.2 mm diameter coaxial slim form Agilent dielectric probe (Keysight Technologies, Santa Rosa, CA, USA) (with a 0.51 mm diameter centre conductor and a 1.68 mm diameter insulator) connected to an N9923A FieldFox Vector Network Analyser (VNA) (Keysight Technologies), was utilised to measure the complex dielectric properties of the soils at different frequencies. These measurements help in evaluating the performance of the capacitive sensors. The slim form probe is reported in the literature to have been used to investigate the relationships between soil dielectric properties and other parameters such as water content, thermal conductivity, temperature, frequency and pH [71–73]. The complex scattering parameter of the material under test is measured and subsequently converted to the complex dielectric permittivity by means of proprietary software [74]. All the experiments were conducted in a controlled laboratory environment with a constant temperature range of 19 to 21 degrees Celsius.
3.3. Capacitive Sensors

The four capacitive sensors used in this study are depicted in Figure 1 alongside an Arduino-based board use as a controller board. The sensors are (1) an AD7746 sensor, denoted as “Circular,” (2) an MPR121 sensor, denoted as “Rectangular,” (3) a PCB Gadget sensor, denoted as “PCB” and (4) a newly designed and built sensor denoted as “AOGAN.” The sensors are Capacitance-to-Digital Converters (CDC). The Circular and Rectangular sensors are typically used as keypads; however, in this work, they were programmed to measure the capacitance of the soil samples. The Circular, Rectangular and AOGAN sensors were connected to an Arduino-based board (Freetronics, Croydon South, VIC, Australia) and utilised a C++ platform to communicate and transmit the measured capacitance values. Similarly, the PCB sensor transmitted the capacitance reading through a USB cable to a CoolTerm computer program (provided by PCB Gadget) without the need of an Arduino-based controller board.

![Figure 1. Capacitive sensors: Circular, Rectangular, PCB Gadget (PCB) and AOGAN sensors (left to right). The Arduino-based board controller is also shown to the right.](image)

Regarding sensor specifications, the Circular sensor is composed of two concentric plates comprising the electrodes. This sensor can measure up to 24 pF capacitance, with a linearity of ± 0.01% and accuracy of ± 4 fF factory calibrated. The positive supply voltage can vary between + 0.3 and + 6.5 V and it has an operational frequency of approximately 32 kHz [75]. The Rectangular sensor has 12 capacitance sensing inputs and was programmed to measure a capacitance range from 0.45 pF to over 340 pF (depending on the programming code), has a positive supply voltage of 1.71 to 3.6 V operated at 400 kHz [76] and the sensing electrodes are covered with an insulating layer. The PCB sensor is a capacitive sensor comprising a single electrode to measure changes in the capacitance of a material operating at a frequency of 500 kHz [77]. The fourth sensor, the AOGAN sensor, was manufactured by adopting a similar shape to the Circular sensor, with an insulating layer, with a similar controller board as the Rectangular sensor and with an operating frequency of 400 kHz. The sensor was also operated by an Arduino-based board.

4. Experimental Procedure

A description of the testing and development of the sensors for the non-invasive soil water content estimation is presented in the following sections.

4.1. Sample Preparation and Dielectric Measurements

Soil samples were crushed and subsequently prepared from the air-dry condition to saturation, by incrementally adding deionised water. This incremental addition of water was achieved by thoroughly mixing the soil and allowing adequate curing time for the samples to attain a homogeneous state. Deionised water was used to minimise the introduction of any foreign ions to the soil samples, which may have potentially influenced the dielectric properties. The soil was then transferred to a non-dielectric (PVC) container with a known volume and a size adequate to accommodate the Agilent
dielectric probe and capacitive sensor. We initially used a PVC container with similar dimensions to a standard compaction mould (approximate volume of 1000 cm³, see [78]) and later changed to a smaller PVC mould with the same diameter (10 cm) and a volume of approximately 160 cm². We initially tested the bulk density effects, by preparing samples at different dry densities using the larger mould. However, since the sensitivity of the sensor to density variation was deemed to be insignificant, we opted to use a smaller mould to expedite the experimental program. It is important to note that the size of the smaller PVC mould was selected such a way that the thickness of the soil was larger than the sensing sphere and the sensing geometrical element of the sensor(s) and the open-ended coaxial probe. For each dielectric and capacitance measurement, the container volume and the mass of the soil were recorded, to be used in the computation of the sample’s volumetric water content. The PVC containers were chosen to minimise electromagnetic interference. Prior to the dielectric measurements, the probe was calibrated against air, a shorting block and deionised water. Thereafter, at least three measurements were taken for a given sample, on different parts of the sample’s surface area to ensure that the dielectric constant measurement was an accurate representation of the entire sample. Contact between the probe and the soil was carefully maintained to ensure that there was no air trapped between them. Figure 2 depicts a typical instrument and sample setup used in the experiment.

The dielectric probe measurements were followed by measurements using the four capacitive sensors (explained in detail in the next section). Lastly, a sub-sample was retrieved for subsequent gravimetric and volumetric water content, θ, calculations, using the soil sample dry density derived from the known volume of the container and the measured soil mass [79]. It is worth mentioning that the sub-samples for oven drying were retrieved from the uppermost layer of the sample (around 10 mm) which was estimated to be within the sensing volume of the various probes used. This was to ensure that the sensor outputs were calibrated against a representative volume. The approach undertaken to conduct the capacitive measurements is described in the next section.

4.2. Capacitive Sensor Measurements

Once the sample was prepared, the following measurement protocol was followed for each of the sensors. Firstly, a measurement was conducted whilst the sensor was free in the air and recorded as an air measurement. Subsequent measurements were undertaken by placing the sensor against
the surface of the sample and by applying a weight (minimum 200 g) on top of the sensors to ensure a good soil-sensor contact was maintained, without any noticeable air gap between the soil and the sensor. Air gaps could potentially lead to errors in the capacitive reading and thus in the soil water content estimation. To ensure the soil-sensor contact was maintained, a slightly heavier load was used for sensors with a larger footprint. Once the full contact was maintained and consistent readings were obtained from the sensor, the data was recorded on a computer. This procedure was repeated typically three times for each sample to obtain readings that were accurate representations of the entire sample. Once the air and sample readings were recorded, the air reading was subtracted from the reading taken from the sample. This was done to minimise the effect of the environment (such as humidity and temperature) on the measurements. Moreover, this can be considered as a basic and simple calibration to normalise the measurements with respect to the air reading.

It is worthwhile to note that the effect of pressure on the output of the sensor was tested through a separate set of experiments. The sensor readings were monitored while various pressures were applied to the sensor as it was sitting on a flat surface. Once full contact was maintained between the sensor and the material under test, changing the amount of pressure was proven to have no impact on the readings (results are not shown).

The approach for the Rectangular sensor was slightly different due to its multiple-electrode design. As this sensor is comprised of twelve sensing electrodes, twelve readings were obtained from a ‘single’ measurement. In addition, due to the use of 12 electrodes and the relatively larger size of the sensor unit compared to the Circular sensor, some variations were observed in the readings (results are shown later in the paper in Sections 5.2 and 5.7). This is likely due to the fact that despite the sample surface being levelled, there still existed some relative surface roughness which may have created an uneven contact between the soil and some of the electrodes, causing noticeable dissimilarities between different electrode readings. To overcome this issue, instead of averaging the twelve readings, which was the approach adopted in the work previously reported by Orangi, et al. [80], the maximum reading among the twelve readings for a given measurement was used for the analysis. Based on the observations throughout this work and the findings highlighted by Orangi, Withers, Langley and Narsilio [80], it was assumed that for a given sample, the larger reading values were derived from the better soil-sensor contact conditions and thus more representative of the true soil water condition. Further details are included in the following section.

With regard to the PCB sensor, the measurements were conducted without using a weight; the sensor was simply held by hand against the sample surface whilst ensuring full contact was maintained. The measurements with the Circular and AOGAN sensors were conducted as described in the general procedure.

5. Results, Analyses and Discussion

Firstly, the results are summarised for each sensor and soil sample and individual calibrations are derived. Next, an evaluation of the applicability of a single calibration (all soil types) for each sensor is presented. This is followed by an evaluation of the efficacy of using a separate calibration for sandy soils (i.e., combining the Brighton Group Sand and Silty Sand data—referred to as sand group in this manuscript) and for cohesive soils (i.e., combining Camb Clay and Bun Silt data—referred to as clay groups in the manuscript) for each sensor. The dielectric properties of the samples are then estimated based on capacitive measurements and lastly, the effect of soil sensor coupling and surface roughness on sensor performance is evaluated by using the results of the present study and of Orangi, Withers, Langley and Narsilio [80].

5.1. Circular Sensor

Results of the Circular sensor performance against volumetric water content are shown in Figure 3. Each plot includes capacitance readings measured by the sensor and the dielectric constants from the dielectric probe versus the volumetric water content for each soil sample. The capacitance and
dielectric measurement data are plotted with blue squares and black triangular markers, respectively. Moreover, the “expected” volumetric water content based on the Topp calibration and the measured dielectric constant (Equation (4)) is superimposed on the plot (dashed grey trend line).

Figure 3 illustrates an increasing trend captured by the Circular sensor for the four samples; however, with different levels of accuracy. As was explained in the theory and background section, an increase in the soil volumetric water content causes an increase in the dielectric constant of the soil, due to the larger number of water dipoles. An increase in the capacitance is also expected since Equation (4) shows that the relationship between capacitance and the dielectric constant is directly proportional.

For the Brighton Group Sand and the Silty Sand samples (i.e., the coarse-grained soil samples), the sensor was able to capture the variation of water content with capacitance; however, the correlations show errors in the order of 10%.

For the Camb Clay and Bun Silt (i.e., the fine-grained soil samples), it is observed that the Circular sensor is able to capture the increasing trend; however, the correlations compared to the sand samples are significantly less obvious, as shown by the significantly reduced coefficient of correlation, $R^2$.

The Topp calibration predictions shown by the dashed grey trendlines show a good agreement up to approximately 5% and 12% for the Brighton Group Sand and Silty Sand, respectively. However, as the water content increases, the Topp calibration overestimates the data. Surprisingly, the Topp
calibration seems to fit the measured data for the cohesive soils tested here better than for the sandy soils, which is contrary to the assumptions made in deriving the calibration. It is worth mentioning that the $R^2$ for the Topp calibration describes how well this calibration captures the data.

Table 2 quantitatively summarises the best fit models and the measure of errors obtained for the Circular Sensor and the dielectric probe for the four soil samples. Additionally, the universal Topp calibration performance for each soil type is assessed. The results in the table confirm that the Circular Sensor can capture the increasing trend for the sand samples. Furthermore, for the cohesive samples, a very weak increasing trend could be identified from the data for both Camb and Bun samples, however, with an unacceptable level of accuracy and large errors. Despite the relatively low $R^2$ values for capacitive readings, it is worth mentioning that the dielectric probe measurements have shown some similar variations compared to the corresponding capacitive measurements for the first two soil samples.

Table 2. Summary of the Circular Sensor and dielectric probe performance against each soil sample.

<table>
<thead>
<tr>
<th>Soil Sample</th>
<th>Circular Sensor</th>
<th>Dielectric Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation</td>
<td>$R^2$</td>
</tr>
<tr>
<td>Brighton Group Sand</td>
<td>$\theta = 0.43C^{0.16}$</td>
<td>0.71</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>$\theta = 2.57C^{0.88}$</td>
<td>0.67</td>
</tr>
<tr>
<td>Silty Clay (Camb)</td>
<td>$\theta = 2.26C^{0.96}$</td>
<td>0.35</td>
</tr>
<tr>
<td>Clayey Silt (Bun)</td>
<td>$\theta = 2.31C^{1.12}$</td>
<td>0.50</td>
</tr>
</tbody>
</table>

$\theta = \text{Volumetric Water Content}, C = \text{Capacitance (pF)}, R^2 = \text{Coefficient of Correlation}, \text{RMSE = Root Mean Square Error}.$

A two-fold cross-validation analysis for the Circular Sensor was conducted (similar to other sensors in the next sections). In this analysis, half of the data is used for conducting a calibration and subsequently, the remainder of the data is used for validation. The results are summarised in Table 3 which further proves the weak performance of the Circular Sensor based on the low $R^2$ values and large errors.

Table 3. Cross validation analysis for the Circular sensor for each soil.

<table>
<thead>
<tr>
<th>Soil Sample</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>RMSE (%)</td>
</tr>
<tr>
<td>Brighton Group Sand</td>
<td>0.69</td>
<td>7.63</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>0.63</td>
<td>4.25</td>
</tr>
<tr>
<td>Silty Clay (Camb)</td>
<td>0.31</td>
<td>11.82</td>
</tr>
<tr>
<td>Clayey Silt (Bun)</td>
<td>0.44</td>
<td>11.27</td>
</tr>
</tbody>
</table>

It is important to note that during measurement with this sensor, an instability issue of the reading occurred and the sensor could not retrieve any readings for some samples. This instability issue is attributed to the controller board of the Circular Sensor, as well as the lack of permanent insulating coating on the electrodes which may have created short circuits during measurements and the difficulties in achieving full soil-sensor coupling.

These reasons collectively have resulted in the relatively low performance of the Circular Sensor, particularly for fine-grained soils. Despite its weak performance, Circular Sensor demonstrates promising potential in detecting the variation in soil water content using non-invasive capacitive sensors. In view of the observed limitations, we have developed the Rectangular Sensor, whose results are described next.

5.2. Rectangular Sensor

The Rectangular sensor comprised 12 electrodes and each electrode returned a reading upon being in contact with the soil sample. Essentially, since the water content of the sample is envisaged
to be homogeneous due to the sample preparation method, it is expected that the output from
the 12 electrodes are similar or only with marginal variations due to electrodes layout. Therefore,
it would be reasonable to report the mean of the 12 readings as the capacitive value for a given
sample. This approach was adopted in a previous study by Orangi, Withers, Langley and Narsilio [80];
however, the Rectangular sensor performance was deemed unsatisfactory in that preceding study.
In this work, the maximum reading (instead of the average) was adopted. The rationale for this choice
was explained previously in Section 4.2 and the results are given in Section 5.7.

Figure 4 summaries the results of the Rectangular sensor against the volumetric water content.
With the Brighton Group Sand and the Silty Sand samples, the (directly proportional) trend between
the sensor readings and the volumetric water content can be clearly seen. In Figure 4a,b (coarse-grained
soils), the sensor readings (blue square markers) show a strong correlation with increasing volumetric
water content, which resembles the variations observed in the measured real dielectric constants (black
triangular markers).

For the fine-grained soils tested, the proportional trend between the capacitive reading and the
volumetric water content can be clearly seen for both samples, as opposed to for the Circular sensor,
where this trend had a weak resemblance due to the discussed limitations. Moreover, the instability of readings and the limited measurement range issues encountered by the Circular sensor are resolved here. The improvements are considered to be the result of the new controller as well as the larger geometry of the sensor, which facilitated maintaining full contact between the soil and sensor. However, it can be seen that electrodes returned almost constant readings despite the increase in sample water content (Zone A in Figure 4d), presumably due to the partial contact of electrodes for the Bun Silt samples with rougher soil surfaces. Indeed, soil trimming and surface smoothing were more difficult to achieve for the Bun Silt samples with water content between 20% and 30% (close to optimal water content). Otherwise, the trend is well captured by the Rectangular sensor for each of the sandy and cohesive samples.

The issue with the limited measurement range appeared for this sensor as well; however, at a much higher water content than when using the Circular sensor. As a result, the measured capacitive data beyond approximately 45% volumetric water content form a cluster of data points, as illustrated in Zone A of Figure 4c. That is, beyond approximately 40% water content, the sensor reached its upper limit and could no longer capture variation in the water content. Although the sensor was unable to differentiate the water content beyond this threshold, this situation is not commonly encountered in practice, since the threshold would be generally above the soil field capacity for most of the soils. Hence, this is not considered a major issue for the Rectangular sensor.

Table 4 summarises the correlations obtained for the Rectangular sensor and the dielectric probe against volumetric water content. A power fit between the capacitive reading and the volumetric water content describes the correlations and indicates a good agreement (refer to Figure 4).

Table 4. Summary of the Rectangular sensor and dielectric probe performance against each soil sample.

<table>
<thead>
<tr>
<th>Soil Sample</th>
<th>Rectangular Sensor</th>
<th>Dielectric Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation R² RMSE (%)</td>
<td>Equation R² RMSE (%)</td>
</tr>
<tr>
<td>Brighton Group Sand</td>
<td>( \theta = 0.63C^{0.77} ) 0.96 4.11</td>
<td>( \theta = 0.057C^2 + 2.48C - 3.92 ) 0.98 1.08</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>( \theta = 1.03C^{0.65} ) 0.96 3.52</td>
<td>( \theta = -0.025C^2 + 2.04C - 2.5 ) 0.93 2.86</td>
</tr>
<tr>
<td>Silty Clay (Camb)</td>
<td>( \theta = 1.44C^{0.65} ) 0.92 4.95</td>
<td>( \theta = 0.015C^2 + 2.09C - 2.5 ) 0.95 4.17</td>
</tr>
<tr>
<td>Clayey Silt (Bun)</td>
<td>( \theta = 2.22C^{0.60} ) 0.78 11.22</td>
<td>( \theta = 0.034C^2 + 2.34C - 2.34 ) 0.98 1.80</td>
</tr>
</tbody>
</table>

\( \theta = \text{Volumetric Water Content, } C = \text{Capacitance (pF), } R^2 = \text{Coefficient of Correlation, RMSE = Root Mean Square Error.} \)

Based on these results, the Rectangular sensor appears to have effectively predicted the variation of the volumetric water content. However, the size of the sensor may hinder good soil-sensor coupling (e.g., Bun Silt). This is thought to be due to the relatively larger size of the Rectangular sensor which made working with samples such as Bun Silt harder where the sample surface presented large undulations.

The results of the cross-validation study for the Rectangular sensor are summarised in Table 5.

Table 5. Cross validation analysis for the Rectangular sensor for each soil.

<table>
<thead>
<tr>
<th>Soil Sample</th>
<th>Calibration R² RMSE (%)</th>
<th>Validation R² RMSE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brighton Group Sand</td>
<td>0.96 3.40</td>
<td>0.97 5.35</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>0.95 3.20</td>
<td>0.95 3.95</td>
</tr>
<tr>
<td>Silty Clay (Camb)</td>
<td>0.93 4.90</td>
<td>0.93 5.17</td>
</tr>
<tr>
<td>Clayey Silt (Bun)</td>
<td>0.78 10.32</td>
<td>0.78 14.18</td>
</tr>
</tbody>
</table>

The calibration function for each soil, which was based on half of the experimental data, is shown to be able to predict the behaviour of the remainder of the dataset with a strong correlation. Moreover, the RMSEs of the validation dataset are comparable to the ones from the calibration. This analysis further demonstrates the capability of the Rectangular sensor in predicting the variation in soil moisture.
content of different soil types. Nonetheless, there are limitations with regard to the multiple electrode design as well as the size of the sensor; these limitations were addressed in the development of the fourth sensor.

5.3. PCB Sensor

The PCB sensor had a large geometry and sensing area compared to the Circular sensor, however, was smaller than the Rectangular sensor. Therefore, maintaining good coupling between the soil and the PCB sensor was relatively easy due to its size and being a single electrode. Figure 5 depicts the variation of PCB sensor outputs with water content, alongside the measured dielectric constants for all of the samples. A clear trend between capacitive readings and volumetric water content is shown across the samples; however, with a much lower sensitivity to water content beyond 15%. For the soil samples shown in Figure 5, the change in sensor readings is significantly larger for a water content variation from dry to approximately 15%, than for a water content variation beyond 15%. This clearly indicates that the PCB sensor is able to distinguish the changes in the water content; however, with a significantly reduced ability to accurately estimate the water content beyond 15%. This further highlights the limited capability of this sensor to estimate the water content of the fine-grained soils tested here, which can generally have water content above 15% in natural conditions.

Figure 5. PCB sensor capacitance, C, readings (blue square markers and trendline) and dielectric constant, \( \kappa' \), measurements (black triangular markers and trendline) shown against the volumetric water content, \( \theta \); the Topp equation is also shown (dashed grey trendline). Shown for: (a) Brighton Group Sand (b) Silty Sand (c) Camb Clay and (d) Bun Silt.

Table 6 summarises the calibration obtained for the PCB sensor as well as for the dielectric probe. The values show that the performance of the PCB sensor in predicting the water content is...
comparable to that of the dielectric probe; nonetheless, with the aforementioned limitation regarding the measurements for samples with water content beyond 15%, indicated by higher errors despite high $R^2$ values (see Table 6).

**Table 6.** Summary of the PCB sensor and dielectric probe performance against each soil sample.

<table>
<thead>
<tr>
<th>Soil Sample</th>
<th>PCB Sensor Equation</th>
<th>PCB Sensor $R^2$</th>
<th>PCB Sensor RMSE (%)</th>
<th>Dielectric Probe Equation</th>
<th>Dielectric Probe $R^2$</th>
<th>Dielectric Probe RMSE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brighton Group Sand</td>
<td>$\theta = 0.007C^{2.63}C$</td>
<td>0.91</td>
<td>3.96</td>
<td>$\theta = 0.057C^2 + 2.48C - 3.92$</td>
<td>0.98</td>
<td>1.08</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>$\theta = 0.017C^{2.40}$</td>
<td>0.77</td>
<td>7.10</td>
<td>$\theta = -0.029C^2 + 2.11C - 2.5$</td>
<td>0.95</td>
<td>2.38</td>
</tr>
<tr>
<td>Silty Clay (Camb)</td>
<td>$\theta = 0.003C^{2.28}$</td>
<td>0.84</td>
<td>9.67</td>
<td>$\theta = 0.015C^2 + 2.09C - 2.5$</td>
<td>0.95</td>
<td>4.17</td>
</tr>
<tr>
<td>Clayey Silt (Bun)</td>
<td>$\theta = 0.008C^{2.8}$</td>
<td>0.96</td>
<td>3.75</td>
<td>$\theta = 0.034C^2 + 2.34C - 2.34$</td>
<td>0.98</td>
<td>1.80</td>
</tr>
</tbody>
</table>

$\theta =$ Volumetric Water Content, $C =$ Capacitance (pF), $R^2 =$ Coefficient of Correlation, RMSE = Root Mean Square Error.

Cross-validation analysis was performed for the PCB sensor and the results are summarised in Table 7. The results suggest that the PCB sensor is able to capture the increasing trend between the capacitive reading and volumetric water; however, the errors are relatively large. The large errors are assumed to be the result of the reduced sensitivity of the PCB sensor.

**Table 7.** Cross validation analysis for the PCB Sensor for each soil.

<table>
<thead>
<tr>
<th>Soil Sample</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2$</td>
<td>RMSE (%)</td>
</tr>
<tr>
<td>Brighton Group Sand</td>
<td>0.91</td>
<td>3.36</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>0.76</td>
<td>6.72</td>
</tr>
<tr>
<td>Silty Clay (Camb)</td>
<td>0.855</td>
<td>9.44</td>
</tr>
<tr>
<td>Clayey Silt (Bun)</td>
<td>0.96</td>
<td>0.95</td>
</tr>
</tbody>
</table>

From these results, it is concluded that the geometry of the PCB sensor rectifies the sensor-soil contact issue. Moreover, the design is further enhanced by being a single electrode (similar to the Circular sensor) as opposed to being a multiple electrode design (e.g., the Rectangular sensor). However, there is the issue of sensitivity, caused by the controller board of the PCB sensor, which precludes accurate and reliable estimation for soils with water content above 15%.

### 5.4. AOGAN Sensor—An Integrated Sensor Designed Utilising the Advantages of the Previous Sensors

It is shown in the previous sections that the Circular, Rectangular and PCB sensors are able to capture changes in soil water content. However, there are advantages and limitations associated with each of the sensors.

In summary, the advantages are as follows: Firstly, a single electrode helped to maintain superior soil-sensor contact (Circular and PCB sensors) and showed a lower sensitivity to high frequency surface undulations relative to the sensor size (PCB sensor). Secondly, the controller board of the Rectangular sensor provided a reliable capacitive sensing range, facilitated stable readings and enabled working with samples with high water content. Moreover, the insulating agent coating the Rectangular sensor effectively prevented potential short circuit issues when dealing with very wet soil samples. Similar to that of the PCB sensor, the larger geometry of the Rectangular sensor created a better platform for conducting the measurements and maintaining good soil-sensor coupling or contact. Nonetheless, the significantly larger design of the Rectangular sensor proved to be problematic for some measurements (e.g., Bun Silt samples). Furthermore, from the perspective of conducting the measurements, the shape of the Circular sensor proved to be superior than that of the other two sensors, in maintaining contact and in the ease of use.
On the other hand, key limitations include the inadequate sensing range and the instability issue of the Circular sensor, the multiple electrodes and significantly larger geometry of the Rectangular sensor and the limited sensitivity issue of the PCB sensor.

The AOGAN sensor was designed by combining the identified advantages of the Circular, Rectangular and PCB sensors and eliminating their identified limitations. As such, the design of the AOGAN sensor was inspired by the shape and single electrode design of the Circular sensor and the larger geometry of the PCB sensor and incorporated a board designed and printed to act as the sensing component. This sensing component was almost three times larger than that of the Circular sensor to help with increasing the sensing range and was accompanied by a waterproof agent (similar to the Rectangular and the PCB sensors) to eliminate the potential short circuit issue. It is important to note that using an insulating film creates a sensor that is measuring two capacitors in series: formed by the insulating film and the soil, respectively. However, since the thickness of the insulating film was less than 0.05 mm, we assumed that the effect on the soil water content estimation was minimal. The larger geometry and the single electrode design improved practicality for conducting measurements. Furthermore, the sensing component was controlled by a board similar to the one used in the Rectangular sensor (which provided a more stable and larger sensing range and readings). The sensing component and the controller board were then connected to an Arduino-based board which communicated with a laptop. The program used for controlling the AOGAN sensor was the same as the one used for the Rectangular sensor.

An experiment was designed to estimate the sensing range of the sensor. Based on the methodology described by Orangi and Narsilio [71], a wet soil sample was prepared with the Silty Sand and was placed on a lab jack. The initial distance between the sample and the sensor was at 50 mm and the sample has subsequently approached the sensor at small increments controlled by a dial gauge. The capacitance measurements were recorded until a full contact between the soil and sensor was achieved. The result of this experiment is shown in Figure 6. The normalised sensor output, $S_N$, is plotted against the separation between the soil sample and the sensor, $\Delta$. The figure shows that the sensing range is within 10 to 16 mm. We have estimated, therefore, that the depth that the sensor is able to estimate soil water content is around 10 mm. It is worth mentioning that the full contact between the soil and the sensor resulted in a more reliable sensor output.

![Figure 6. Normalised Sensor reading, $S_N$, against the distance between the soil sample and sensor $\Delta$.](image)

Figure 7 depicts the strong correlations obtained between the AOGAN sensor capacitive readings and water contents for all of the samples that were tested. Minimal issues were encountered with regard to soil-sensor coupling, instability, sensing ranges and low sensitivity to water content variation,
which were observed for the previous sensors. It is assumed that this enhanced performance is a result of the advantageous features incorporated in the design of the AOGAN sensor.

**Figure 7.** AOGAN sensor capacitance, $C$, readings (blue square markers and trendline) and dielectric constant, $\kappa'$, measurements (black triangular markers and trendline) shown against the volumetric water content, $\theta$; the Topp equation is also shown (dashed grey trendline). Shown for: (a) Brighton Group Sand (b) Silty Sand (c) Camb Clay and (d) Bun Silt.

It is important to note that the preparation of samples plays a key role in the surface quality status of the soil samples, which impacts the quality of the soil-sensor contact or coupling. In practical applications, it is crucial to note that the deployment of sensors in the field requires the development of a mechanism that maintains full soil-sensor contact. This is to ensure a reliable sensor performance, as was observed during the laboratory measurements where the contact was maintained by using a weight.

As shown in Figure 7d, there are some samples for which the standard deviations of the measurements (error bars) are relatively large, possibly due to the contact issue between the soil and the sensor. These are some of the same samples for which the rectangular sensor was unable to capture the soil water content variations; however, the AOGAN sensor showed less sensitivity to surface undulations due to its smaller size. The large standard deviations may, therefore, be the result of inadequate trimming of the samples and not the sensor hardware. Additionally, the inconsistency in the soil water content of a given sample was most likely not the reason for such discrepancies, since the samples were mixed thoroughly and cured during the preparation stage. As a result, it can be assumed that the water content was relatively homogenous for a given sample. The errors involved in
soil water content estimation based on the calibration for this sensor were less than 5%. A summary of the results is shown in Table 8.

### Table 8. Summary of the AOGAN sensor and dielectric probe performance against each soil sample.

<table>
<thead>
<tr>
<th>Soil Sample</th>
<th>AOGAN Sensor</th>
<th>Dielectric Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation R² RMSE (%)</td>
<td>Equation R² RMSE (%)</td>
</tr>
<tr>
<td>Brighton Group Sand</td>
<td>( \theta = 0.94C^{1.23} ) 0.91 3.88</td>
<td>( \theta = 0.057C^2 + 2.48C - 3.92 ) 0.98 1.08</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>( \theta = 1.41C^{1.15} ) 0.91 4.8</td>
<td>( \theta = -0.025C^2 + 2.04C - 2.5 ) 0.93 2.86</td>
</tr>
<tr>
<td>Silty Clay (Camb)</td>
<td>( \theta = 1.23C^{1.31} ) 0.97 2.78</td>
<td>( \theta = 0.045C^2 + 2.74C - 2.5 ) 0.88 4.96</td>
</tr>
<tr>
<td>Clayey Silt (Bun)</td>
<td>( \theta = 1.49C^{1.18} ) 0.96 4.4</td>
<td>( \theta = 0.034C^2 + 2.34C - 2.34 ) 0.98 1.80</td>
</tr>
</tbody>
</table>

\( \theta \) = Volumetric Water Content, \( C \) = Capacitance (pF), \( R^2 \) = Coefficient of Correlation, RMSE = Root Mean Square Error.

Overall, considering the improved performance attributes, the AOGAN sensor shows great potential to estimate the soil water content non-invasively.

The cross-validation analysis results for the AOGAN sensor are given in Table 9. Overall, the statistical measures for the calibration and validation functions show the strong capability of the AOGAN sensor to capture the variations of the volumetric water content of soils. The values in the table also show the superior performance of this sensor compared to the other three sensors (See Tables 3, 5 and 7).

### Table 9. Cross validation analysis for the AOGAN sensor for each soil.

<table>
<thead>
<tr>
<th>Soil Sample</th>
<th>Calibration</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R² RMSE (%)</td>
<td>R² RMSE (%)</td>
</tr>
<tr>
<td>Brighton Group Sand</td>
<td>0.89 3.83</td>
<td>0.89 4.66</td>
</tr>
<tr>
<td>Silty Sand</td>
<td>0.92 4.13</td>
<td>0.92 4.79</td>
</tr>
<tr>
<td>Silty Clay (Camb)</td>
<td>0.97 2.48</td>
<td>0.97 3.07</td>
</tr>
<tr>
<td>Clayey Silt (Bun)</td>
<td>0.96 4.02</td>
<td>0.96 4.75</td>
</tr>
</tbody>
</table>

5.5. Effect of Soil Type on the Calibration of the Sensor

It is reported in the literature that the relationship between a soil’s electrical properties and its water content is determined by the soil type [81–83]. It is, therefore, imperative to evaluate the extent of soil type effects on the performance of the sensors in this work. In the results section, we showed that for sensors with good performance, a separate calibration could adequately describe the data for each soil sample. However, employing a single calibration for each individual soil type may not be practical and could become a tedious task in practice. This likely explains why a single calibration has been adopted for a range of soil types in previous studies (e.g., see [53,54,84,85]). The empirical Topp calibration proposed by Topp, Davis and Annan [53] was based on soils ranging from heavy clay to sandy loam; however, it is unable to accurately estimate the water content of some soil samples tested in the current study and also in a number of previous studies (e.g., [86–90]). Nonetheless, it is currently one of the most widely used empirical calibrations for estimating water content using soil dielectric properties. Therefore, following the same approach, we evaluated the efficacy of using a single calibration for each sensor in the present study. Data from the four samples was collated as a dataset and the performance of each sensor and the dielectric probe was analysed against it.

Figure 8 shows the collated capacitance readings and real dielectric constant data for the four samples plotted against volumetric water content. The Topp calibration is also shown for comparison. For clarity, the standard deviations of the measurements have been removed. The collation of capacitive data is shown by highlighted yellow markers and different markers correspond to different soil types, captured by a blue trendline. The capacitive readings are fitted with a power function as in the previous section. The measured dielectric constants and the corresponding trendlines are shown by black triangular markers and black trendlines, respectively.
Figure 8. Combined capacitance, C and dielectric constant, $\kappa'$, data versus volumetric water content, $\theta$, for: (a) Circular, (b) Rectangular, (c) PCB and (d) AOGAN sensors. Highlighted yellow markers capture the capacitive data for all soils and different markers represent different soil samples captured by the blue trendline. Black triangular markers and dashed trendlines correspond to dielectric measurements. Topp calibration is shown by the dashed grey trendlines.

As seen previously, the Circular sensor was unable to capture the variation of soil water content for the cohesive samples (Figure 8a); it was better able to capture the trend for the sandy samples. In addition, the instability issue occurred for all of the soil samples. Therefore, due to these two issues, combining the data for this sensor to evaluate the efficacy of a single calibration has resulted in a weak correlation ($R^2 = 0.53$) and large errors ($\approx 10\%$) as presented in Table 10.

Table 10. The response of each sensor against the combined dataset. The response of the dielectric constant data against the corresponding dataset used for each sensor is also shown.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Dielectric Probe</th>
<th>Equation</th>
<th>$R^2$</th>
<th>RMSE (%)</th>
<th>Equation</th>
<th>$R^2$</th>
<th>RMSE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular</td>
<td></td>
<td>$\theta = 2.09C^{1.05}$</td>
<td>0.53</td>
<td>9.92</td>
<td>$\theta = 0.029\kappa'^2 + 2.21\kappa' - 2.5$</td>
<td>0.90</td>
<td>3.51</td>
</tr>
<tr>
<td>Rectangular</td>
<td></td>
<td>$\theta = 1.31C^{0.66}$</td>
<td>0.87</td>
<td>7.35</td>
<td>$\theta = -0.008\kappa'^2 + 1.82\kappa' - 2$</td>
<td>0.95</td>
<td>3.70</td>
</tr>
<tr>
<td>PCB</td>
<td></td>
<td>$\theta = 0$</td>
<td>0.78</td>
<td>11.94</td>
<td>$\theta = -0.007\kappa'^2 + 1.79\kappa' - 2$</td>
<td>0.95</td>
<td>3.6</td>
</tr>
<tr>
<td>AOGAN</td>
<td></td>
<td>$\theta = 1.24C^{1.23}$</td>
<td>0.92</td>
<td>4.85</td>
<td>$\theta = -0.023\kappa'^2 + 2.09\kappa' - 2.5$</td>
<td>0.92</td>
<td>3.54</td>
</tr>
</tbody>
</table>

$\theta$ = Volumetric Water Content, $C =$ Capacitance (pF), $R^2 =$ Coefficient of Correlation, RMSE = Root Mean Square Error.
By contrast, for the Rectangular sensor shown in Figure 8b, a single calibration describes the dataset with relatively good agreement and resembles the calibration obtained using the dielectric constant data. Nonetheless, using the single calibration for the sensor may clearly lead to overestimating the water content of the sand samples (i.e., Brighton Group Sand and Silty Sand samples that are shown by orange and black markers, respectively) for soils with moisture content above approximately 20%. This is highlighted in Table 10 showing a lower R^2 value (R^2 = 0.87) and relatively large errors (≈7.5%) compared to the calibration for individual soil samples (Table 4). Considering the capacitive measurements obtained by this sensor, one can see two distinct clusters of data versus volumetric water content. These two clusters, in fact, can be categorised as sandy soils and cohesive soils. Thus, two separate calibrations are expected to better estimate the water content for each cluster.

With regard to the PCB sensor, it can be seen in Table 10 that employing a single calibration for describing the capacitive reading versus volumetric water content has resulted in a lower R^2 than for the Rectangular sensor and larger errors. This further suggests that deriving separate calibrations for sand and clay groups can help in better describing the water content variation using the capacitive reading. However, the performance of the PCB sensor was proved to be questionable in the previous sections.

For the AOGAN sensor depicted in Figure 8d, a single calibration is shown to effectively capture the capacitive readings and volumetric water content relationship for the combined dataset (see Table 10). Compared to the previous sensors, due to a weaker contrast between the measurements made for the sand and clay groups, it is suggested that there is a lesser dependency on the soil type for the AOGAN sensor. The improved geometry and controller board design of the AOGAN sensor appears to provide better soil-sensor coupling and readings, which are, in turn, less affected by the soil type. Nonetheless, the data is treated separately in two groups in order to refine the correlations.

Table 10 includes a summary of the data corresponding to the sensors and the dielectric probe calibrations. These calibrations were derived and assessed against the corresponding dataset used for each sensor. It is worth mentioning that the relationship between volumetric water content and dielectric constant data could be adequately described by adopting single calibrations, which are superior to the Universal Topp calibration, as these here become site specific calibrations.

It is shown that the performance of the AOGAN sensor against the combined dataset is superior to that of the other sensors and that it is less affected by the soil type. However, it is suggested that adopting separate calibrations could provide improved predictions for the sensor. Moreover, for the other sensors, distinct behaviour was observed for the sand and clay groups and relatively larger errors were introduced by adopting a single calibration.

Figure 9 shows for each sensor the combined capacitive readings for all of the soils but data are grouped into sands (described by the black solid trendline) and clays (described by the blue dashed trendlines).

It was concluded from previous analyses in Sections 5.1 and 5.5 that the Circular sensor is unable to detect changes in water content of the clayey samples and therefore that the performance of this sensor is not satisfactory at least for the clayey samples. It is unsurprising, therefore, that for this sensor, better performance is observed when using separate calibrations. For the Rectangular sensor, separate calibrations seem to capture the individual groups, rendering smaller errors for each group and higher R^2 values for the sand group, as shown in Figure 9b and Table 11. For the PCB sensor, the predictive performance has smaller errors for both the sand and clay groups compared with the single calibration; whereas, the performance of the AOGAN sensor is less dependent on the soil type, as shown by only a marginal improvement upon employing separate calibrations.
Figure 9. Combined capacitance, $C$ and dielectric constant, $\kappa'$, data versus volumetric water content, $\theta$, for the: (a) Circular, (b) Rectangular, (c) PCB and (d) AOGAN sensors. Highlighted yellow markers capture the capacitive data for all soils and different markers represent different soil samples. Separate calibrations are used for describing the sand group (black solid trendline) and clay group (blue dashed trendline).

Table 11. Performance of the sensors against combined soil, combined sand group and combined clay group data.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>All Soils</th>
<th>Sands</th>
<th>Clays</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation</td>
<td>$R^2$</td>
<td>RMSE (%)</td>
</tr>
<tr>
<td>Circular</td>
<td>$\theta = 2.09C^{1.05}$</td>
<td>0.53</td>
<td>9.92</td>
</tr>
<tr>
<td>Rectangular</td>
<td>$\theta = 1.31C^{0.66}$</td>
<td>0.87</td>
<td>7.35</td>
</tr>
<tr>
<td>PCB</td>
<td>$\theta = 0.006C^{2.78}$</td>
<td>0.78</td>
<td>11.94</td>
</tr>
<tr>
<td>AOGAN</td>
<td>$\theta = 1.24C^{1.23}$</td>
<td>0.92</td>
<td>4.85</td>
</tr>
</tbody>
</table>

It is shown that by employing separate calibrations, all of the sensors obtain better goodness-of-fit and lower error in soil water content estimation. Nonetheless, the predictive performance of the AOGAN sensor improved the least by adopting this approach, which again highlights the superiority of the AOGAN sensor among the other sensors.

5.6. Dielectric Constant Approximation through Capacitive Measurements

It was shown in the previous sections that the readings from the four capacitive sensors correlate (with different goodness-of-fits; 0.57 for the Circular sensor, 0.91 for the Rectangular sensor, 0.87 for the
PCB sensor and 0.94 for the AOGAN sensor) with variation in the volumetric water content. On the other hand, it is known that the capacitance of a capacitor is derived by its geometry and the dielectric constant of its material (refer to Equation (4)). Therefore, can the dielectric constant of the material under test be reliably estimated using the capacitive sensor readings? In this section, correlations between the sensor readings and the dielectric constant data (measured by the Agilent dielectric slim form probe) are obtained, for both the sand and clay groups, for each sensor.

Figure 10 shows the sensor readings versus the dielectric constant data. For each sensor, the data are divided into sand and clay groups and for each a linear correlation which passes through the origin illustrates the relationship shown in Equation (4). This approach enables estimation of the geometry factor, $g$, for the sensors and the dielectric constant from the sensor output.

The performance of the Circular sensor was shown to be unsatisfactory in the previous section and this is verified by the relationship obtained here, represented by the trendline. The Rectangular sensor shows stronger correlations for both soil groups. It is shown that the equations describing the relationships for the sand and clay groups are quite similar, which, in turn, result in similar geometry factors. The geometry factor for any capacitor is a constant value and this is somewhat explained by the similar slopes of the two trendlines of two soil groups. For the PCB sensor, as was explained previously, due to the weak signal-to-noise ratio (i.e., lower sensitivity), the correlation between the sensor reading and the measured dielectric constant is not strong for any of the soil groups. With regard to the AOGAN sensor, due to its improved design and performance, correlations between the sensor readings and the dielectric constant are strongest. In addition, the correlation between capacitive readings obtained from the AOGAN sensor and dielectric constant data are similar for both soil groups and return almost identical geometry factors (See Figure 10d).

The superior performance of the AOGAN sensor (followed by the Rectangular sensor) is demonstrated in this analysis by the strongest proportionality between the sensor readings and the measured dielectric constants.
readings and the measured dielectric constant are strongest. In addition, the correlation between capacitive readings obtained from the AOGAN sensor and dielectric constant data are similar for both soil groups and return almost identical geometry factors (See Figure 10d).

The superior performance of the AOGAN sensor (followed by the Rectangular sensor) is demonstrated in this analysis by the strongest proportionality between the sensor readings and the measured dielectric constants.

In the next section, the effect of sample preparation on the performance of the sensors is discussed.

5.7. Effect of Surface Contact and Roughness

Contact between soil and a sensor and the roughness of a sample’s surface, are demonstrated by the experimental data to be important factors influencing the quality of measurements made with the sensors. It was suggested by Orangi, Withers, Langley and Narsilio [80] that the soil-sensor coupling and soil surface roughness could be responsible for the poor performance of the Rectangular and PCB sensors in their work. Hence, in this section, the raw data from Orangi, Withers, Langley and Narsilio [80] are re-examined to investigate the importance of these factors.

In this present work, of the twelve readings obtained from a single measurement with the Rectangular sensor, the maximum reading was taken as the representative capacitance value instead of using the mean value. This decision was based on the result of the following analysis conducted on the experimental data published by Orangi, Withers, Langley and Narsilio [80] on the Brighton Group Sand. That is, for a set of experiments conducted on the Brighton Group Sand, we have adopted two methods for the analysis. Firstly, for each sample, the variation of capacitance with water content was investigated, using the mean value of the readings from 12 electrodes. The second approach was to use the maximum of the 12 readings obtained by the Rectangular sensor. The results are shown in Figure 11.

![Figure 11](image)

**Figure 11.** Effects of soil sensor coupling on the estimation of volumetric water content, θ, using the Rectangular sensor on the Brighton Group Sand: (a) Mean of 12 readings (Partial contact), (b) Maximum of 12 readings (Improved contact). Data adapted from [80].

As illustrated in Figure 11, the ability of the Rectangular sensor to detect water content variation is improved when the maximum value of the 12 readings is considered as the capacitance value (Figure 11b). It is observed that the $R^2$ value increases by more than 35% when choosing the maximum sensor reading instead of the mean (Figure 11a). Nonetheless, for the Rectangular sensor and the Brighton Group Sand, the value of $R^2$ obtained in the above study ($R^2 = 0.63$) is less than the value obtained in the current study ($R^2 = 0.95$, Figure 4a, Table 4). This is likely attributed to partial contacts exist during the previous experimentation. Therefore, these results suggest that soil-sensor coupling can significantly affect the performance of the sensors. The issue associated with the number of
electrodes discussed in Section 4.2 does not apply to the PCB sensor or other sensors comprising a single electrode; however, by using the data for the Rectangular sensor we can demonstrate the importance of effective coupling, as well as justifying the rationale behind utilising the maximum output as the reading of the Rectangular sensor.

The surface of the soil samples tested by Orangi, Withers, Langley and Narsilio [80] were less smooth than those used in the current study. Figure 12 shows the relationship between the Rectangular sensor readings and the water content data for a Basaltic Clay tested by Orangi, Withers, Langley and Narsilio [80] and for the Camberwell Clay tested in this work. Figure 12a shows the capacitive values (recorded as the mean of the 12 readings) of the Basaltic Clay samples tested by Orangi, Withers, Langley and Narsilio [80], which had rough surfaces. It can be seen in this figure that the correlation between the sensor readings and the water content is very weak. Figure 12b shows the mean capacitive readings for the Camb Clay, which had smooth surfaces. It can be seen that the correlation between the sensor readings and the water content improves significantly with a smoother soil surface. However, the soil-sensor(s) coupling is considered to not be evenly maintained, due to using the mean of 12 readings. Figure 12c shows data for the Basaltic Clay in which the maximum of the 12 readings was taken as the sensor reading. Improved contact and correlation can be seen compared with Figure 12a; however, since the surfaces of the samples were rough the correlation is still weak.

**Figure 12.** Effect of soil surface roughness and sensor contact on the performance of sensors for two clay samples: Basaltic Clay and Camb Clay samples. Basaltic Clay data are from Orangi, Withers, Langley and Narsilio [80].
The weak performance observed in Figure 12a,c is due to the rough soil surfaces associated with sample preparation. Moreover, the standard deviation of the capacitance values from multiple measurements made for a given sample are larger compared to the results of the current study. This appears to be the result of samples having uneven surfaces, creating large variations in sensors readings. However, in Figure 12d, a significant improvement in the quality of the data is shown, owing to the smoothness of the sample surfaces as well as good soil-sensor contact, achieved by taking the maximum measured value of the 12 readings. Therefore, by comparing the results of the current study with the previous study [80] for two clay samples using the Rectangular sensors, it can be concluded that the surface roughness of samples and the soil-sensor contact play vital roles in ensuring reliable measurements.

The Camb Clay and Bun Silt samples had similar surface finishes. Moreover, Figure 13d shows an example of the surfaces of clay samples (i.e., Basaltic Clay) used by Orangi, Withers, Langley and Narsilio [80]. The surface roughness visible in this figure was a result of inadequate trimming of the samples during the preparation step by Orangi, Withers, Langley and Narsilio [80]. It is thought to be the underlying reason for the weak performance of the Rectangular and PCB sensors shown in Figure 12, compared to the results of the current study.

![Figure 13. Typical examples of the prepared samples of: (a) Brighton Group Sand, (b) Silty Sand and (c) Camb Clay from the present study and (d) Basaltic Clay from Orangi, Withers, Langley and Narsilio [80].](image)

Based on the analysis conducted in this section, it is suggested that a smooth surface as well as full coupling between the soil sample surface and the sensor are key factors in ensuring that sensors can effectively estimate the soil water content and detect its variations.

### 6. Potential Applications and Limitations

The new sensors developed in this work do not require insertion into the soil, nor do they require subsamples to be retrieved for subsequent gravimetric calculations. Furthermore, due to their non-invasive nature and the speed of measurements (milliseconds to retrieve a reading), repetitive measurements at the exact same location are possible, which makes these sensors suitable for large-scale near surface soil water content monitoring. A potential application in the agriculture sector could be high spatial and temporal resolution mapping of surface soil moisture, beneficial for farm management. The non-invasive characteristic of the sensors enables frequent soil moisture measurement across a
farm, which aids in decision making concerning sowing time, irrigation and fertiliser scheduling. Moreover, the sensors can provide ground truth data to calibrate satellite image and remotely sensed soil moisture data. Additionally, the new sensors can be used as a real-time monitoring system of near surface soil water content, for quantifying the risk of bushfire and generating warnings to the pertinent authorities when the soil water content falls below a certain threshold. Another potential application includes the use of the new sensors as a quick way of estimating the moisture content of sub-base and stockpile materials in the road construction industry. However, regardless of the application, the quality of the surface where the measurement is conducted against is an imperative parameter. Therefore, a smooth surface must be somehow achieved in the agricultural fields. With the current sensor design, however, it may be impractical to be used as a field sensor. Thus, it is deemed necessary that further mechanical features are added to the sensor to help with soil surface preparation in the field. On the other hand, in road construction applications, when quality assurance (i.e., water content and density measurements) is conducted, the surface of the sub-base layer after each run is considered to be adequately flat and smooth for direct measurement with this sensor.

Regarding limitations of the sensors, it is important to state that the estimation of soil water content is currently limited to approximately 1 cm deep, based on the width of the electrodes, W and their spacing, S, estimated using the approach proposed by Gao, Zhu, Liu, Qian, Cao and Ni [49]. Thus, measurements of deep soil moisture (e.g., up to approximately 1 m), which may be required in precision agriculture, particularly for the horticulture sector, cannot be conducted directly by the sensor from the surface. However, there are crops with shallower root zones, such as vegetables, whose management could benefit from shallower soil water content information. Furthermore, in terms of the accuracy of the data, the errors involved in the soil water content estimation using the AOGAN sensor were found to be in the order of 1 to 5%. Despite the sensor not being able to satisfy the desirable 1% resolution of soil water content data for precision agriculture, suggested by Terry A. Brase [91], it can still be used as a mapping tool for providing comparative assessments of soil water content on large scales. Moreover, accessing surface soil moisture information across large areas and frequently in time allows calibration of evapotranspiration soil models for continuous estimation of soil moisture with depth, valuable for agricultural and hydrological applications (e.g., see [19,27–29]).

Overall, whilst considering the aforementioned limitations, these sensors show promising potential in estimating surface soil water content, with implications in diverse fields including agriculture, bushfire protection management and road construction.

7. Conclusions

The non-invasive estimation of soil water content using capacitive-based sensors was investigated in this research. The experimental program entailed testing four new capacitive sensors, the AD7747 (Circular), MPR121 (Rectangular), PCB and AOGAN sensors, against four soil types. Measurements of the dielectric constant of the samples with an Agilent slim form dielectric probe connected to a FieldFox network analyser aided in the comparison of results, analysis and calibration of sensors. The AOGAN sensor was designed and manufactured based on the key advantages of each of the AD7747 (Circular), MPR121 (Rectangular) and PCB sensors. Promising capabilities were observed for the Rectangular and AOGAN sensors, with relatively small errors to estimate the soil water content, particularly for the latter sensor. The effect of soil type on the performance of the sensor was tested by combining data from the samples and it appeared that a single calibration could be adopted to estimate the soil water content. However, adopting a single calibration for all of the four samples resulted in inferior sensor performance compared to when adopting individual calibrations for sand and clay groups separately. Finally, it was demonstrated that the performance of each of the sensors was affected by the level of contact maintained between the sensor and the soil surface and more importantly by the roughness of the soil surface which impacted the soil-sensor contact area.
Author Contributions: A.O. was primarily responsible for the design, manufacturing, and assembly, of the sensors, undertaking the experimental program, data collection, subsequent data analysis and writing the manuscript. G.A.N. contributed to the design and manufacturing of the sensor, designing the experimental program, data analysis and writing and editing the manuscript. D.R.’s contribution was towards data analysis and editing the manuscript.

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7 Conclusions

7.1 Summary

The use of geophysical methods in soil and site characterisation has become increasingly popular due to their non-destructive nature which, in turn, enables gathering richer spatiotemporal soil information data than by conventional methods in a given timeframe. In particular, electromagnetic EM wave-based techniques have been used in engineering (e.g., geotechnical site investigations, agricultural applications) and non-engineering applications (e.g., archaeological studies) to characterise the subsurface, mapping soil and rock conditions, studying near-surface soil water content, and to gather information about underground features. In these, the key to an efficient use and result interpretation of EM geophysical methods is a robust and clear understanding on the relationship between soil or geotechnical parameters such as water content, density and salinity and its electrical properties, such as dielectric permittivity. Further, to enhance the quality and speed of data acquisition as well as increasing the spatiotemporal availability of the data without compromising costs, the development of new alternative ways to measure soil parameters is crucial. Thus, through an experimental investigation, this thesis has investigated the relationship between geotechnical and other soils physical parameters and their dielectric properties as well as the development of an alternative way of measuring soil water content and density non-invasively.

Firstly, geophysical and geotechnical characterisation on soil samples recovered from eight sites at the ANZAC battlefield were conducted. Geophysical testings included measurements of real and imaginary dielectric constants as well studying the broadband dielectric behaviour for a range of water contents (i.e., oven dried to saturation point) within frequencies varying between 200 MHz and 6 GHz - which cover a range of field geophysical survey techniques (from GPR to remote sensing applications). Site specific empirical correlations between dielectric properties and volumetric water content and frequency were drawn from the characterisation. These correlations are helpful to plan further geophysical studies in this region given that the generic universal correlations may not be accurate for these soils. The findings can be used by other researchers for the purpose of feasibility studies and planning to conduct geophysical surveys in the ANZAC sites. Essentially, the applicability of particular geophysical prospecting (e.g., Ground Penetrating Radar) to this site can be assessed based on the result of this kind of characterisation. Furthermore, other important aspects of geophysical prospecting such as appropriate time of the year (i.e., season) to conduct a survey, effective survey depth and vertical resolution can be determined accordingly. Lastly, the suggested site specific empirical calibrations can be used to link soil parameters such as water content, as proxies to dielectric permittivity to further facilitate result interpretation for future geophysical studies in this iconic region.

As part of the second study we have extended the testings to selected Australian soils from distinct geological formations in Victoria. Similar characterisations were conducted, however, using the combined data set, a new mixture model based on the Soil Mixing Dielectric Model (SMDM) was developed for 500 MHz, 1 GHz and 6 GHz incorporating soil Specific Surface Area as an input parameter in lieu of sand and clay contents. The Specific Surface Area was
found to be a better parameter describing the dielectric behaviour of soil. In addition, we have proposed polynomial calibrations which use specific surface area as an input parameter linking geotechnical and soil dielectric properties.

In the third study, the effects of compaction on the dielectric properties of soil water mixtures with different specific surface areas were experimentally investigated. Compacted specimens at different gravimetric water content were prepared by modifying the compaction test procedure, subsequently followed by dielectric measurements at 1 GHz for the soils ranging from sand to bentonite clay. The results of the experimental work were evaluated based on the use of two simple mixture models (De Loor and Birchak). The effects of dry density on the soil dielectric constant was found to be soil type dependent based on the soil water content. When the water phase in the soil matrix primarily is present in the form of bound water, there is a direct proportionality between the soil dielectric constant and the dry density, irrespective of the soil type. Conversely, when water in soil consists of both free and bound water, the relationship between the dry density and the real dielectric constant becomes soil type dependent. As such, for soil samples with low Specific Surface Area, this relationship remains directly proportional whereas for soils with large Specific Surface Area, this relationship changes to an inversely proportional correlation. Thus, the Specific Surface Area of the samples was proven to be the governing parameter which controls this relationship. Furthermore, refined ranges for the dielectric properties of bound water as well as the geometrical parameter were defined. To further define the threshold for Specific Surface Area further testing conducted on soil samples with similar Specific Surface Area is required. Additionally, soil suction was not also considered in this study, which can be an interesting parameter in investigating the dry density effect on dielectric properties of soil particularly in evaluating the state of soil water. Soil Specific Surface Area and suction are known to be highly correlated in the literature.

In the last part of this research, a new way for estimation soil water content was developed. We initially developed, tested and evaluated three capacitive sensors against four different soil types. Based on the observation from these sensors, a new sensor was designed which is capable of estimating the surface soil water content. It was concluded that among the four sensors, the new sensor is the least sensitive sensor to soil type in estimating soil water content.

It is, however, important to state that the estimation of soil water content is currently limited to approximately 1 cm depth, based on the width of the electrodes. Thus, measurements of deeper soil moisture (e.g., up to approximately 1 m), which may be required in precision agriculture, particularly for the horticulture sector, cannot be conducted directly by the sensor from the surface. Nonetheless, the sensor can be used as a mapping tool for providing comparative assessments of soil water content on large scales. Moreover, accessing surface soil moisture information across large areas and frequently in time allows calibration of evapotranspiration soil models for continuous estimation of soil moisture with depth, valuable for agricultural and hydrological applications. However, to expand the practicality of the sensor, further research is suggested, particularly towards increasing the sensing depth. The sensors were also tested against dry density variations, however, they were deemed insensitive to changes in dry density.
7.2 Limitations

Within the framework of this research, we have studied the dielectric properties of soils from the iconic ANZAC battlefield in Turkey, and soils from different geological formations in Melbourne, Australia. These have resulted in developing site-specific empirical calibrations and mixture models which correlates the dielectric properties of soil with geotechnical parameters using specific surface area of soil samples applicable to soil science, geotechnical and remote sensing applications. Additionally, it was shown that in the gigahertz frequency range the dielectric response of soil to change in dry density is a soil type dependent behaviour controlled by soil Specific Surface Area. At last, we have successfully developed a new sensor to estimate the surface soil water content non-destructively and non-invasively.

One of the limitations of this work was the restricted amount of soil samples that were allowed to be retrieved from the ANZAC battlefield which precluded the investigation of the effects of salinity and mineralogy in the analysis and developing the site-specific models. Furthermore, due to the limited number of soil samples retrieved from Melbourne geological formations and ANZAC battlefield from which the models are derived, the models could be primarily applicable to these particular sites and using these calibrations and models for other sites may not be appropriate. In addition, within this context, we did not investigate the effects of salinity in the overall performance of the newly developed empirical calibrations and mixture models.

Further, the most time-consuming part of the experimental program was the preparation of soil samples. Overall, more than 500 samples were prepared and nearly 2000 dielectric measurements were conducted. Thus, given the nature of this study, experimental errors were inevitable, particularly when an individual sample had to be prepared to study the effect of an individual parameter (e.g., dry density) on dielectric properties. For instance, for investigating the effect of density on dielectric properties (Chapter 5), an individual sample with a different density had to be prepared for each series of dielectric measurement. We could not continuously measure the dielectric properties of a confined sample in a chamber that undergoes densification due to having limited access to a Network Analyse that is compatible with a compatible Electronic Calibration (ECal) module. Further research, therefore, could utilise a network analyse in conjunction with an ECal module to conduct continuous measurements while a sample is densified under a loading machine.

In addition, within our experimental program the frequency range was limited between 200 MHz and 6 GHz due to either the inability of the probe to measure lower frequency bands to study the bound water phase or the limited capability of the network analyser frequency working in higher frequency ranges. These limitations hindered studying the bound water relaxation behaviour with respects to variation in the geotechnical properties (e.g., water content, dry density, mineralogy and specific surface area) and development of models for higher frequency measurements (i.e., > 6 GHz). With regard to the bound water, the thickness of the bound layer was estimated using an existing equation in the literature which could have some errors compared with direct measurements techniques.

The capability of the non-invasive sensor developed is currently limited to approximately 1 cm depth. This can pose some limitations on the immediate use of this sensor in the geotechnical
engineering field. Furthermore, the type of the soils that were used in this part of research did not capture the soil types which are typically used in road construction where the sensor could potentially become an alternative method for soil water content estimation. Furthermore, the soil sensor contact was found to be a crucial element in the performance of the sensor which was effectively maintained by using a weight during our experimentation.

7.3 Future works and recommendations

Based on the preceding research summary and the limitations, the following are suggested to be considered in future researches:

1. Considering the effects of salinity and mineralogical composition on dielectric properties by using a diverse range of soil types in the development of empirical calibrations and mixing models.

2. Utilising a broadband dielectric analysis from kilohertz to gigahertz range which enables a better understanding of the mechanism involved in electromagnetic characterisation of soil, in particular, to study the bound water phase.

3. The above point requires electrical engineering advancement to develop probes and measurement systems that can operate between low and high frequency range (i.e., kilohertz to megahertz). Further, it is suggested to modify the geotechnical laboratory standard testing apparatus such as compaction moulds, oedometer and triaxial cells to accommodate sensors to study dielectric behaviour against geotechnical parameters.

4. It was hypothesised and experimentally investigated that the effect of density on soil dielectric properties is controlled by Specific Surface Area. Further research in this context should focus on phenomenological relaxation models to incorporate the effect of suction which might help in identifying the state of soil water phase based on soil water characteristic curve. Additionally, in relation to the estimation of bound water thickness, direct measurement methods such as Nuclear Magnetic Resonance can be utilised instead of the estimation which was used in this study.

5. With regard to non-invasive sensor development, future studies can focus on the effect of geometry on the performance of the sensors, particularly the sensing depth and sensitive area. Furthermore, to resolve the soil sensor contact issue, further research in electrical engineering could focus on the development of flexible sensor plates or design of mechanical means to aid in improving the contact. Additional research can be devoted to developing a non-invasive sensor for the estimation of soil dry density or both soil water content and dry density simultaneously. In doing so, it is suggested that a wider range of soil types is used to evaluate the sensor performance to further expand the applicability of the sensor within geoenvironmental applications. This development will require interdisciplinary collaboration between geotechnical and electronic and electrical engineering researchers.
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